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# Fatigue life analysis of bolt joints with use of ANSYS software

## Analiza trwałości zmęczeniowej połączeń śrubowych z wykorzystaniem oprogramowania ANSYS

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**The paper presents selected problems of fatigue life of bolt joints. An analysis of factors influencing fatigue life of bolt joints was performed and selected methods of improving life were described. Authors presents examples of numerical calculations with use of ANSYS software which depict influence of pre-tension in the bolt on fatigue life of the joint. Presented results of life calculation were carried out for bolt joint loaded along bolt axis and for bolt lap joint loaded perpendicular to bolt axis.**

**KEYWORDS: bolt joints, pre-tension in the bolt, fatigue life, numerical calculation**

Damage due to material fatigue often occurs in joints of structural elements and can lead to serious failures or catastrophes. Calculation of strength and fatigue life of connections, more and more often performed using numerical methods, are thus an important element of the design process [1-3].

The screws subjected to cyclic tensioning have a shape that is unfavorable from the point of view of fatigue strength. A high concentration of stresses occurs in three parts of the screw: in the place where the screw head passes into the shank of the bolt, in the groove between shank and the thread and in the thread itself.

The screw head is loaded in an unfavorable way because the load is close to the notch (the shank penetrates the screw head). Unfortunately, the radius of rounding between the screw head and the shaft cannot be large due to the cooperation with the edges of the hole. The lower plane of the bolt head and the plane of the joining element should ideally be parallel - otherwise the bolt head is additionally loaded by bending, which weakens the fatigue strength of the bolt.

The groove between the shank and the thread present in some of the bolts is not "critical" from the point of view of fatigue, because its radius is greater than the radius of the grooves in the screw thread where there is a significant concentration of stresses. In addition, the load transmitted from the bolt to the nut is not evenly distributed in the thread. The majority of damage caused by fatigue occurs precisely at this point of the screw.

## Ways to improve the fatigue life of screw connections

In the design process, there are several ways to improve the fatigue life of screws [4-6]. One is to increase the radius of transition between the head of the bolt and the shank, which reduces the concentration of stresses in this location. Another way is to make screw and nut threads by rolling, which results in a fibrous structure that is compatible with the thread profile. Rolling also improves the surface quality and introduces compressive stresses in the screw thread. The durability and fatigue strength of a rolled screw are much better than a screw with a cut screw thread. However, specially made bolts and nuts are not often used in structures exposed to fatigue loads. Designers prefer to rely on screws made of high-strength steel, which allow the use of initial bolt tension, so-called pre-tension.

During assembly it is important to use the proper tightening torque. This increases the average stress, but the amplitude of the stress decreases. Considering the predominance of stress amplitude values, a significant increase in fatigue strength can be achieved in this way.

The mechanism of the influence of initial tension in the bolts on fatigue strength is explained in fig. 1. Elements *A* and *B* are compressed by the preload of the bolt, which creates a compressive force in the contact area between these elements ($P_{contact}$). In unloaded connections $P_{contact} = -P_0$, where $P_0$ is the preload in the bolts. If the connection is loaded with force P, the screw load ($P_{bolt}$) increases, while the force in the contact area $P_{contact}$ is smaller. This means that the load transmission in the connection occurs partly through the bolt and partly through the contact area. The load increase in the screw will be smaller than the load increase of the entire connection. The load increment equation is as follows:

$$P = \Delta P_{bolt} + \Delta P_{contact} \Rightarrow \Delta P_{bolt} = P - \Delta P_{contact} \qquad (1)$$

In the case of increasing load *P* the force in the contact area will be smaller, which means that $P_{contact}$ becomes "less negative", while $\Delta P_{contact}$ is positive. Therefore:

$$\Delta P_{bolt} < P \qquad (2)$$

If the load *P* increases from zero to $P_L$, the contact force decreases from the value $P_{contact} = -P_0$ to reach the value

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$P_{contact} = 0$ at point $E$ (fig. 1). During the same load increase from $P = 0$ to $P = P_L$, the load in the bolt increases from the preload $P_0$ to $P = P_L$. It turns out that the load variation in the screw is much smaller than the load variation of the entire connection, because the preload in the screw increases the average stress value $S_m$ in the load cycle and at the same time reduces the amplitude $S_a$ of this cycle. However, it should be remembered that if $P > P_L$, the contact between the surfaces of the connection elements is lost and the load of the $P_{bolt}$ screw is equal to the applied load $P$.

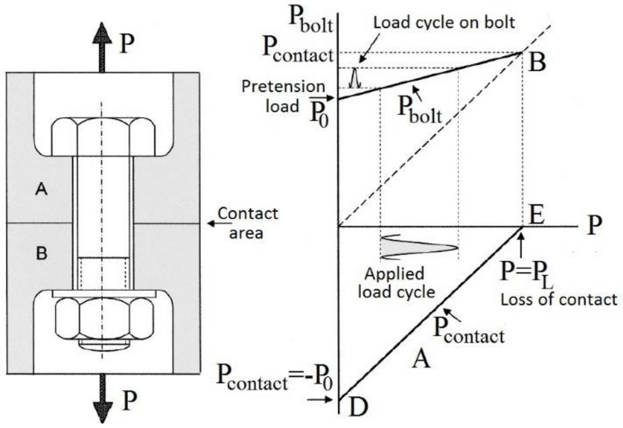

Fig. 1. Illustration of the effect of screw pretension load application [4]

The effect of applying the preload can be enhanced by reducing the stiffness of the screw:

$$\begin{aligned}\Delta P_{bolt} &= C_{bolt}\Delta l \\ \Delta P_{contact} &= C_C \Delta l\end{aligned} \tag{3}$$

where: $C_{bolt}$ - coefficient of stiffness of the bolt, $C_c$ - coefficient of stiffness of the compression material of the joint, $\Delta l$ - elongation of the bolt.

After substituting for equation (1):

$$\frac{\Delta P_{bolt}}{P} = \frac{1}{1 + C_C / C_{bolt}} \tag{4}$$

According to equation (4), the lower coefficient of rigidity of the $C_{bolt}$ screw reduces the force value in the $P_{bolt}$ bolt and the positive effect of the pre-stress is reinforced. The lower coefficient of stiffness of the $C_{bolt}$ screw can be achieved by using a narrowing of the bolt spindle or by using a screw made of a titanium alloy with a smaller (compared to the steel) Young's modulus.

Pre-tensioning has beneficial effects until separation between the contact surfaces is present. For this reason, high-strength steel screws are pre-tensioned up to 70% of the value of the yield point $S_{0,2}$. This also contributes to a more uniform load transfer along the screw thread.

The introduction of bolt preload affects not only the fatigue life of the bolt itself, but also the fatigue life of the entire joint. The load transfer between the overlapping elements, loaded as shown in fig. 2, is provided partly by friction forces. If the initial tension of the bolt is not applied, cracks caused by fatigue begin at the edge of the hole on the surface $A$ (fig. 2).

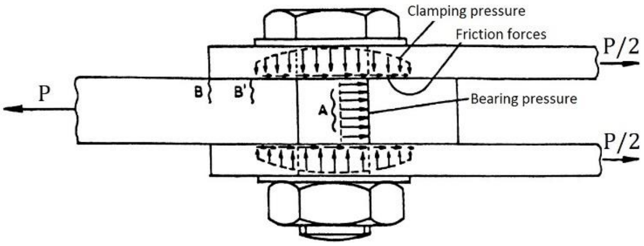

Fig. 2. Changing the crack initiation point after applying the initial screw tension [4]

After introducing the initial tension, the frictional displacement bolts are reduced and a more favorable distribution of stresses takes place. As a result, the fatigue crack initiation moves to point $B$ or $B'$. The improvement of strength and fatigue durability is achieved by increasing the initial value of the bolt tension, but only until the crack initiation is moved to point $B$ or $B'$. Further increasing the value of the initial screw tension will no longer improve the fatigue properties of the joint.

## Numerical calculations of fatigue life of connections with a preloaded screw

Numerical calculations of fatigue life of selected screw joints were carried out in the ANSYS software. The first object studied was a bolt tensioned in the direction of its axis (as in fig. 1). It was assumed that the tested elements were made of structural steel with the Young's modulus $E = 2 \cdot 1011$ Pa, Poisson's ratio $v = 0.3$ and the fatigue strength described in the Wöhler chart (fig. 3). In addition, the fatigue strength correction due to the average stress value was carried out according to the Goodman theory.

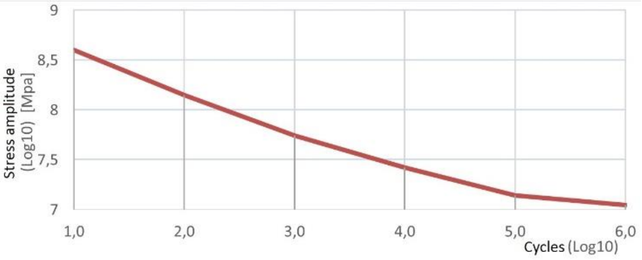

Fig. 3. Wöhler chart for the adopted material [7]

Numerical analysis of the fatigue life of the bolt in the joint was carried out for two load variants:

- without pre-tension and with tensile force varying from 0÷5000 N,
- with a constant bolt preload of 2500 N and with a tensile force varying in the range of 0÷2500 N, which in total gives a maximum load of 5000 N.

It should be noted that the variability of the load applies only to tension, while the constant, initial pretension of the screw increases the value of the average stresses.

As a result of numerical calculations, the fatigue life value for the first variant of the screw load of 90 cycles was obtained, while for the second variant (with preload) fatigue life was 331 cycles (fig. 4).

The obtained results of the calculations confirm the previously formulated conclusion that thanks to applying the initial screw voltage, the predominant positive effect of reducing the stress amplitude is obtained despite increasing the average stress in the screw (disadvantageous from the point of view of fatigue). As a consequence, the fatigue life of the connection is improved.

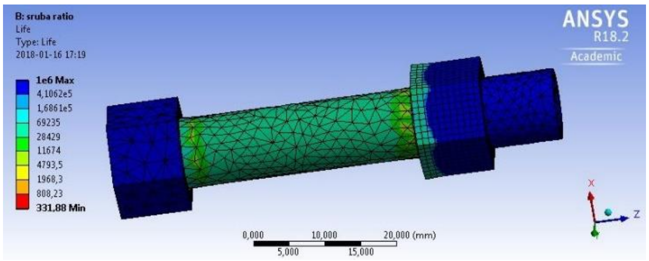

Fig. 4. Result of calculation of fatigue life of the pre-tensioned screw [7]

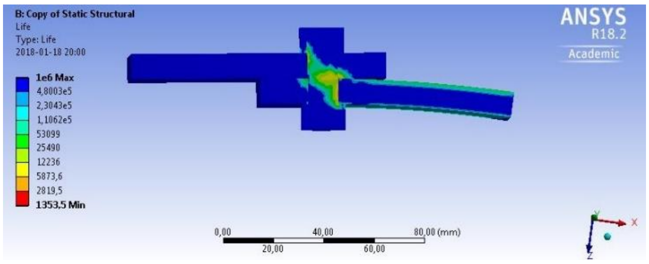

Fig. 5. Calculation of fatigue life of the connection with the preload of the screw [7]

The second type of screw connection analyzed was the overlap connection subjected to load in two variants - with pre-tensioned screw and no pre-tension. This allowed to find an answer to the question how the initial tension of the screw affects the fatigue life of this type of connection. The overlapping model was fixed at the outer end of one overlap, and a 5 MPa drawing load was applied to the outer end of the second overlap. In addition, in the second variant of the calculations, the bolt was tensioned with a force of 2000 N. Between the overlaps, friction was assumed with the coefficient $\mu = 0.3$.

First, the calculation of fatigue life of the overlap joint without the pretension of the bolt was made - its durability was 1,210 cycles. However, for the connection with the initial tension bolts fatigue life (fig. 5) was greater and amounted to 1353 cycles.

According to the analysis made initially, the application of the preloading of the bolt in the overlap joint has a positive effect on its fatigue durability - in the tested case it increased by approx. 150 load cycles.

## Conclusions

The article presents selected ways to improve the fatigue life of screw connections. Particular attention was paid to the use of initial bolt tension. Described by means of mathematical relations and a graphically illustrated mechanism of the effect of initial tension in the bolts on fatigue strength allowed to determine the boundary conditions of occurrence and the possibility of reinforcing the positive effect of the preload of the bolt - both for butt and lap joints.

The examples of numerical calculations with the use of the ANSYS software show the effect of the initial screw tension on the fatigue life of the joint. The presented results of durability calculations, obtained for a bolt loaded along its axis and for a screw joint overlap loaded perpendicularly to the bolt axis, are confirmed by conclusions formulated on the basis of the considerations made in the first part of the article.

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