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RELIABILITY ASSESSMENT OF THE PRETENSIONED BOLTS BASED ON PROBABILITY

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Abstract: *The experience indicates that the most common reason of the construction or assembly incoherency are not really irregular outside loads or influences but unpredictable standard behaviour of the bolted joints. Incorrect application or design of the bolted joints can lead to catastrophic accidents. The most common mistakes are under-sizing or inappropriate over-sizing, ignoring the fatigue, creep or anticorrosion protection. Bolted joints are in their working conditions exposed to action of internal or external forces with a different magnitudes and orientations. Presented article should provide a basic guide how to set certain loads acting on the bolted joint and calculate the reliability of the bolted joint considering the probabilistic approaches. In order to capture random variables in design and validation stage of the bolted joints, Simulation Based Reliability Assessment (SBRA) using Monte Carlo method is presented.*

Keywords: Pretensioned bolted joint, Probability, Reliability, AntHill, Monte Carlo.

1. Introduction

Presented paper is further development in the problems of the pretensioned sealing joints presented in articles Maťas et al. (2014) and Frydrýšek et al. (2014). Author's attention in the previous articles was focused on the specific problem solved by deterministic and semi-probabilistic approaches. Nowadays, relatively big number of researches deals with the problems of the bolted joints using deterministic methods. However, many factors such as type of loading, operational loads, desired pretension in the bolts, cyclic loading or the presence of the heat loads need to be taken into account. Unfortunately, all this factors are hand in hand with tolerances which make the design and reliability assessment of the bolted joints even more difficult. This paper should demonstrate completely new and modern approach in this area, developed towards the Simulation Based Reliability Assessment (SBRA), i.e. probabilistic direct Monte Carlo approach. Hence, all inputs are given by truncated histograms. For more information about SBRA method see Frydrýšek (2010), Frydrýšek (2008), Frydrýšek (2012), Marek et al. (2003).

2. Reliability assessment of the bolt based on probability

The following text outlines an example how to carry out a reliability assessment analysis of the bolt, considering not only pretension force but also additional loading such as bending and temperature. This procedure will be demonstrated on the M8 bolt with the material grade 10.9.

Tab. 1: Independent random variables for the pretension force of the M8 screw.

Input variable	Description	Distribution function	Nominal	Minimum	Maximum
M_{ut} [N.mm]	Wrench torque	Normal distr. ±6 %	32 000	30 080	33 920
f [1]	Friction coefficient	Uniform distr.	0.12	0.11	0.13
d_2 [mm]	Middle diam. of the thread	User defined distr.	7.10	7.04	7.16
P [mm]	Pitch of the thread	Normal distr. ±1 %	1.250	1.237	1.262
s [mm]	Screw head diam.	Normal distr. ±1 %	13.00	12.87	13.13
δ [mm]	The screw hole diameter	Normal distr. ±1 %	9.00	8.91	9.09

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2.1. Pretension force of the bolt

First of all will be generated pretension force based on the six independent variables (see Tab. 1) defined by the bounded histograms. The theoretical bolt pretension force is given by the following equation:

$$F_Q = M_{ut} / \left(\frac{d_2}{2} . tg(\gamma + \varphi') + f . r_s \right) \text{ [N]} . \qquad (1)$$

The necessary subequations are as follows:

$$\gamma = arctg(P/\pi . d_2) \text{ [°]} , \quad \operatorname{tg} \varphi' = f [1] , \quad r_s = (s + \delta)/4 \; [mm], \qquad (2)$$

where γ - angle of the thread pitching, φ'- friction angle and r_s - friction radius.

AntHill software allows defining any type of bounded histograms. It's possible to use a library with the distribution functions or to use user defined distribution. You can see the example in following Fig. 1.

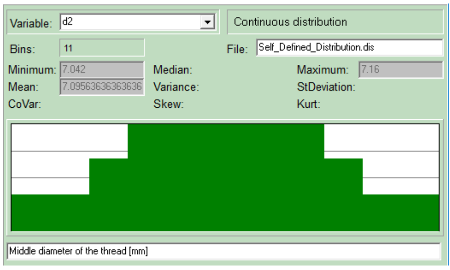

Fig. 1: User defined distribution function for d_2 (ANTHILL).

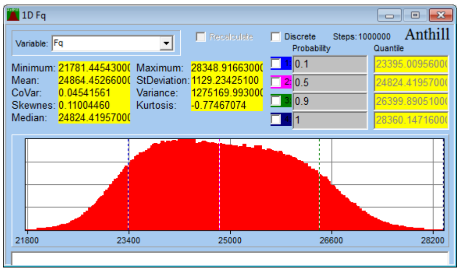

Fig. 2: Output histogram of the pretension force F_Q (ANTHILL).

Outputted bounded histogram of the bolt pretension force is shown in Fig. 2. Demonstrated variables are pure examples; the more accurate the bounded histograms are defined the closer are the results to the reality. The next step is to take into account operation loads.

2.2. Bending and temperature loading

Bending loading can easily occur when the flanges of the bolted joint are deformed due to operational loads such as for instance pressure. Another case could be inclined surface under the bolt head or nut. Bending stress can be a couple of times higher than the tensile stress of the screw. This inappropriate loading reduces the screw capacity significantly and mostly results in the screw breakage at the thread run-out. The formula to calculate the bending stress σ_O of the bolt is following

$$\sigma_O = \varphi . E . d_3 / l \quad \text{[MPa]} \qquad (3)$$

In following Tab. 2 can be found the variables used in eq. (3). These variables were again defined by the bounded histograms; similarly to histograms in Fig. 1.

Tab. 2: Independent random variables for the bending loading of the screw

Input variable	Description	Distribution function	Nominal	Minimum	Maximum
***φ* [rad]**	Bolt deformation angel	Uniform distr.	0.001	0.000	0.002
***E*[MPa]**	Young modulus	Normal distr. ±3 %	210 000	203 700	216 300
***d_3* [mm]**	Minor diam. of the thread	User defined distr.	6.466	6.272	6.619
***l* [mm]**	Clamped length	Normal distr. ±5 %	22.0	20.9	23.1

The Fig. 3 shows that the bending stress can cause really high additional loading. In this case it's almost 135 MPa. The way to reduce the bending stress is to extend the length of the clamped flanges or to reduce the screw diameter. It is necessary to mention that the input values of the loading angle φ were defined again just as an example. The temperature influence depends on the thermal expansion coefficient of the bolted flanges and of the screw as well. If this thermal expansion coefficient is the same for both, warming up the bolted joint to the same temperature of all parts will not cause significant influence to the joint.

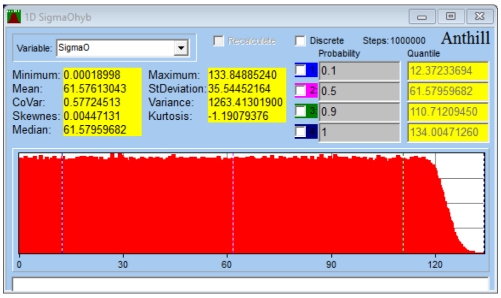

Fig. 3: Output histogram of the bending stress σ_O (ANTHILL).

In the bolted joints with a bigger gap between the bolt and flanges is the thermal transfer to the bolt much more difficult. That means the temperature of the bolt will be lower than the temperature of the flanges. This phenomena will cause additional loading of the bolt due to the thermal expansion of the flanges, especially at the beginning of the heating. Considering a different thermal expansion coefficient for a bolt and for flanges, while the temperature of the bolt is lower by Δt, then the formula to calculate the extension of the bolted flanges is following

$$\Delta l_1 = l.[(\alpha_2 - \alpha_1)(t - t_0) + \alpha_1.\Delta t] \ \ [\text{mm}]. \tag{4}$$

Corresponding force to this extension is calculated by the equation

$$\Delta F_V = \Delta l_1 (C_1.C_2)/(C_1 + C_2) \ \ [\text{N}] \, , \tag{5}$$

where C_1 is the stiffness constant of the bolt and C_2 is the stiffness constant of the clamped flanges.

$$C_1 = E_1.S_1/l \ [\text{N.mm}^{-1}] \, , \quad C_2 = E_2.S_2/l \ [\text{N.mm}^{-1}] \tag{6}$$

In order to calculate the resultant force ΔF_V based on probability, the following variables shown in Tab. 3 were defined. Variable E_1 and E_2 are equal to variable E defined in Tab. 2.

Tab. 3: Independent random variables for the force ΔF_V.

Input variable	Description	Distribution function	Nominal	Minimum	Maximum
α_1 [K^{-1}]	Thermal expansion coeff.	Normal distr. ±3 %	0.000011	0.00001067	0.00001133
α_2 [K^{-1}]	Thermal expansion coeff.	Normal distr. ±3 %	0.000017	0.00001649	0.00001751
t [K]	Operation temperature	Normal distr. ±10 %	373.15	298.52	447.78
t_0 [K]	Base temperature	Normal distr. ±20 %	293.15	263.84	322.47
Δt [K]	Temp. difference bolt-flanges	Normal distr. ±25 %	293.15	219.86	366.43
S_1 [mm^2]	Bolt section area	Dependent variable	32.82	30.90	34.41
S_2 [mm^2]	Flanges section area	5 x S_1	164.10	154.48	172.05

Fig. 4 shows output histogram of the force resulting from the different thermal expansion of the bolt and the flanges. It's very important to notice that not the whole component of the force will be transmitted to the bolt. Most of the force will actually flow through the flanges. More information about the force distribution in the pretensioned bolts is excellently explained in reference Málik et al. (2009). The formula to calculate the force component in the bolt ΔF_{V1} and the force loading the flanges ΔF_{V2} is:

$$\Delta F_{V1} = \Delta F_V.[C_1/(C_1 + C_2)] \ [\text{N}] \, , \ \Delta F_{V2} = \Delta F_V.[C_2/(C_1 + C_2)] \ [\text{N}] \tag{7}$$

Presented paper shows the results only of the force acting in the bolt - ΔF_{V1} (see Fig. 4).

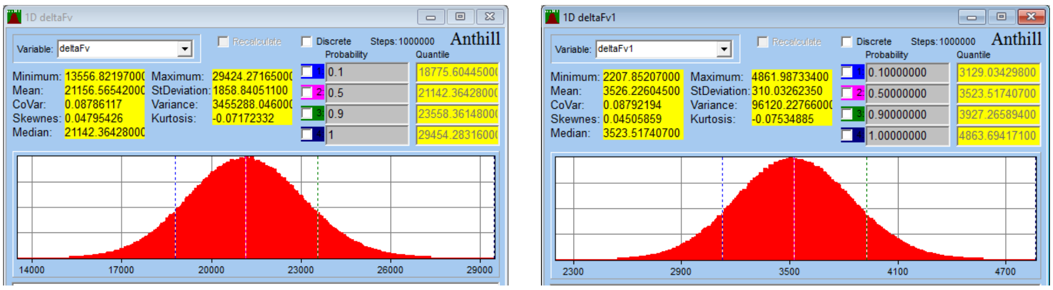

Fig. 4: Output histogram of the force ΔF_V and ΔF_{V1} (ANTHILL).

While designing the bolted joint loaded by heat, it is necessary to consider following rules: to secure a good heat transfer to the bolt so the temperature of the flanges and of the bolt will equalize and stabilize as quick as possible, by screwing the bolt to the bottom flange or by filling the gap between the bolt and the flanges by conductive material such as metal or graphite powder; to secure higher elasticity of the bolt by local diameter reduction at the bolt non-threaded area; to use metal with high Yield strength and low ultimate tensile strength; define adequately reduced pretension force F_Q, for instance $F_Q < 3\Delta F_{V1}$.

2.3. Resultant loading of the bolt

The resultant stress σ acting in the analyzed bolt is calculated simply as a sum of stresses.

$$\sigma = \sigma_{F_Q} + \sigma_O + \sigma_{\Delta F_{V1}} \tag{8}$$

Outputted bounded histogram of the resultant stress σ is shown in Fig. 5. The stress range is from 740 MPa to 1142.5 MPa. Using SBRA method, the probability of failure is obtained by analyzing the reliability function *RF*:

$$RF = Re - \sigma \tag{9}$$

The probability of failure is the probability that σ exceeds Re (material Yield strength), i.e. P(*RF* ≤ 0). For the studied bolt M8, the probability of failure P(*RF* ≤ 0) = 0.0007 (app. 0.1 %).

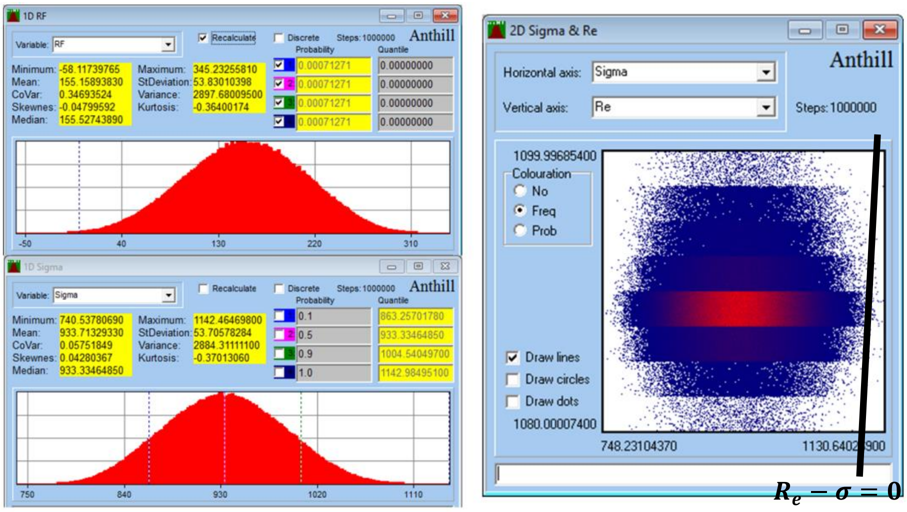

Fig. 5: Output histogram of the total stress σ and 2D diagram of the reliability function RF (ANTHILL).

3. Conclusions

Using bolts to join parts together introduces lots of problems which is necessary to understand in order to design reliable connection. Using presented SBRA method allows to do a reliable construction design, while variables used in this method include realistic safety coefficients. As already mentioned in the text above, the more precisely bounded histograms are defined, the more accurate and more realistic results are. This means that by using SBRA method engineers are not forced to blindly define safety coefficients which usually leads to inappropriate over-sizing of the construction but on the contrary, they have a full control over the whole design or validation of the construction. Presented article shows only operational loads of the bolts such as bending and temperature loading due to article size constraints. However, one of the most common fastener failure modes is fatigue crack initiation and growth. Therefore, as a future enhancement, fatigue of the bolts will be analyzed by using probabilistic SBRA method.

Acknowledgement

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