What makes Bolt Self-loosening Predictable?

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Abstract

In mechanical engineering, bolts are frequently used as standard fastening elements, which have to fulfil important mechanical functions like strength and safety. In Finite Element (FE) analysis, there exist a great number of possibilities to model bolts dependent on their importance for the desired analysis and on the focus on global or local structural behaviour. When it comes to local stress and strength, there is a clear trend to apply solid models for the bolts, where all parameters are like the real bolt including pretension but the thread is not detailed.

Fasteners can be mission critical, i.e. if bolts lose pretension during operation, the structure will fail. In those cases, the simulation requires a bolt model with detailed thread. Additional important points are the time-dependent loading and the way pretension is applied. Both more model details and more loading details are increasing the computation time drastically, which makes this approach not usable for multi-bolt designs. So, simplified bolt models are needed, which gives reliable indication for bolt loosening.

The current understanding of bolt self-loosening is that bending of bolts is at least one important trigger. In the well-known Junker test an alternating shear load is bending a pre-stressed bolt, which loses its pretension after a smaller or larger number of load cycles. Simulation is able to show such a behaviour with FE models using geometrically non-linear contact analyses. Material nonlinearities are possible but are neglected to facilitate the interpretation of the results.

To get a deeper understanding of self-loosening, a parameter study is performed, where the results of a detailed model are compared with the results of a simplified model. The goal is to identify the necessary properties of the simplified model and the parameters, which are able to indicate self-loosening. Among others, such parameters are bending load parameters, bolt geometry, and frictional coefficients.

The paper wants to contribute to the discussion about self-loosening of bolts. It uses an experimental set-up described in the literature, which is used as simulation set-up with a detailed and a simplified bolt model. Analysis, sampling, and result evaluation are performed with an industrial FEA code (PERMAS with VisPER).

1. Example model with detailed thread

Figure 1 shows the used FE-model as described in [1]. The model geometry is based on real model from experiment. [1] shows that the FE results agree with the experimental results.

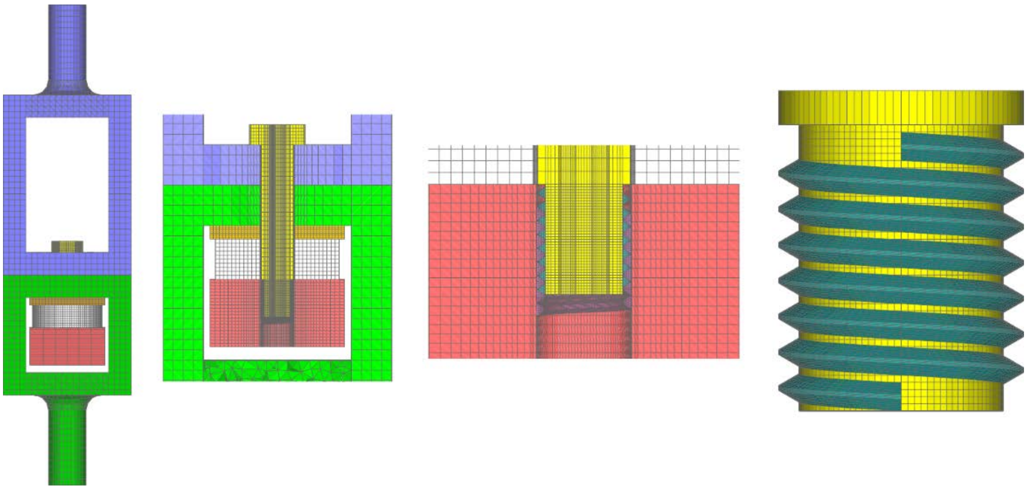

Figure 1: Bolt test model as described in [1].

Thread mesh of the bolt and square nut are both meshed independent of the basic regular mesh. Both threads are coupled incompatibly. Contact between inner and outer thread includes friction. Pretension is applied in the plane of the bolt shank directly under the bolt head. The contact between lower and upper bolt test fixture frames is defined without friction.

The FE-model is additionally equipped with several measurement facilities to get characteristic results for all time steps. In addition to location on the outside, locations inside of the bolt are used which are difficult to measure during experiment. The following results are checked explicitly to get xy-plots for comparison of variants:

- bolt pretension,
- bolt rotation,
- bolt tilt angle,
- relative displacement and
- force to apply the enforced displacement.

The characteristic dimensions of the bolt and the thread of the square nut are given in table 1.

Bolt thread diameter, D	12mm
Square nut thread outer diameter, D	12.2mm
Thread pitch	1.75
Thread flank angel	60°
Bolt thread length	14mm
Bolt shaft (shank) length	50mm
Bolt nominal length	50mm+14mm=64mm

Table 1: Bolt and thread dimensions.

2. Bolt self-loosening finite element analysis

Finite element analysis for bolt self-loosening by repeated lateral enforced displacement is described here. For this purpose the upper fixture frame (Figure 1, left picture) is moved from one side to the other by enforced displacement with an amplitude of ±0.3mm. The bolt does not touch the bolthole during that movement. On the left hand side of Figure 2 the load step history is shown. Pretension force is applied from the beginning and then directly this state is locked. That means that the pretension force is free to be changed by outer forces. All contact parameters like initial gaps and friction coefficients are kept the same for the duration of the analysis. Nine cycles of enforced displacement are applied.

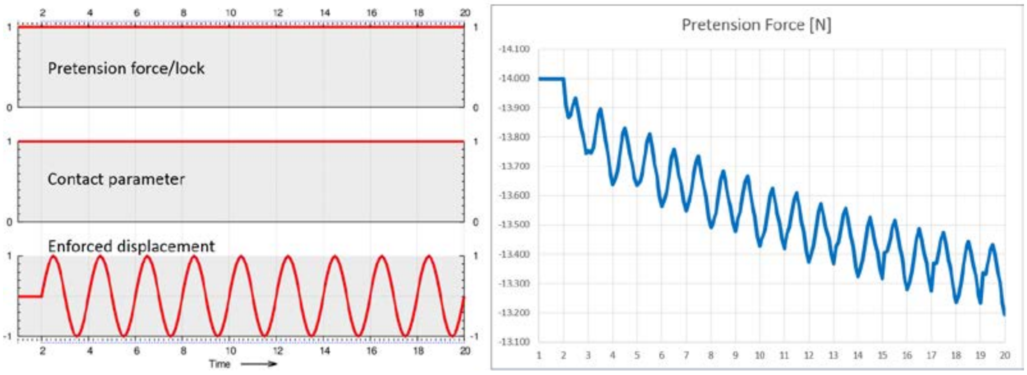

Figure 2: Load step history and loss of pretension for lateral enforced displacement.

During the first nine alternations of the enforced displacement, the pretension force sinks continuously. During each movement period, the pretension force shows two peaks, each for the position with the highest enforced displacement.

The relaxation based on plastic material effect was examined in [1] and [2]. It was shown that the effect of plastic material mainly influenced pretension force in the first load cycle. After this initial effect, the influence of plastic material is no longer significant.

The reduction of pretension for this study is based on untwist of the bolt. Figure 3 shows the rotation of the bolt head. The continuous trend line shows constant untwisting during the enforced displacement is acting. The dashed line is the rotation result based on one single node at the bolt head, which shows influence of the alternating displacement on the rotation movement.

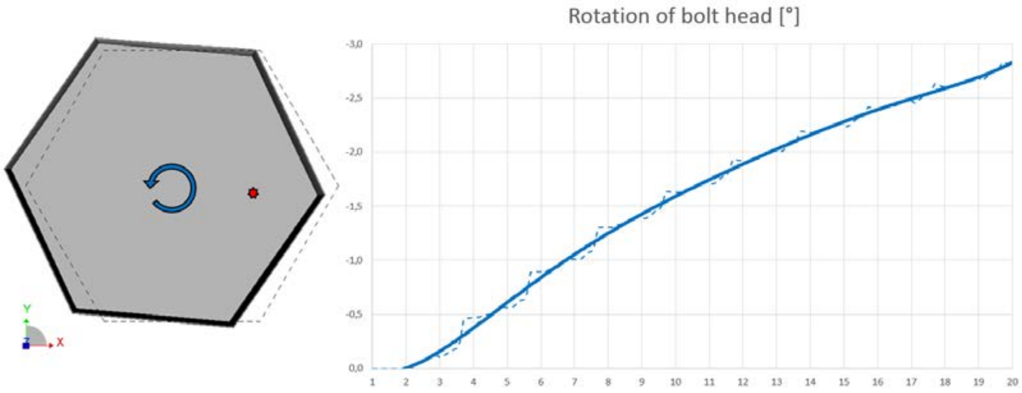

Figure 3: Rotation angle of bolt head [°] (deformation scaled by factor 150 at t=3.0) and trend line for behaviour during FE-analysis

Pretension loss and bolt head rotation are results that will only appear for bolt model with detailed thread model. Therefore, results that are more general are required for comparison with simpler bolt model. The tilt angel as shown on the left hand side of Figure 4 is such a result. The two nodes for the measurement are located on the mid axis of the bolt. The upper node is located at the intersection of the bolt mid axis with the bottom side plane of the bolt head. The second node is located on the bolt axis at the half of the shaft length. Because of the typical deformation with two changes of curvature direction, this angle is bigger and more significant than angle for two nodes located at the top and bottom of the bolt.

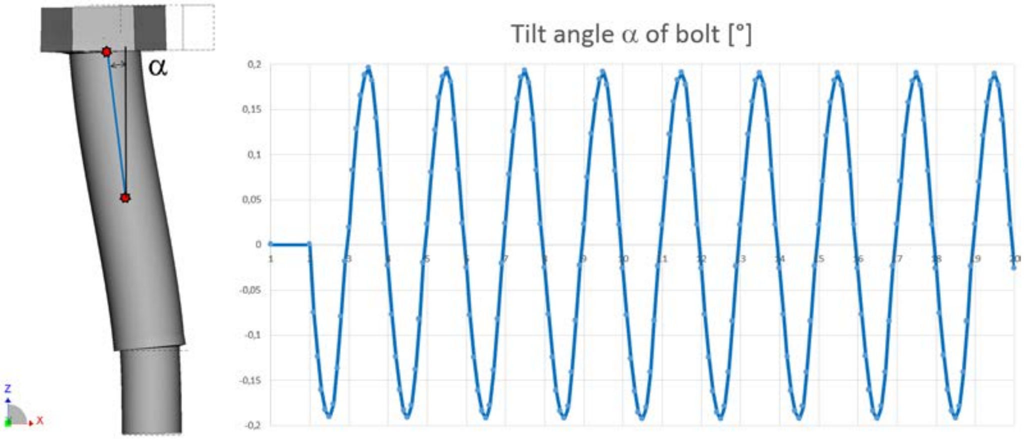

Figure 4: Tilt angle of bolt (displacement scaled by factor 50) and behaviour during FE-analysis

As expected the tilt angel alternates between two extreme positions during the complete load history. Therefore, for any comparison based on enforce displacement the maximum amplitude is sufficient.

3. Parameter study of bolt with detailed thread

The dependence on three important parameters is part of this investigation. Initial bolt pretension force, displacement amplitude and friction coefficient vary for applications of bolts. Of course, also different geometries are used for bolts, but not part of this initial investigation.

Values of the initial study for the parameters were bolt pretension P=14kN, displacement amplitude d=0.3mm and friction coefficient μ=0.132 under the bolt head and at thread for sticking and sliding.

Dependent on the assembly process the initial pretension forces vary in a wide range. To judge about this uncertainty it is important to know the influence of the initial pretension force. Figure 5 shows that the influence of the initial pretension force on the general behaviour of the pretension force during enforced displacement excitement is negligible. Friction coefficient and displacement amplitude are kept as in the initial study.

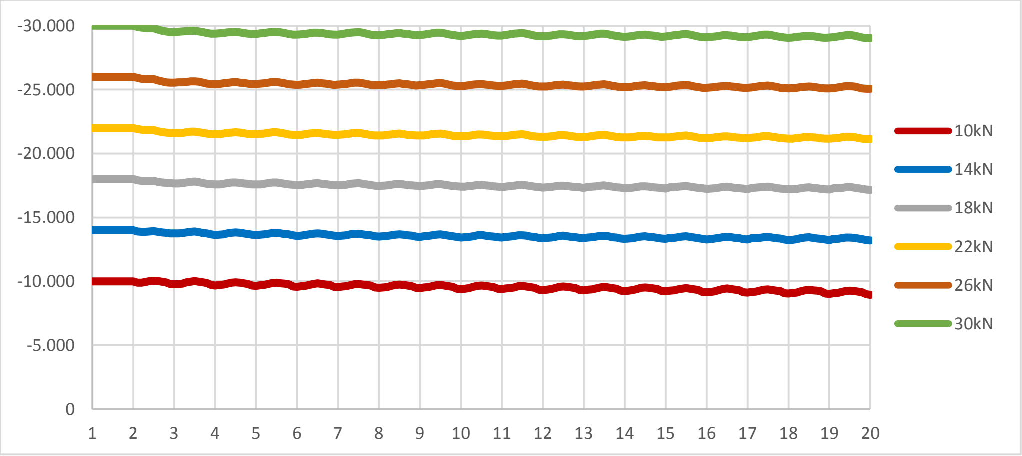

Figure 5: Pretension force [N], variation of initial pretension force

Second parameter is the friction coefficient. Transfer of friction forces acts as main or auxiliary load transmission path between bolt head and upper frame and in the thread area. Changes in surface finish or lubrication leads to changes of the friction coefficient.

Figure 6 shows the pretension force during the given process for several friction coefficients. For the contact of bolt head and for the thread area always the identical values are used. The values are chosen in the common area from μ=0.132 to μ=0.145 in small steps, and to be on the safe side higher values until µ=0.5 in bigger steps. In addition µ=0.05 is checked to cover also oil lubricated contact areas.

The influence of the friction coefficient on the general behaviour is small. There is a clear tendency to more pretension loss for lower friction coefficient. For very small friction coefficients, like for oil lubricated contact areas, there is a drastic change of behaviour, with very fast loss of pretension force.

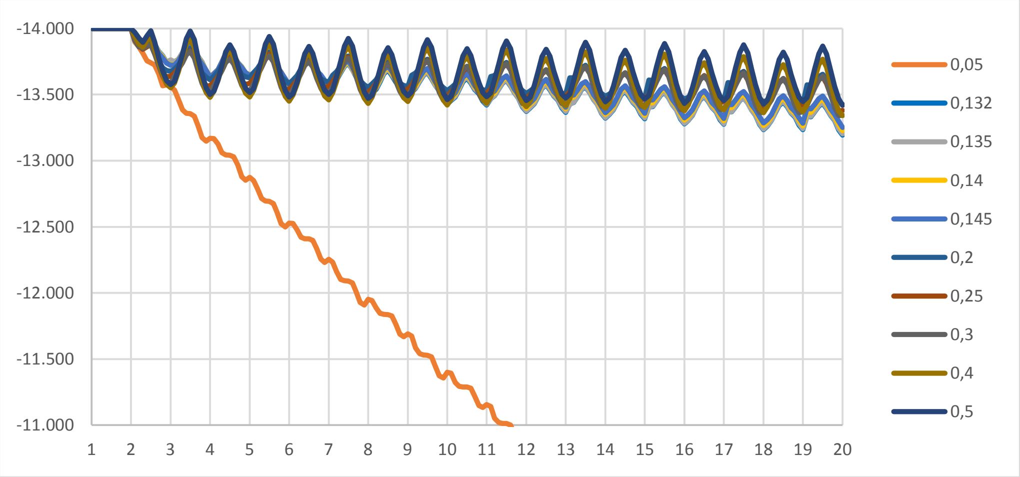

Figure 6: Pretension force [N], variation of friction coefficient

Final and main focus is on the amplitude of the enforced displacement. This is varied from d=0.025mm to d=0.3mm. The influence of the amplitude is shown in Figure 7. Both, the amplitude of actual pretension during the process and the overall pretension loss show significant dependency on the displacement amplitude.

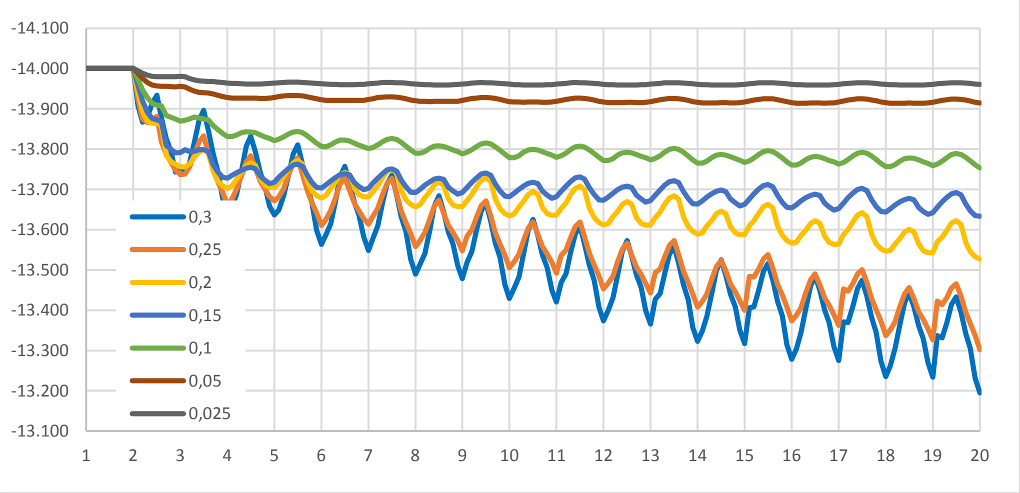

Figure 7: Pretension force [N], variation of amplitude of enforced displacement

As expected the amplitude of pretension force change is directly dependent on the displacement amplitude. Self-loosening is reduced for smaller amplitudes and is nearly gone for amplitudes smaller than d=0.05mm.

To understand the self-loosening dependency on displacement amplitude in more detail the rotation of the bolt head is also checked. The continuous trend lines of Figure 8 show the rotation angle of the bolt during the process.

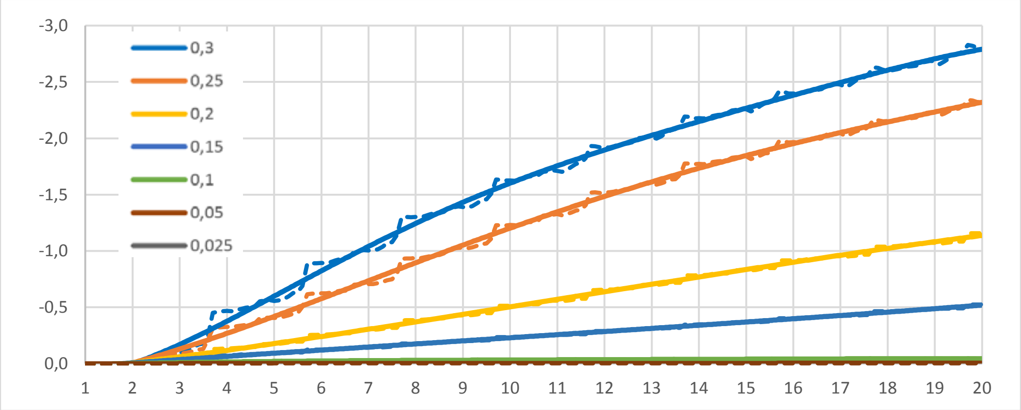

Figure 8: Trend lines for rotation angle of bolt head [°], variation of amplitude of enforced displacement

Dashed lines show the rotation based on the result of one single node, where the influence of the global displacement leads to stepwise raising rotation angle. Higher values for the displacement amplitude lead to larger rotation angles. Values lower than 0.1mm lead to nearly no rotation of the bolt.

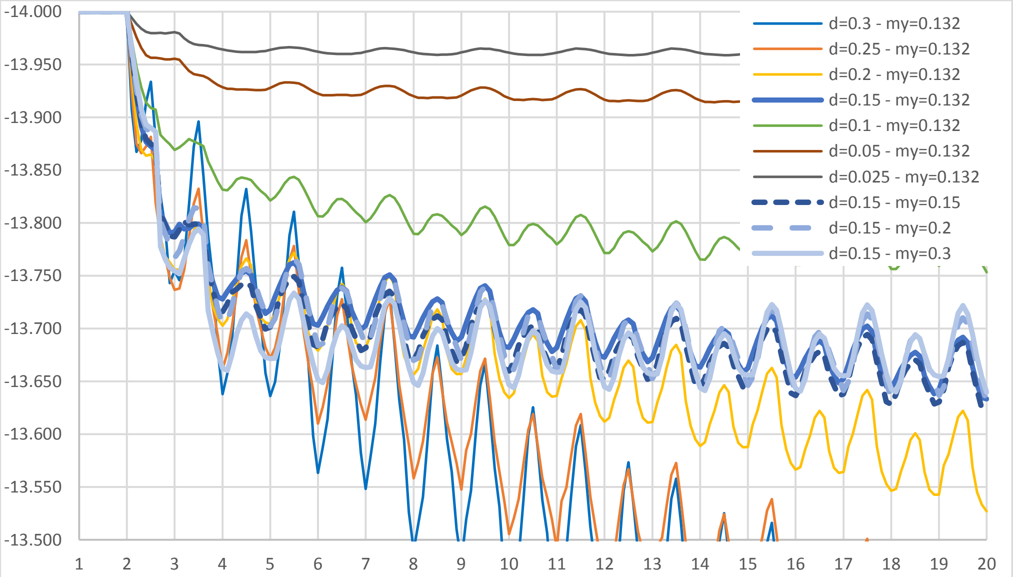

Figure 9: Pretension force [N], variation of amplitude of enforced displacement d and variation of friction coefficient for d=0.15

Finally the sensitivity of the pretension loss regarding parameter amplitude of enforced displacement is compared with the parameter friction coefficient. In Figure 9 the different amplitudes for enforced displacement are shown like in Figure 7, but with different scale for the ordinate to see more details in the region from 13,500kN to 14,000kN. In addition, coloured in several blues and in dashed, for the amplitude d=0.15mm in combination with several friction coefficients are plotted in the same graph. Again, it becomes apparent that the influence sensitivity regarding friction coefficient is much smaller, because all the plotted blue curves are very close to each other and the curves for different amplitudes are much more distributed.

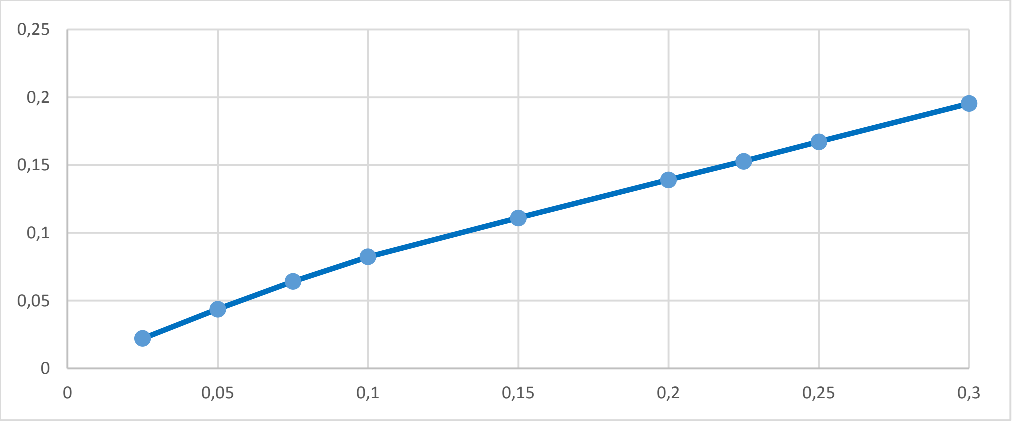

Figure 10: Maximum tilt angle [°] of bolt with detailed thread, depended on variation of amplitude of enforced displacement

As resumed from analysis of tilt angle and Figure 4, the maximum tilt angle is a single value, which characterizes the bolt behaviour for the given process. In Figure 10 the maximum tilt angle is plotted over the most important parameter of enforced displacement amplitude. This relation between maximum tilt angle and enforced displacement characterizes the behaviour of the bolt for the given process very well.

4. Example model with simplified thread

The model with detailed thread is suited for detailed investigations of one single bolt. Maybe also for models with low one digit number of bolts. Nevertheless, for models with more bolts simplified solid bolt models are preferred. They have the best compromise between run time and result quality.

To transfer the results from model with detailed thread to those models a model with simplified thread area is created.

Figure 11 shows both detail levels. On the left, the detailed thread on the right the simplified thread area. All other parts of the model remain the same. The details of the intersection show the thread details. Especially the incompatible coupling between the parts and the thread. The thread profile of at the bolt and the thread at the square nut have different sized areas. Also remarkable is the part that is chopped off the top from the thread profile. This leads to 1mm of free space on the top of both thread sides.

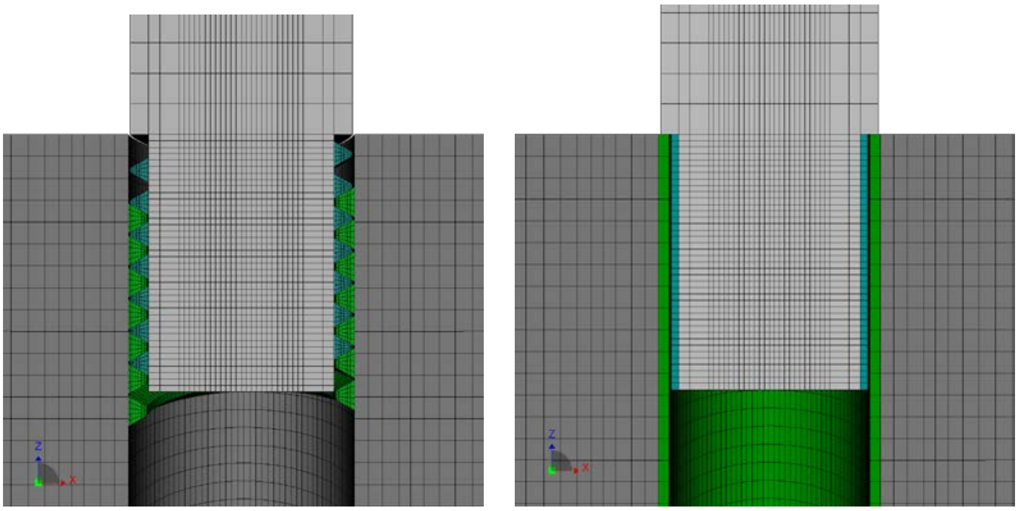

Figure 11: Detailed thread model (left) and simplified thread model (right)

For the simplified model one layer of compatible elements is added to each surface. The thickness is equivalent to the area relation between inner and outer thread. In addition, the gap of 1mm is preserved. Between both surfaces, contact is defined in normal direction. Frictional direction is locked, in a way that outer and inner thread cannot move relative to each other in tangential directions independent of the contact status. This is done, because the simplified thread's contact status represents not the correct conditions of a thread contact status.

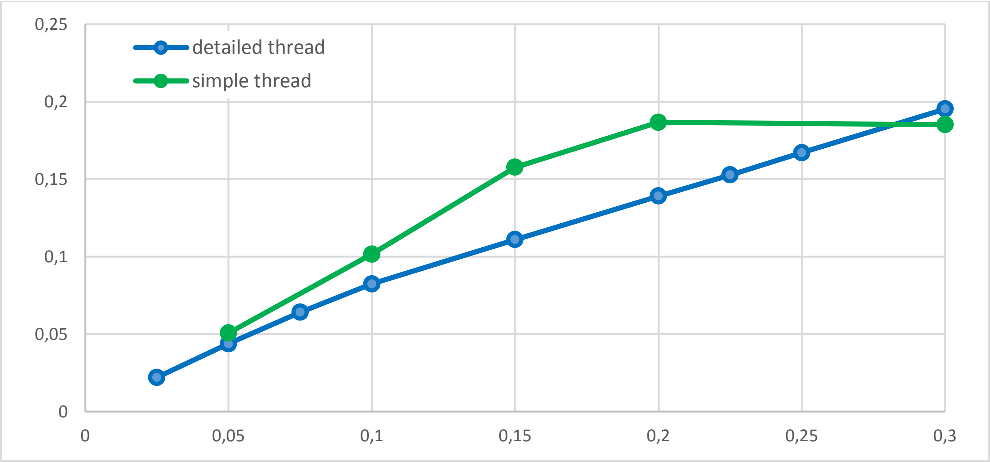

Figure 12: Comparison of maximum tilt angle [°] between bolt with detailed thread and simple thread, depended on variation of amplitude of enforced displacement

The simplified model is not able to show self-loosening based on rotation, because of the missing thread. However, the comparison of the characteristic value, the maximum tilt angle of bolt, is very meaningful. In Figure 12 both, detailed and simple thread, are plotted for several amplitudes of enforced displacement. The stiffer connection in the thread area leads to larger tilt angles for the simple thread. This yields for displacement values from 0.05mm to 0.2mm. Beyond 0.2mm the maximum tilt angle seems to be constant.

To understand this behaviour the tilt angle during the first two periods is examined in more detail.

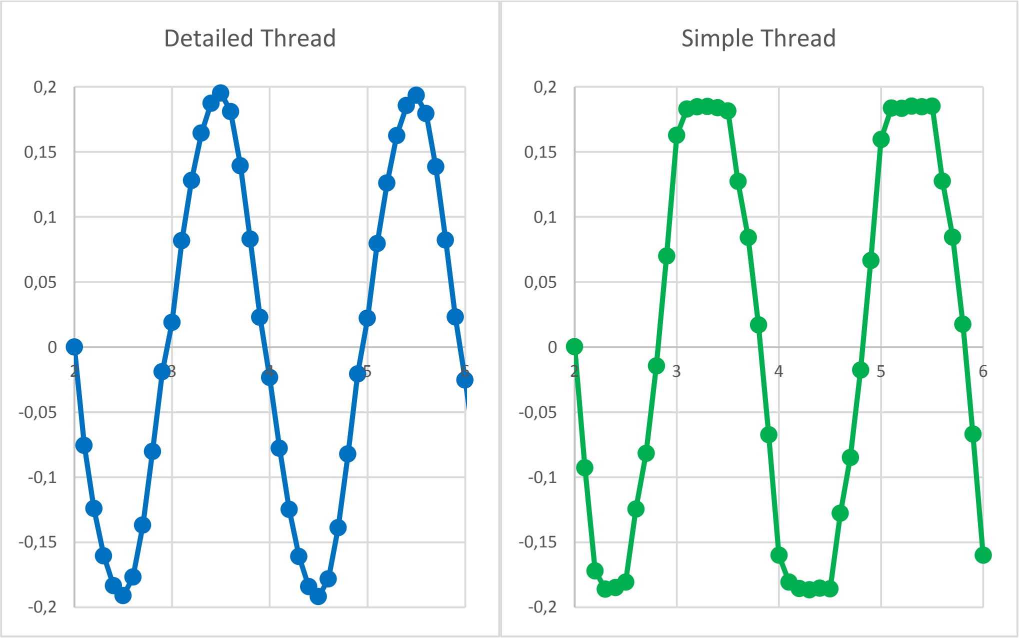

Figure 13: Comparison of tilt angle [°] between bolt with detailed thread and simple thread during first and second period

For the same friction coefficient µ=0.132, the same initial pretension force P=14kN, and the same enforced displacement d=0.3mm, Figure 13 shows the tilt angle during movement. The tilt angle from the detailed thread model on the left side represents the much softer behaviour. The friction in the thread damps the tilt angle to smoother changes. On the opposite side, the simple thread shows more abrupt change from one extreme to the other. During that change, the gap of 0.1mm between the contact partners is easily overcome. The balance between the bending force of the bolt and the friction force between bolt head and the frame limits the movement. So the limit remains the same, also for higher enforced displacements than d=0.2mm.

5. Conclusions and outlook

Parameter study of detailed thread model has shown the parameter which is able to characterize the self-loosening. The investigation has shown that this parameter, the tilt angle of the bolt, is transferable to a simplified thread model. In addition, the differences in behaviour could be understood and explained. With this study the first step to predict self-loosening by simple solid model bolt is done. The simplified thread model drastically reduces the run time with PERMAS.

Therefore, it will be possible to transfer the results of this first step to realistic multi-bolt models. As soon as the limit value for the tilt angle is determined for a detailed thread model, a greater tilt angle found by a simplified bolt model could indicate a potential self-loosening of the bolt.

6. References

[1] J. Liu, H. Ouyang, J. Peng, C. Zhang, P. Zhou, L. Ma, M. Zhu: Experimental and numerical studies of bolted joints subjected to axial excitation. Wear 346-347 (2016) 66-77.

[2] R. Helfrich, M. Klein, N. Wagner: Schraubenlösen unter wechselnden Lasten. NAFEMS Germany Conference 2016, April 25-27, Bamberg.

[3] PERMAS: PERMAS Version 16, User Manual 2016.