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Method of accumulation of preload loss of bolted joints due to rotational self-loosening caused by cyclic, transversal excitation

Marius Hofmann [a,*], Markus Faß [b], Andrea Eberhard [a,c], Marcus Klein [a], Jörg Baumgartner [d], Matthias Oechsner [a], Tobias Melz [b,d]

[a] Center for Structural Materials, Technical University of Darmstadt (MPA/IfW), 64283 Darmstadt, Germany
[b] Research Group System Reliability, Adaptive Structures, and Machine Acoustics, Technical University of Darmstadt (SAM), 64287 Darmstadt, Germany
[c] Deutscher Schraubenverband e.V. (DSV), 58093 Hagen, Germany
[d] Fraunhofer LBF, Institute for Structural Durability and System Reliability, 64289 Darmstadt, Germany

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ABSTRACT

This paper presents a new method to experimentally characterize the rotational self-loosening behavior of bolted joints. Furthermore, a method to calculate the preload loss due to certain relative displacements of the clamped parts was developed. The method obtains all required calculation parameters from the experimental tests performed and neither needs further experimental determination of friction coefficients nor numerical simulations to predict the preload loss. The method accumulates the preload loss of load cycles. Thereby, it can be used to estimate the time a machine can operate until a critical amount of preload is lost. Non-linear dependencies of the preload loss to the displacement amplitude and the remaining preload are considered. The calculation method also applies to load cases with variable load amplitudes. This is validated experimentally.

1. Introduction

Bolted joints are the most commonly used detachable connections in various applications. They are encountered by people with or without technical background in their daily lives. Despite their widespread use, certain properties of bolted joints, such as rotational self-loosening behavior, have not been fully understood and still cannot be described entirely neither by analytical nor numerical approaches.

Self-loosening of bolted joints is a process occurring during operation that steadily decreases the bolt's preload. Driven by the pitch torque of the thread, the bolt will rotate in loosening direction, when the contact areas at the head bearing surface and the engaged threads slip alternating. This rotation leads to a loss of preload [1,2]. The slip may be initiated by different kinds of loads, either by an external load bending [3,4] or twisting [5] the bolt shank or an additional axial tension causing slip in the engaged threads due to transversal contraction [6,7,8]. If these loads are repetitive, the preload may fully decrease during service loading. Also if the friction coefficients decrease, for example due to a temperature change, self-loosening may occur. However, an increase in friction coefficients, for example due to corrosive attack or fretting, will lead to a reduction of self-loosing speed or risk.

In mechanical engineering, bolted joints are mostly designed as frictional connections. Thus, the functionality of the connection

* Corresponding author.
E-mail address: marius.hofmann1@tu-darmstadt.de (M. Hofmann).

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essentially depends on the preload. Without a critical amount of preload being exceeded, the clamped parts can move relatively to each other or may lift off [1,2]. This leads to failure of the joint and, depending on the place of action, may cause danger to people, the machine itself and the environment. However, a bolted joint may slip due to load peaks but remain capable of transferring regular service loads. For example, the spectra used in automotive engineering to emulate suspension loads caused by the road roughness contain a small amount of very harsh peak loads. Typically, just ten out of one million cycles in spectra of this kind reach 80 % of the maximum peak load. These may represent the impacts of pothole crossings or accidental lateral collisions with the curbstone. Meanwhile, for 100.000 cycles out of one million cycles, respectively 90 % of the lifetime, the loads are even smaller than 20 % of the maximum peak load [43]. Nowadays, automotive manufacturers invest huge effort in experimentally determining such peak loads and numerically simulating the load of bolted joints within the suspension parts. Nonetheless, the peak loads in service are still random and there is still no officially approved rule how to prevent rational self-loosening in this way. So, some uncertainties remain, which raise the interest in how damage tolerant bolted joints are regarding rotational self-loosening.

Actually, there are different ways to deal with self-loosening. One common way is to secure the bolt with an additional locking device, such as adhesive thread lockers or lock washers with interlocking features [9]. The efficiency of these locking devices can be tested experimentally under transversal excitation with standardized testing procedures [10,11]. In order to assess the risk of self-loosening, one may apply finite element analysis (FEA) [12 –20]. Modelling bolted joints numerically is challenging. Furthermore, FEA needs plenty of computation power and time. This restricts the complexity of the investigated assembly for modelling and the number of simulated load cycles. Nonetheless, FEA delivers good results in predicting the occurrence of self-loosening even for complex load cases [21]. The amount of preload loss due to self-loosening remains hard to determine. Furthermore, the results strongly depend on the supposed friction coefficients [12]. So, there is a huge uncertainty, unless experimental tests run parallelly.

Also, incremental analytic mechanical models can explain the mechanism of self-loosening [22 –36]. Therefore, the bolt shank is modelled as an elastic beam which may twist due to torsion. Further, the friction in the contact surfaces at the head bearing and the engaged thread is usually modelled as shear tension and described by a vector field. The transverse force and the torsion torque transmitted by the friction are calculated with the surface integral of these vector fields in the respective contact surface. Such models comply well with comparing experimental tests and are more efficient concerning computation time. In our opinion, there are two main causes why these models are not widely spread in industrial use: The models are not standardized and mathematically quite complex. So, it is not easy to adapt them for an individual use case. In addition, the mathematical complexity is opposed to a high level of construction details, which may practically be crucial for the self-loosening process.

The self-loosening behavior might also be investigated experimentally. Therefore, a servo-hydraulic testing system applied a cyclic transverse load to a bolted joint with a controlled displacement amplitude. The numbers of cycles, in which a certain amount of preload loss ΔF_M was reached, were determined for different displacement amplitudes [37,38]. Similar to S-N curves, boundary curves plotted the displacement amplitude over the number of cycles in double logarithmic scale. Different boundary curves for different amounts of preload loss were presented for the test series. Furthermore, a boundary curve for the beginning of global slipping in the head bearing surface was generated.

Building upon these investigations, this paper proposes a calculation method to predict the preload loss due to variable displacement amplitudes. Therefore, the idea of linear damage accumulation rule according to Palmgren and Miner in fatigue [39,40] was adapted. This allows the description of self-loosening with just a few parameters, which can be determined experimentally in a simple testing procedure.

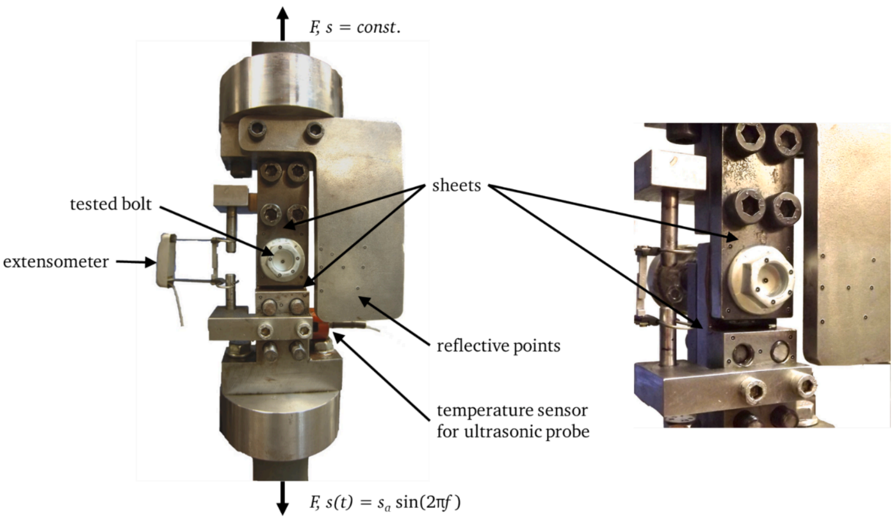

Fig. 1. Testing unit for transverse excitation on a bolted connection in frontal view (left) and in perspective (right).

2. Material and methods

2.1. Experimental studies

To determine the self-loosening behavior of bolted connections, tests on single interface connections were performed with a cyclic alternating transverse displacement. The focus was the influence of the displacement amplitude on the rate of preload loss per cycle. Therefore, the investigated connections were mounted in a servo-hydraulic testing machine with a specially developed testing unit, Fig. 1.

In this unit the bolt connects two metal sheets, which act as clamped parts. The free length of the sheets measured from the edge of the clamping jaws was only 32.5 mm to prevent buckling. Within this length, both sheets were clamped in a square-shaped area of 30 mm in edge length. The deformations of the sheets are regarded as small compared to the bending deformation of the tested bolts. The testing machine's piston applied the sinusoidal displacement $s(t) = s_a \sin(2\pi f)$ on the testing unit with a constant displacement amplitude s_a and a frequency f. Thereby a pure shear force F was transmitted transversely to the bolted joint. The local relative displacement amplitude $s_{a,E}$ between the two clamped parts was controlled to be constant with an extensometer. In addition, a piezo-electronic ultrasonic probe was applied at the end of the bolts. The time of flight of an ultrasonic wave from the end of the bolt to the head and backwards was used to calculate the bolt's preload with an intellifast LP-Touch® system. With a PT100 temperature sensor the temperature influence on the time of flight was compensated. Furthermore, reflective points were applied adhesively to observe the three-dimensional movement of the bolt and the testing unit with a digital image correlation device.

The connections were tested cyclically with different constant displacement amplitudes. The ultrasonic probe was used to identify the number of cycles for each bolt until a specified preload loss ΔF_M (e.g., 25 % of the initial preload) was reached. In this setup bolts usually loosened in less than 1000 cycles. If a bolt did not loosen, the test stopped after 20,000 cycles to guarantee that the bolt do not loosen delayed. These cycles do only represent the harsh peak loads, which represent much less than 1 % of service lifetime in any way.

2.2. Generation of boundary curves for self-loosening of bolted joints

In the tests, the bolt's diameter, the ratio of clamping length to diameter, the head bearing friction as well as the initial preload varied [41]. The diameters were M8 and M12x1.5 (fine pitch), the clamping length was adjusted with the sheet thickness to once the nominal thread diameter respectively twice the nominal thread diameter. The bolts had a zinc flake coating with different lubrications for adjustment of the friction coefficient. The sheets used as clamped parts consisted of S700MC steel. They were manufactured used laser cutting and were barrel finished to remove oxides. To avoid fretting the interface between both sheets was lubricated with anti-seize paste, which would be unusual for real bolted connections. Out of these parameters, twelve different combinations were characterized. For each of these, a program consisting of 28 single tests was performed orientated to DIN 50100 [42], which is the German standard for load-controlled fatigue testing.

Following the horizon method, six bolts on three displacement amplitude horizons were used to determine the preload loss depending on the applied displacement amplitude in each case. For each of these three amplitudes, the median number of cycles to the specified preload loss and the standard deviation were evaluated. Similarly to S-N curves, the displacement amplitude was plotted over the number of cycles on a double logarithmic scale. Although the used specimens were identical, the results spread due to small

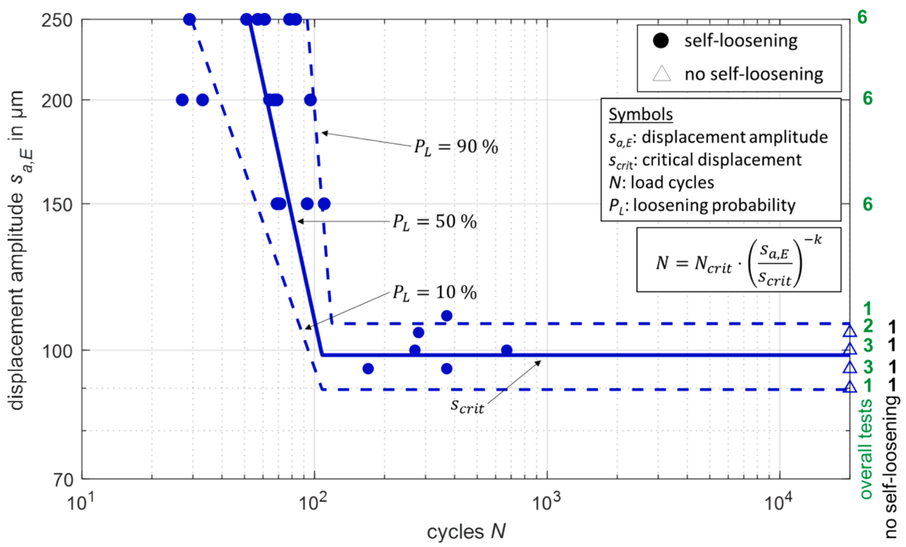

Fig. 2. Boundary curve of a M12x1.5 bolted connection with a clamping length of $l_K = 12$ mm and an initial preload of $F_M = 50$ kN for an overall preload loss of $\Delta F_M = 0.25\ F_M$ for different loosening probabilities P_L [41].

variations in friction. The results were approximated by a straight line through the medians by the least squares method, Fig. 2.

Like the equations of S-N curves in the domain of fatigue, the equation of the line is:

$$N(s_{a,E}) = N_{crit}\left(\frac{s_{a,E}}{s_{crit}}\right)^{-k} \tag{1}$$

where N_{crit} is the number of cycles when the line reaches the critical displacement and k is the line's gradient. This line represents the number of cycles until a bolt will have lost the specified amount of preload ΔF_M at a certain displacement amplitude with a probability of $P_L = 50$ %. With the evaluated standard deviations such lines were also generated for loosening probabilities of 10 % or 90 % (Fig. 2, dashed) in analogy to DIN 50100 [42]. The loosening probabilities also give an indication on the spread of friction coefficients in the tested specimens. Two tests resulted in smaller numbers of cycles at a displacement amplitude of $s_{a,E} = 200$ μm, which is striking. After an inspection of the relevant specimens no conspicuous features were found. Since the lines for the different loosening probabilities were generated considering all tests on all horizons, just two of 18 specimens deliver results left of the $P_L = 10$ % line. This approximately matches the calculated loosening probability of the boundary curve.

Another ten bolts of each connection variant were used to investigate the critical displacement s_{crit}. This is the amplitude loosening tests require at minimum to initiate self-loosening. Therefore, orientated to DIN 50100 again, a method usually applied to determine the fatigue strength of metallic materials was used. Connections were tested applying a constant amplitude. If they loosened, the displacement amplitude was reduced step by step from test to test. If a connection did not loosen, the displacement amplitude was increased for the next test (see "staircase test" approach [42]). This method delivers the critical displacement with a loosening probability of 50 % and a standard deviation to predict the critical displacement for different loosening probabilities. We empirically determined a step size of $\Delta s_{aE} = 5$ μm as appropriate. With this step size, a staircase test series covered between three and five different amplitudes. According to German standard DIN 50100 [42] this number of different displacement amplitudes is considered to guarantee proper results for the critical displacement s_{crit}. Ten tests are just a small sample size. The values for the critical displacement for all regarded loosening probabilities thus are subjected to an enlarged uncertainty. In DIN 501000 [42] the standard deviation is determined with the variance of the results, the step size and the sample size. A small sample size increases the determined standard deviation. This counterpoises the enlarged uncertainty, since the standard deviation is unlikely to be underestimated. Nonetheless, a lager sample size would have led to more robust results.

3. Theory – development of a calculation method

3.1. Basic requirements and approach for accumulating preload loss

In the majority of experimental tests, the preload loss increases almost linear with the number of cycles, Fig. 6. The linear preload loss at a high preload was also observed in other investigations with displacement controlled testing [37]. This means that the amount of preload loss due to a cycle does not depend on the amount of preload already lost. So, it would be possible to linearly accumulate the preload loss of each cycle.

In practice, bolted joints are often not stressed by a constant service load. Instead, variable loads act during service causing variable displacement amplitudes between the clamped parts. In these applications, the accumulation would allow to predict the preload

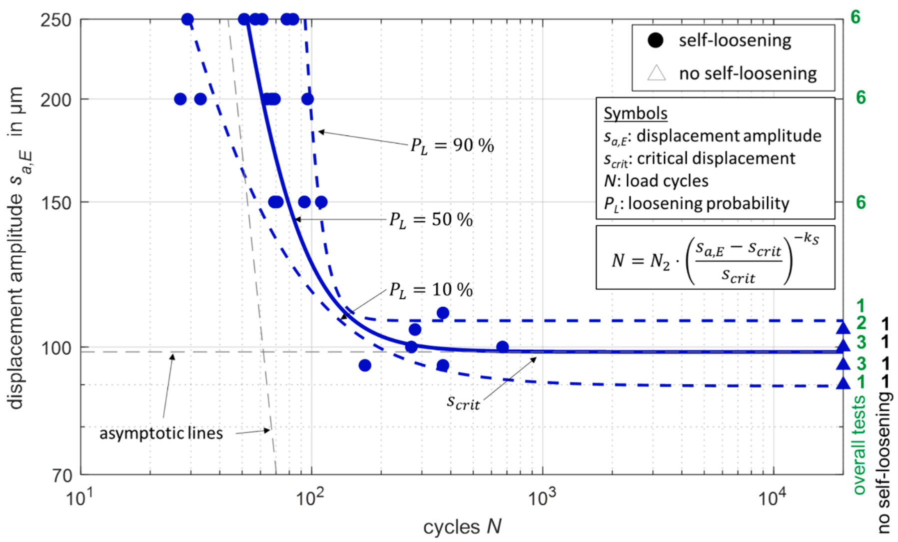

Fig. 3. Boundary curve of a M12x1.5 bolted connection with a clamping length of $l_K = 12$ mm and an initial preload of $F_M = 50$ kN for an overall preload loss of $\Delta F_M = 0.25\ F_M$ for different loosening probabilities P_L [41], identical experimental data as in Fig. 2 but generated with equation (2).

development of a bolted connection.

As expected, it was observed that the critical displacement of a connection that leads to self-loosening becomes smaller with decreasing preload. The critical displacement may decline due to the preload loss caused by load peaks. Displacements that are smaller than the former critical displacement at the initial preload may also cause self-loosening then. This is in contradiction to the approach of a linear accumulation of preload loss. An iterative accumulation is still possible.

A theory is needed which describes the nearly linear preload loss at high displacement amplitudes but also explains the decreasing critical displacement and the accompanying higher loosening effect of small displacement amplitudes. Coming from equation (1), a displacement that is just minimally higher than the critical displacement would directly lead to self-loosening in a relatively short time. A new approach that rates the difference of the displacement amplitude and the critical displacement instead of the absolute value of the displacement amplitude will deliver better matching results. In other words, the estimated slip distance of the bolt's head is rated instead of the relative displacement of both clamped parts. The equation of the new approach is given by:

$$N\left(s_{a,E}\right) = N_2\left(\frac{s_{a,E} - s_{crit}}{s_{crit}}\right)^{-k_S} \tag{2}$$

Boundary curves described by equation (2) are asymptotic to a straight line with the gradient k_S for high displacement amplitudes in double-logarithmic scale, Fig. 3. For an increasing number of cycles, the graph approximates a horizontal line at the level of the critical displacement asymptotically from above, Fig. 3. N_2 works as a grid point and marks the number of cycles when the graph reaches the displacement amplitude $s_{a,E} = 2\,s_{crit}$. As for the former approach, it is possible to fit the parameters k_S and N_2 linearly by the least squares method. The values of the parameters for the shown graphs are $k_S = 0.687$, $N_2 = 44.0$ and $s_{crit} = 89.7$ µm for $P_L = 10$ %, $k_S = 0.379$, $N_2 = 61.8$ and $s_{crit} = 98.6$ µm for $P_L = 50$ % and $k_S = 0.117$, $N_2 = 96.7$ and $s_{crit} = 107.6$ µm for $P_L = 90$ %.

The results of the test series with the other tested bolted connections can be presented in the same way. Fig. 4 shows the results of eight of twelve test series. The test series with varied head bearing friction are not shown due to clarity. As expected, a higher clamping length, head bearing friction or initial preload increase the critical displacement and the reached number of cycles.

3.2. Deduction of the preload loss from the boundary curve's parameters

Since the aim is to develop an accumulation method for the preload loss, it is mandatory to know the preload loss caused in every single cycle. As the boundary curves show, the preload loss depends, among others, on the displacement amplitude and on the critical displacement, Fig. 3. The critical displacement depends on the actual preload, hence the preload loss does as well.

To describe the preload loss for one cycle, the preload loss rate $\Delta F_V/\Delta N(s_{a,E})$ is introduced. As mentioned, the preload approximately decreases linearly for a constant displacement amplitude in a wide range of preload. The linear development of the preload loss leads to a constant preload loss rate. This may sound contradictory to the dependency of the preload loss on the critical displacement and thus on the actual preload. In fact, the effect of the critical displacement on the preload loss rate increases if the difference between the displacement amplitude and the critical displacement becomes small. The constant displacement amplitudes in the conducted tests were much larger than the actual critical displacements and thereby the preload loss rate was effectively independent on the actual preload. Equation (2) delivers the number of cycles to an overall preload loss of ΔF_M compared to the initial preload F_M. The preload loss rate is then calculated of the overall preload loss ΔF_M divided by the number of cycles calculated with the boundary curve:

$$\frac{\Delta F_V}{\Delta N}\left(s_{a,E}\right) = \frac{\Delta F_M}{N_2\left(\frac{s_{a,E}-s_{crit}}{s_{crit}}\right)^{-k_S}} = \frac{\Delta F_M}{N_2}\left(\frac{s_{a,E} - s_{crit}}{s_{crit}}\right)^{k_S} \tag{3}$$

Equation (3) does not take the dependency of the critical displacement on the preload into account. As described before, the dependency of the critical displacement on the preload is necessary for the accumulation method at variable loading amplitudes. In our investigations, the critical displacement of the tested connection variants was experimentally determined for at least two initial preloads. Thereby, a description at the preload F_V through a linear interpolation is possible:

$$s_{crit,lin}(F_V) = \frac{s_{crit}(F_{M2}) - s_{crit}(F_{M1})}{F_{M2} - F_{M1}} \cdot (F_V - F_{M1}) + s_{crit}(F_{M1}) \tag{4}$$

Where F_{M1} and F_{M2} are the two initial preloads, the critical displacement s_{crit} has been experimentally determined for. $s_{crit,lin}(F_V)$ is the linearly interpolated approximation of the critical displacement at the preload F_V. A linear correlation of the preload and the critical displacement was assumed in [3,22] due to the assumption of Coulomb's friction. Indeed, experimental investigations refuted the linear correlation [13,14,41]. Nonetheless, for most technical purposes the permitted preload loss is small compared to the initial preload. If the difference between both interpolation points is small enough, a linear interpolation still applies.

Equation (3) was determined for a critical displacement not depending to the remaining preload. Replacing the critical displacement in equation (3) with the linearized critical displacement from equation (4), the preload loss rate would steadily increase as the remaining preload decreases. The resulting calculated number of cycles to a specified amount of preload loss would be too small. As a compensation, a correction coefficient c is introduced. This coefficient scales the calculated preload loss to counterpoise the growth of the preload loss rate. Equation (5) delivers the preload loss during one cycle ($\Delta N = 1$) depending on the displacement amplitude $s_{a,E}$ and the remaining preload F_V.

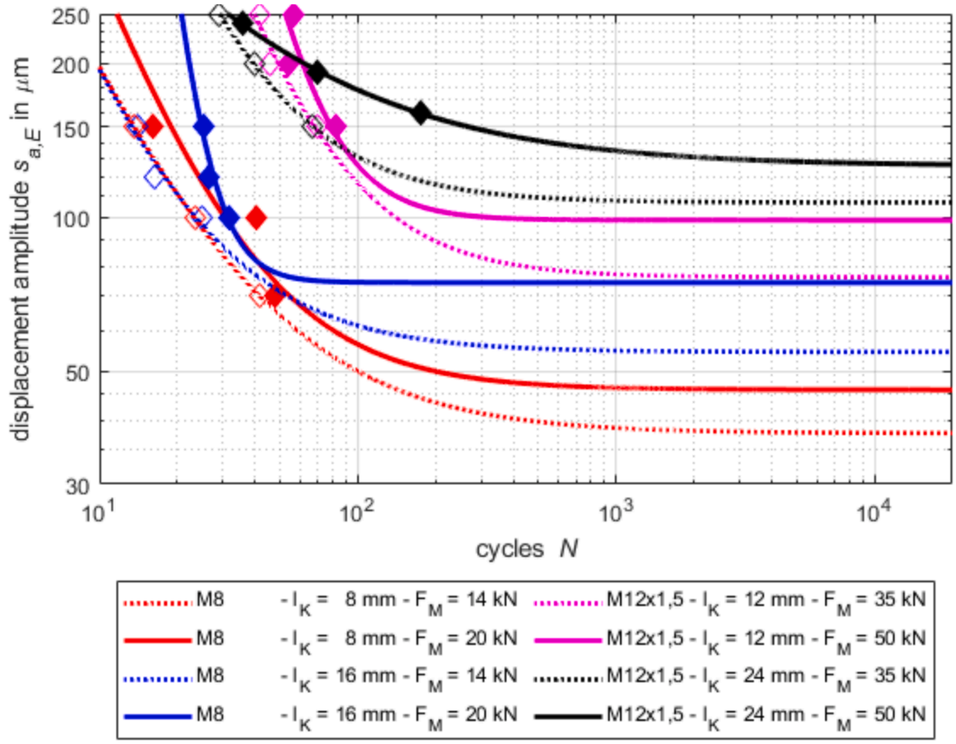

Fig. 4. Boundary curves for a relative preload loss of 25 % of eight different test series with variations in bolt diameter, clamping length and initial preload for a loosening probability of $P_L = 50$ %: Markers show the mean cycle numbers on every displacement horizon for every test series, filled markers belong to the solid lines of the same color and empty markers belong to the dashed lines.

$$\Delta F_V\left(s_{a,E}, F_V\right) = c \cdot \frac{\Delta F_M}{N_2}\left(\frac{s_{a,E} - s_{crit,lin}(F_V)}{s_{crit,lin}(F_V)}\right)^{k_S} \tag{5}$$

The presented formulation of the preload loss depends on the remaining preload and thereby depends on the cumulated preload loss of all cycles before. Thus, it is not possible to linearly accumulate the preload loss for multiple cycles – neither with a constant displacement amplitude nor a spectrum of varying amplitudes. An iterative accumulation is realized instead.

Fig. 5 shows the algorithm of the iterative accumulation. The iterative index *(N)* symbolizes the cycles. Starting with the initial

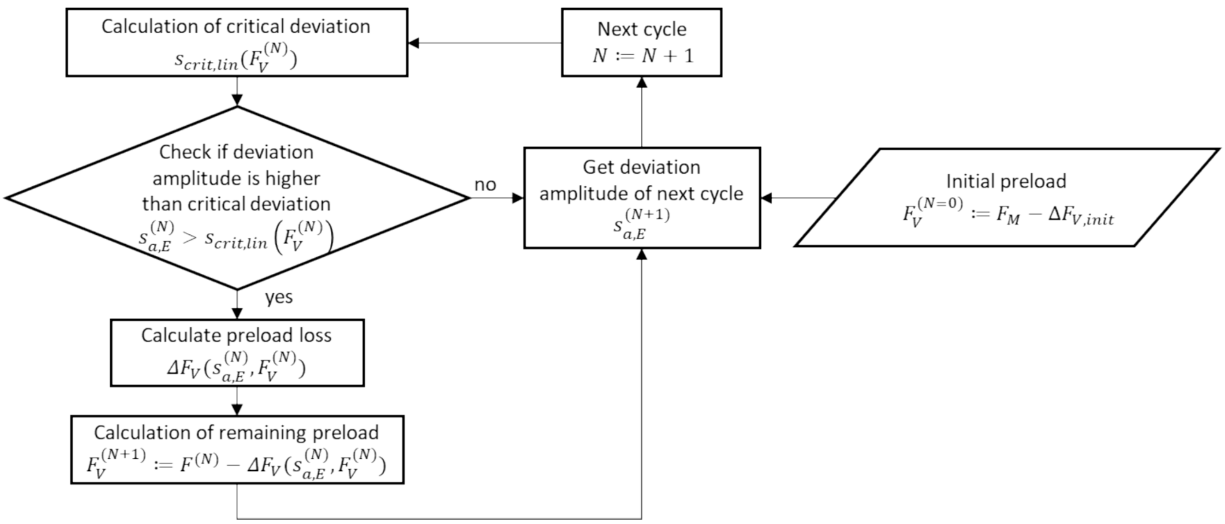

Fig. 5. Algorithm to calculate the preload loss due to self-loosening of bolted joints iteratively cycle wise.

preload, which is the preload after mounting minus an empirically determined initial preload loss $\Delta F_{V,init}$, the displacement amplitude for the first cycle is checked. The initial preload loss occurs due to plasticizing in contact areas of the joint or due to twisting back driven by the torsion remaining in the bolt after mounting. Proceeding with the first cycle, the critical displacement with the remaining preload $F_V^{(N)}$ is calculated, equation (4). Afterwards, it is necessary to check whether the actual displacement amplitude is larger than the actual critical displacement. If it is not, the actual cycle will not drive the self-loosening process and the algorithm continues with the next cycle by determining its displacement amplitude. If the displacement amplitude is larger than the critical displacement, self-loosening occurs during the actual cycle. In this case, the preload loss is calculated and subtracted of the remaining preload before continuing with the next cycle, equation (5). The displacement amplitude is rather given by a known collective or can be evaluated in a finite elements analysis for complex structures.

3.3. Determination of the correction coefficient

In equation (5) the correction coefficient c is introduced. To improve the accuracy of the developed iterative accumulation method the correction coefficient linearly scales the preload loss rate. The approach for boundary curves in equation (2) still seems to overestimate the effect of the preload dependent critical displacement on the preload loss caused by displacement amplitudes close to the critical displacements.[1] Consequently, the preload dependent critical displacement has a notable influence on the preload loss rate of some displacement amplitudes that show a linear preload loss in experiment. As discussed above a linear preload loss means that the preload loss is independent of the actual preload. The calculated preload course may show an accelerated preload loss instead, Fig. 6. The correction coefficient automatically scales the accelerated calculated preload loss so that the mean calculated preload loss rate nearly correlates with the experimentally observed preload loss rate.

For self-loosening tests with a constant displacement amplitude the boundary curves will statistically predict the number of cycles N_{exp} in an experimental test with a given probability of self-loosening, equation (2). The iterative accumulation without the correction coefficient would deliver an accumulated number of cycles $N_{acc} < N_{exp}$ for the same test.

Naturally, the overall preload loss ΔF_M is the sum of the preload loss of every single cycle up to N_{acc}. Using equation (5) for the preload loss of a single cycle, the following equation must be fulfilled, to evaluate the correction coefficient:

$$\Delta F_M = \sum_{N=1}^{N_{acc}} c \cdot \frac{\Delta F_M}{N_2} \left(\frac{s_{a,E} - s_{crit,lin}(F_V(N))}{s_{crit,lin}(F_V(N))} \right)^{k_S} \tag{6}$$

where $F_V(N)$ symbolizes the course of the preload over the cycles N. N_{acc} is evaluated with equation (2). It is not possible to solve equation (6) analytically since the course of preload loss can only be evaluated iteratively. An approximate solution is proposed. The course of the preload is nearly linear at constant displacement amplitudes. So, the preload course is approximated with a linear equation:

$$F_{V,lin}(N) = F_M - \frac{\Delta F_M}{N_{acc}} N \tag{7}$$

Applying equation (7) in equation (6) the correction coefficient for a certain displacement amplitude $s_{a,E}$ results in equation (8). The calculation of the correction factor only needs the parameters of the boundary curve already given in the accumulation method.

$$c(s_{a,E}) = N_2 / \sum_{N=1}^{N_{acc}} \left(\frac{s_{a,E} - s_{crit,lin}(F_{V,lin}(N))}{s_{crit,lin}(F_{V,lin}(N))} \right)^{k_S} \tag{8}$$

Fig. 6 shows the corrective effect of scaling the preload loss rate with c. The continuous grey lines plot the experimentally determined preload courses of six M8-bolts with a clamping length of $l_K = 8$ mm and a nominal initial preload of $F_M = 20$ kN. The displacement amplitude constantly was $s_{a,E} = 70$ μm. The continuous bold black line presents the preload course evaluated following to the scheme shown in Fig. 5 using the correction coefficient c for scaling the preload loss rate. The bold dashed black line displays the evaluated course without scaling the preload loss rate. For both evaluated courses an initial preload loss of $\Delta F_{V,init} = 1$ kN is assumed, which corresponds to 5 % of initial preload. The boundary curve parameters, used for the calculation of the preload loss rate, belong to a loosening probability of $P_L = 50$ %. The dashed grey line marks the level of $F_V = 7$ kN, where the exemplary chosen ΔF_M is reached.

The experimentally generated preload courses vary in their pitch and their number of cycles when the preload falls to $F_V = 7$ kN. Due to the logarithmic scale of the boundary curves, the mean number of cycles for the experimental courses has to be calculated logarithmically. The number of cycles N_{log} that corresponds to the arithmetic mean value of the logarithms of the experimentally determined cycles was evaluated with equation (9).

[1] Another approach for the boundary curve which delivers a better correlation at small displacement amplitudes could be found. This would require further tests close to the critical displacement and would probably increase the complexity of the boundary curve equation. To avoid additional experimental tests and computational afford we chose use the boundary curve formulation of equation (2).

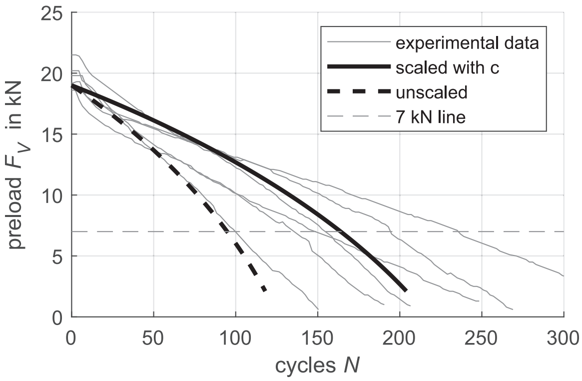

Fig. 6. Influence of the correction coefficient c on the evaluated preload courses [41].

$$6 \cdot \log_{10}(N_{log}) = \sum_{i=1}^{6} \log_{10}(N_i) \tag{9}$$

where N_i are the experimentally determined numbers of cycles for the six shown tests. The experimental mean number of cycles is $N_{log} = 157$. The number of cycles in which the evaluated course with scaled preload loss rates reaches $F_V = 7$ kN is $N_{acc} = 164$. Thereby, it is very near to the actual result. Without scaling the number of cycles for the same preload loss is $N_{acc} = 95$ and underestimates the reached number of cycles. This successfully validates the introduced approach for calculation of the correction coefficient.

4. Results – experimental verification

For validation of the accumulation method, self-loosening tests with a spectrum of variable displacement amplitudes consisting of 20 cycles overall were performed, Fig. 6. The chosen spectrum contains 18 cycles with a displacement amplitude which corresponds to 80 % of the critical displacement $s_{crit}(F_M)$ at the initial preload F_M and will not initially lead to self-loosening. Additionally, two cycles with a higher displacement amplitude $s_{a,E,peak}$ that represented load peaks during operation were applied. These amplitudes are higher than the critical displacement and initiate self-loosening. Overall 18 tests with variable displacement amplitudes were performed. Half of the tests use M8 respectively M12x1.5 bolts each. The clamping length always was once the nominal thread diameter. Further three different peak displacement amplitudes with three identical tests each were performed.

Every time a load peak cycles passes, the preload will decrease. At a certain point the critical displacement $s_{crit}(F_V)$ of the remaining preload will just be equal to the lower amplitude of the displacement spectrum. From this point on, the bolt will expectably loosen at all cycles and the average preload loss per cycle will rise.

Fig. 8 shows a comparison of experimentally preload courses and calculated results. The colored courses were experimentally determined on three different M12x1.5 bolted joints with a clamping length of $l_K = 12$ mm and a nominal initial preload of $F_M = 50$ kN like in Fig. 3. For these joints a critical displacement of $s_{crit} = 99$ μm at a loosening probability of $P_L = 50$ % was determined. The connections were subjected to a displacement amplitude of $s_{a,E} = 80$ μm for 18 cycles followed by two cycles with $s_{a,E,peak} = 150$ μm. The continuous black line shows the calculated preload course for this displacement collective, whereby the boundary curve parameters for a loosening probability of $P_L = 50$ % were used. The two dashed lines also show the calculated results for loosening probabilities of $P_L = 10$ % and $P_L = 90$ %.

As expected, the experimental courses show a slow and nearly linear decrease of preload in the beginning. When the remaining preload reaches a level of $F_V = 35$ kN up to $F_V = 40$ kN, the preload starts to decrease faster and asymptotically approaches a steeper linear course. For identical connections but with an initial preload of $F_M = 35$ kN, a critical displacement of $s_{crit} = 76$ μm at a loosening probability of $P_L = 50$ % was experimentally observed. So, at this preload level, it is just reasonable that with a certain probability the connections will start self-loosening due to the lower amplitude of the spectrum. For both linear sectors, the gradients of all tests are still similar. It can therefore be concluded that the calculated preload loss rates reproduce realistic results for both displacement amplitudes.

The calculated courses start at different initial preload values. This is due to the initial preload loss $\Delta F_{V,init}$ which estimates the preload loss due to plasticizing and snapping back due to the torsion applied for mounting, Fig. 5. It is reasonable to vary its value for different loosening probabilities, too. For the performed tests the initial preload loss was empirically determined to 10 % of the initial preload for a loosening probability $P_L = 10$ % and to 5 % of the initial preload for a loosening probability $P_L = 50$ % and to 0 % of the initial preload for a loosening probability $P_L = 90$ %. To prevent misunderstandings, it is to be said that these values fit well for the tests presented in this paper but may differ for other joints and cannot just be assumed for other applications.

For the chosen initial preload loss values the two dashed preload courses surround the experimentally detected courses down to a remaining preload of $F_V = 20$ kN, Fig. 8. So, the two calculated courses for a low and a high loosening probability are likely for reliability regarding the presented accumulation method. Even below $F_V = 20$ kN the preload courses are quite similar.

5. Discussion

To rate the reliability, accuracy and conservativity of the method for preload loss accumulation, the experimental data was compared statistically to the calculated results. Representatively for all conducted tests with variable displacement amplitude, the bolted joints with M12x1.5-bolts with a clamping length of $l_K = 12$ mm and a nominal initial preload of $F_M = 50$ kN like in Fig. 3 and Fig. 8 are presented. For M8-joints the results are equivalent. For an overall preload loss to a remaining preload of 75 % of the initial preload, the median, maximum and minimum reached number of cycles in different tests with variable load amplitudes were identified.

Fig. 9 comparatively shows the experimental and the calculated results. On the y-axis the number of cycles N is shown at which a residual preload of 75 % of the initial preload is reached. All tests used a displacement spectrum according to Fig. 7. The plotted data is separated in three groups. Every group stands for a different peak displacement amplitude $s_{a,E,peak}$. Each group contains three bars which show the calculated number of cycles, using the boundary curve parameters for loosening probabilities of $P_L = 10$ %, $P_L = 50$ % and $P_L = 90$ %. Additionally, in the middle of each bar group the figure maps the logarithmic mean value of the experimental tests with the same peak displacement amplitude with a black dot. On each of these dots two error bars show the maximum and the minimum number of cycles reached experimentally. Like in Fig. 8, for each peak displacement amplitude three tests with variable displacement amplitude have been performed. Finally, the difference of experimental median to the calculated value for $P_L = 50$ % relative to the experimental median is noted above each error bar.

The experimental and the calculated results match well for a peak displacement amplitude of $s_{a,E,peak} = 150$ µm and $s_{a,E,peak} = 200$ µm. For $s_{a,E,peak} = 250$ µm the accuracy decreases. At this point, it must be mentioned that the control loop of the used servo-hydraulic testing machine was challenged by those quick changes in amplitude and tended to overshoot, especially at high peak displacement amplitudes. The calculated results were computed with the peak displacement amplitudes actually reached experimentally. These were 155 µm instead of 150 µm, 230 µm instead of 200 µm and 320 µm instead of 250 µm. Since the boundary curves were generated of experimental tests with a maximum displacement amplitude of $s_{a,E} = 250$ µm, the calculation method has to extrapolate the preload loss for the highest displacement amplitude actually reached of 320 µm. This might increase the inaccuracy of the developed method for high peak displacement amplitudes.

Nevertheless, the calculated numbers of cycles for a loosening probability of $P_L = 10$ % are always smaller than the minimum experimental results. At the same time, the calculated results for $P_L = 90$ % are always higher than the maximum experimental results. So, the loosening probability efficiently adjusts the conservativity of the developed accumulation method. This behavior is similar to the field of high cycle fatigue, where S-N curves with different failure probabilities are used for the linear damage accumulation developed by Palmgren and Miner [39,40].

The introduced testing procedure may be suitable to dimension real bolted joints subjected to shear load. By replacing the metal sheets with the bolted sections of jointed parts, the self-loosening behavior of a bolted joint can be determined realistically. Since the method characterizes the bolted joint experimentally, it works without complex numeric analyses. The spread in friction and disturbing influences is indirectly expressed in the loosening probability. This saves further investigations characterizing the bolted joint. On the other hand, the testing procedure just is valid for one single type of bolted joint. The boundary curve parameters cannot be transferred to different bolted joints, yet. If just one quantity like the clamping length, the bolt type or a surface coating changes, a new experimental characterization is required. Thereby the method will be most likely for selected critical joints but not for the general use. Furthermore, changes in friction coefficients at real bolted connections due to corrosion during service cannot be considered in our method. As corrosion usually leads to an increase in friction, we rate changes in friction as normally uncritical. Nevertheless, the danger of decreasing friction coefficients for example due to temperature changes or contamination with lubricating fluids should be checked for every individual use.

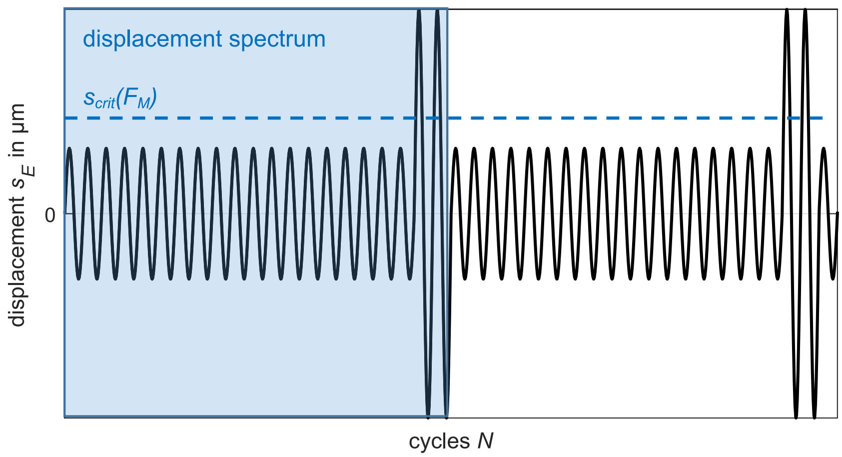

Fig. 7. Experimentally used displacement collective to simulate variable loads with peaks.

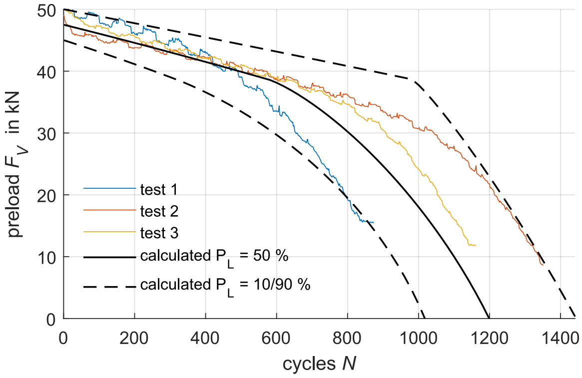

Fig. 8. Comparison of experimental tests with variable amplitudes and calculated preload courses with different loosening probabilities.

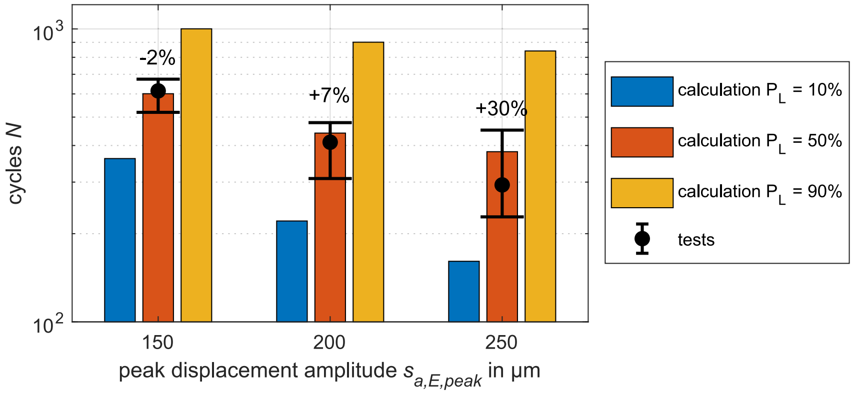

Fig. 9. Comparison of experimental tests to calculated preload loss concerning the loosening probability [41].

6. Conclusion

Self-loosening of bolted joints is a phenomenon, on which research has been conducted for a long time. Today, its mechanism still is not fully understood and no theoretical design specifications exist to avoid it reliably. This paper presents a new method to describe the preload loss due to self-loosening produced by cyclic transversal displacements. Experimental tests fully provide all parameters needed. This makes the method suitable to experimentally characterize critical bolted joints. For the general use its experimental effort may be too high. For the first time, it is possible to design and test bolted connections concerning their self-loosening behavior based on a fixed testing plan. The experimental tests allow to use original connection parts and statistically consider the spread of results.

In the testing plan, a controlled oscillating relative displacement was applied to both clamped parts with a constant displacement amplitude. From these tests so-called boundary curves were generated, similar to S-N-curves. These describe the cycles until a defined preload loss occurred depending on the displacement amplitude. Building upon the boundary curve parameters, a method for the iterative accumulation of preload loss was deduced. The method takes the dependency of the critical displacement on the remaining preload into account. Furthermore, the spread of results is statistically expressed by different loosening probabilities. Comparing the iterative accumulation method to the role of linear damage accumulation for fatigue failure and comparing the preload loss to damage, this paper delivers an analogy of self-loosening to fatigue strength. The accumulation of preload loss has to be iterative and thereby differs from the linear damage accumulation for fatigue strength.

Despite the observation that the number of cycles calculated with the developed method show good correlation with the results of our experimental tests, we have to acknowledge that our investigations were limited to a small amount of bolted joint dimensions. Further investigations are necessary to validate the developed method for general use.

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CRediT authorship contribution statement

Marius Hofmann: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Markus Faß:** Writing – review & editing, Software. **Andrea Eberhard:** Writing – review & editing, Methodology, Methodology, Funding acquisition, Conceptualization. **Marcus Klein:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Jörg Baumgartner:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Matthias Oechsner:** Writing – review & editing, Supervision, Conceptualization. **Tobias Melz:** Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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