Self loosening of prestressed bolts

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ABSTRACT: The effect of self loosening of high strength bolts has been assessed since the 1940's. Still a lot of questions are unsolved. This is especially the case in the field of bolts for steel structures with diameters of 16 to 36 mm, where the number of results is low. At risk for self loosening are steel structures under cyclic loads, such as cranes, mast constructions, smokestacks and bridges. To protect connections against the self loosening several antiloosening devices were on the market. Recent results showed that unfortunately almost all of them were malfunctioning. Due to that in 2003 all German regulations for these elements were withdrawn. At the moment a research project is running at the Technische Universität Darmstadt, Germany, to analyze the mechanism of self loosening. The aim is to find a constructive way to protect a bolted connection from self loosening. Therefore several tests to identify the important parameters were performed, especially the variation of the clamping length. Within the paper the results of the project so far were presented.

1 SELF LOOSENING OF PRESTRESSED BOLTS

1.1 *Introduction*

Bolted connections under cyclic loads have to be protected against self loosening. Especially cranes and their secondary construction, mast constructions, smokestacks and bridges are at risk. To avoid self loosening several safety elements are on the market. Unfortunately recent results showed the malfunctioning of most of these devices. Due to that in 2003 all German regulations for the safety elements were withdrawn (Esser, Hellwig 2004).
Within a research project at the Technische Universität Darmstadt, Germany, the mechanism of self loosening is analyzed. The aim is to protect bolted connections from self loosening without any additional devices.

1.2 *Mechanism of self loosening*

To fasten a bolt usually a moment is necessary. The tightening moment (M_A) can be split up into three parts (e.g. in Blume, Illgner 1988):

$$M_A = M_{T,P} + M_{T,F} + M_{H,F} \quad (1)$$

Only the moment originating from the thread pitch ($M_{T,P}$) leads to preload. The other parts result from the friction: $M_{T,F}$ is the friction in the thread, $M_{H,F}$ the friction under the head of the bolt. To unfasten the bolt the moment M_L is necessary:

$$M_L = -M_{T,P} + M_{T,F} + M_{H,F} \quad (2)$$

The moment $M_{T,P}$ helps to unfasten the bolt. It is obvious that when the thread pitch moment $M_{T,P}$ is bigger than the retention moments, self loosening can take place.

$$M_{T,P} > M_{T,F} + M_{H,F} \quad (3)$$

In a theoretical place without any friction, pretensioning of bolts is not possible at all. Under normal friction conditions the threat pitch moment is always smaller than the moment due to friction. This circumstance is called self-locking.
But self-locking can be disabled when a displacement in the connection occurs. That is the result of a physical effect: When the static friction between two bodies is resolved by a force in one direction, the friction between the bodies in any other direction but the same plane is disabled. That means, when a displacement takes place in the connection, the friction in the thread and under the head is reduced, self-locking can be disabled and the self loosening process starts.
To realize a displacement under the head of the bolt the motion between the two clamped plates has to exceed a specific amount, the marginal slip. The marginal slip ‘a’ can be calculated by (Blume 1969):

$$a = \frac{F_v \cdot \mu \cdot l_k^3}{12 \cdot EI} \quad (4)$$

With: F_v: Preload in the bolt
μ: Friction number under the head of the bolt
l_k: clamping length of the bolt
EI: stiffness of the bolt

The formula is based on a model of the bolt as a rigid beam (see figure 1). The reset forces due to slip in the connection have to be smaller than the retention due to friction.

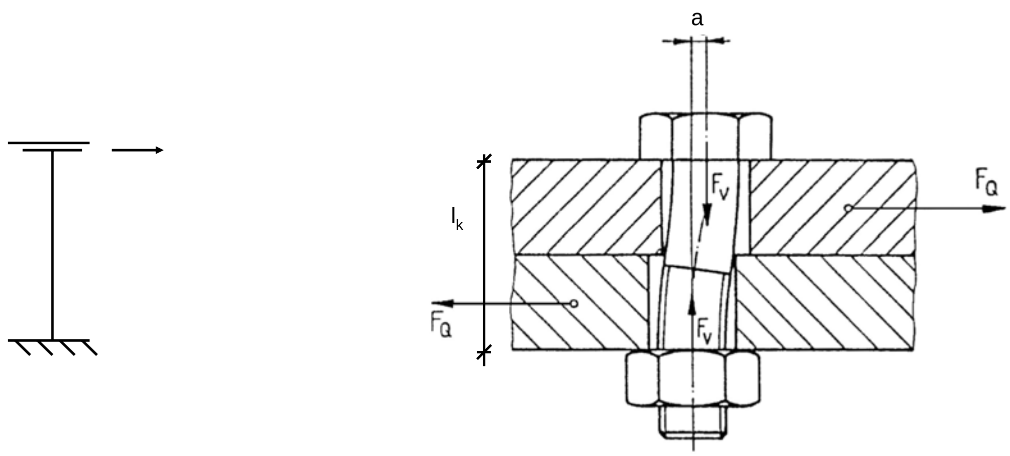


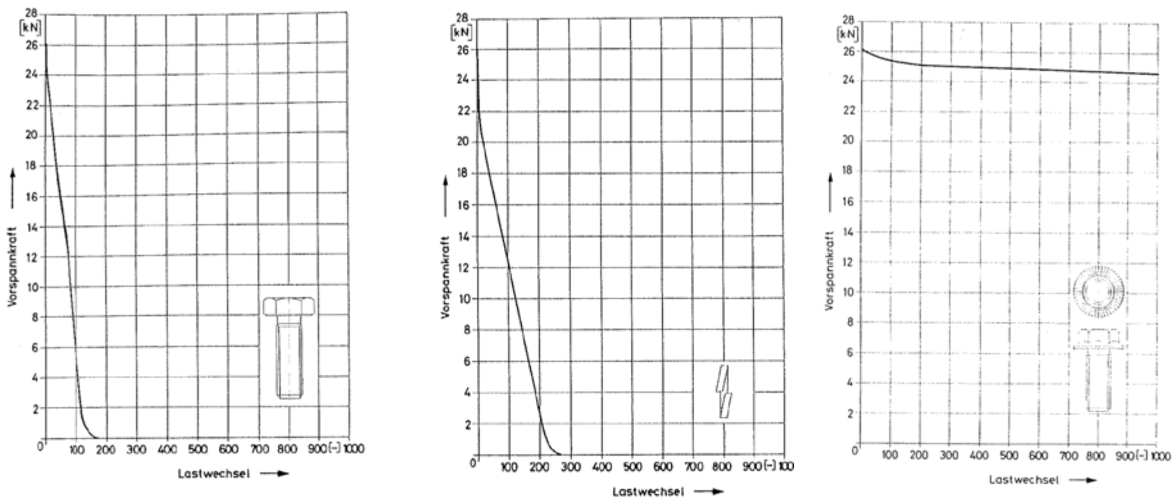
Figure 1: Model for the marginal slip (Blume, Illgner 1988)

From equation 4 several possibilities to inhibit self loosening can be deduced:

- increase the preload
- use of thin and long bolts
- enlarge the clamping length
- reduce the possible displacement, e.g. by using fitting bolts
- raise the friction coefficient

1.3 *Vibration test*

A dynamic test was developed by Junker (Junker, Strelow 1966). With that test it is possible to analyze the locking characteristics of fasteners under transverse loading conditions. In that test a bolted shear connection is moved by an eccentric rotating engine. Due to an elastic centerpiece the deformation controlled load is transformed into a mixture of deformation and force. The Junker test is standardized by the German regulation DIN 65151. With the Junker test it is not possible to affirm a secure connection but to compare different connections and safety devices.
The result of the test is the development of the preload versus the number of load cycles. In figure 2 some results with bolts M10 x 30 - 8.8 are shown. The vertical axis shows the preload, the horizontal axis the number of load cycles. The behavior of a single bolt is shown in figure (2a). After approximately 150 load cycles the preload is gone. Safety devices like helical springs (2b) can not avoid the self loosening. Only locking elements like serrated bolts (2c) can secure the connection: The preload is reduced but stays constantly on a high level.



a) single bolt b) with helical spring c) serrated bolt

Figure 2: Preload versus load cycles of different fasteners (Strelow 1983)

2 SELF LOOSENING TESTS AT TU DARMSTADT

2.1 *Introduction*

At the Technische Universität Darmstadt, Germany, several tests for a better understanding of the mechanism of self loosening were realized and are still in progress. The intention is to find a solution to protect bolted connections for steel constructions (M16-M36) without any additional devices. The main key point of the test series so far is the influence of the clamping length.

2.2 *Tests*

Figure 3 shows the sketch of the test stand. Two steel plates (S235, hole Ø 22 mm, thin coated) were fixed in a testing machine. To minimize eccentricities the load runs right through the shear plane of the plates. The plates were connected with a bolt M20 10.9. The bolt was fully tightened (F_v = 160 kN, M_A = 450 Nm, DIN 18800-7) by a torque-controlled

wrench. To measure the axial forces in the bolts, they were equipped with special strain gauges. Each bolt was calibrated in advance. After the tightening a cyclic displacement of ± 2 mm was applied. The frequency varied between 0.2 and 1 Hz. The development of the axial load in the bolt was recorded. After at most 1000 cycles the test was stopped.
Especially the influence of the clamping length was assessed. Therefore plates with different thicknesses were used. Table 1 gives an overview of the tested parameters so far. For each parameter three tests were run. Due to the test situation not all results could be taken into account. But for each parameter at least two results were proper.

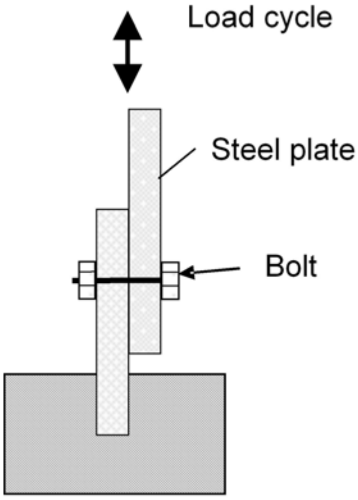


Figure 3: Test stand

Table 1: Tested parameters

Test No.	clamping length mm	bolt type	displacement +/- mm	frequency Hz
1	20	M20 10.9	2	0,2
2	40	M20 10.9	2	0,5
3	60	M20 10.9	2	0,5
4	80	M20 10.9	2	0,5
5	90	M20 10.9	2	0,2/1 **
6	100	M20 10.9	2	0,2/1
7	120	M20 10.9	2	0,2/1
8	60 *	M20 10.9	2	0,2/1
9	100 *	M20 10.9	2	0,2/1

* The clamping length was realised by an additional nonfixed plate
** The test started with a frequency of 0,2 Hz and run after 500 cycles with a frequency of 1 Hz

2.3 *Results*

Some results of the self loosening tests are given in figure 4. The plot shows the percentage of the preload versus the load cycles. The lines represent the average results of at least two tests. The percentage is based on the maximum preload after assembling.
After starting the test, the preload decreases immediately. After at most 400 load cycles the preload in the bolts with a clamping length less than $l_k < 90$ mm is gone and it was possible to unfasten the bolts by hand. The bolts with a clamping length of $l_k \geq 90$ mm are holding a rest of the preload after 1000 cycles. But the axial load has decreased drastically.

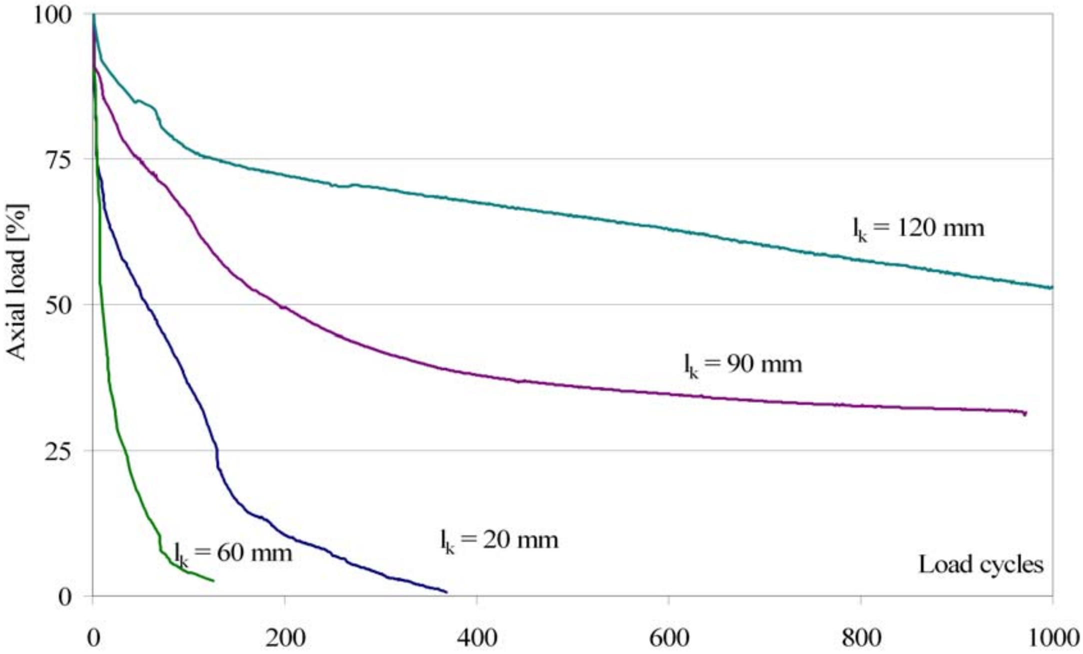


Figure 4: Self loosening of single bolted connections (M20 10.9)

Figure 5 shows in another way the influence of the clamping length. On the horizontal axis the clamping length is given, on the vertical axis the axial load in percentage. The different lines are the number of load cycles. It shows that the worst characteristic concerning the self loosening the connection has with a clamping length of $l_k = 60$ mm. Even the smaller clamping lengths perform better. But still only clamping lengths above $l_k \geq 90$ mm secure the connection from the complete loosening after 1000 cycles.

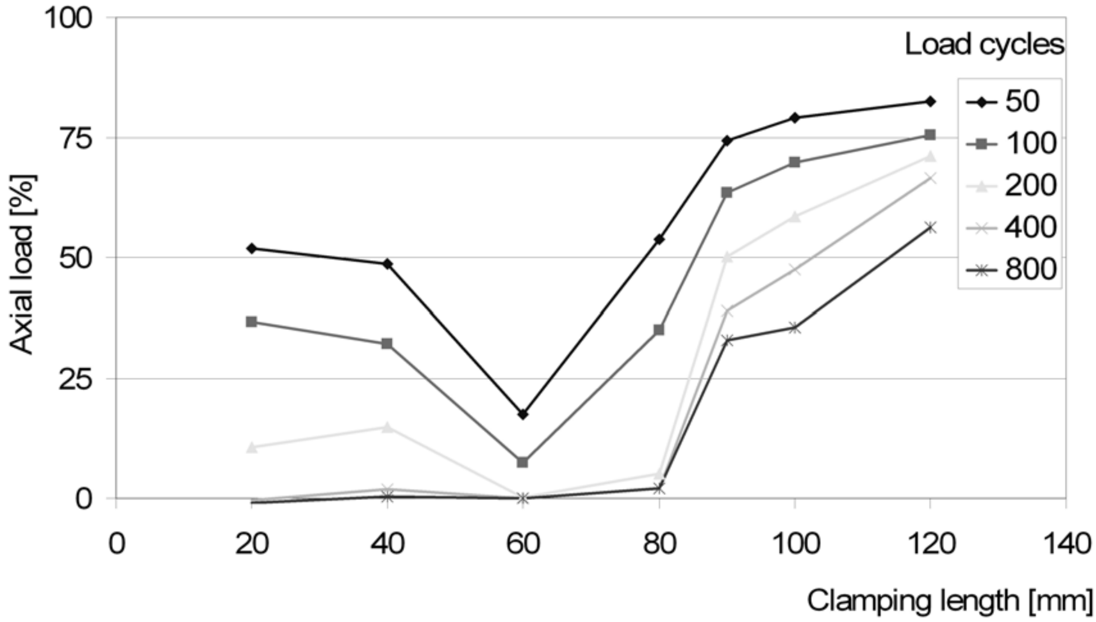


Figure 5: Influence of the clamping length on the self loosing effect (M20 10.9)

In the tests number 8 and 9 the clamping length was realized by additional not fixed fillers. The results of the tests with the fillers lay above the lines of the comparable tests number 3 and 6 as seen in figure 6.

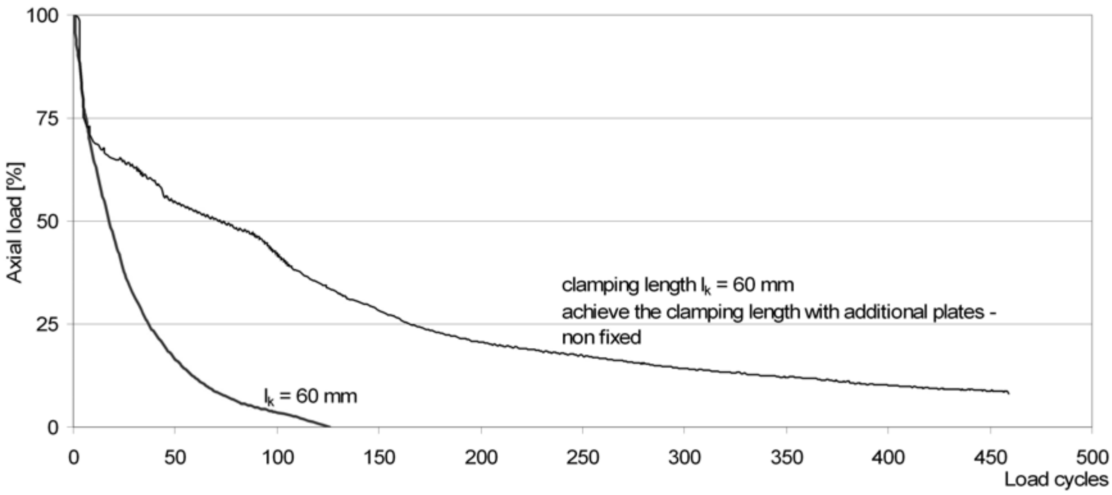


Figure 6: Influence of non fixed filler plates of the self loosening (M20 10.9)

2.4 *Future tests*

Table 1 shows the parameters tested so far. The main viewpoint of these tests laid on the influence of the clamping length. In further tests the followed conditions will be tested:

- Influence of the size of the bolt (M16, M24)
- Connections with two shear planes
- Influence of the amount of cyclic displacement
- Influence of an additional axial load

2.5 *Interpretation*

The effect of self loosening could be reproduced in a test field. Under transversal cyclic displacements bolted connections loosened and the preload decreased. Within these tests the clamping length showed a major influence on the effect of self loosening.
The decreasing of the preload as described in this text is not only a result of self loosening but a combination of loosening and embedding. Especially the thin coat of the plates together with the cyclic displacement leads to a large amount of embedding and furthermore to a large loss of preload which could not be verified within the self loosening tests. In another project at the TU Darmstadt the effect of embedding was assessed (Proff 2007). Especially these new results of connections under cyclic movement showed that the embedding leads to a major loss of preload.
Nevertheless the influence of the clamping length could be clearly verified. The connections with a slenderness (clamping length / diameter) under $l_k/d = 4.5$ loosened completely after less than 400 load cycles. A slenderness of 4.5 and above secured the connection but could not avoid the loss of preload. The loss of the preload is interpreted as a combination of loosening and embedding.
During the tests a cyclic displacement of ± 2 mm was applied. The result of the tests (a slenderness of 4.5 secures the connection) fits quite well with the marginal slip after (4), shown in table 2. The development of the preload and the uncertain friction coefficient makes it very difficult to calculate a proper marginal slip but it seems that (4) gives a good approximation. In further tests the marginal slip will be further analyzed.

Table 2: Equation (4) leads to the following marginal slips:

assembly preload [kN]	friction coefficient [-]	clamping length [mm]	slender-ness [-]	marginal slip [mm]
160	0.3	20	1	0.019
160	0.3	40	2	0.16
160	0.3	60	3	0.53
160	0.3	80	4	1.24
160	0.3	90	4.5	1.77
160	0.3	100	5	2.43
160	0.3	120	6	4.19

In some tests the clamping length was realized by filler plates which were not fixed with the connection. The results show that these fillers lead to a better behavior concerning the self loosening (see figure 6). The reason for this behavior is that the fillers soften the connection in transversal direction. A displacement in the plane ‘plate - filler’ can release the reset force of the bolt. It shows that the large clamping length can be realized also by fillers.

3 CONCLUSION

For bolted connections with cyclic loads the preload is very important: On one hand for the fatigue resistance and on the other hand as locking device. Especially cranes and their secondary construction, mast constructions, smokestacks and bridges are at risk.
Within a research project at the Technische Universität Darmstadt, Germany, the mechanism of self loosening is analyzed. The intention is to find a solution to protect bolted connections for steel constructions (M16-M36) without any additional elements. The main key point of the test series so far is the influence of the clamping length.
The results show that cyclic transversal displacements in the shear plane of the connection lead to a reduction of preload due to self loosening and embedding. If the displacement exceeds a special amount the connection loosens and the preload is gone after a very low

number of load cycles. In the tests the complete loss of preload took place in between 125 and 400 cycles, a number that is far away from being associated with a fatigue problem.
The height of the necessary displacement is called the marginal slip. Previous publications give a formula to calculate it (4). The tests showed that this equation is a good approximation. For the marginal slip the clamping length has got a big influence. The tests with a displacement of ± 2 mm showed that a slenderness (clamping length / diameter) of equal or above $l_k/d \geq 4.5$ secures the connection significantly and reduces the loosening (figure 4).
Tests were held with additional filler plates to reach the clamping length. The results show that these non fixed fillers have got a good influence and inhibit the self loosening process compared with single plated connections (figure 6).

Nevertheless in all tests the preload was reduced dramatically due to a combination of self loosening and embedding. This effect has to be taken into account during the designing process. Under cyclic loads, especially when they are in transversal direction, the displacement in the shear plane has to be avoided necessarily.
If it cannot be avoided the following list can help to construct a secure connection:

- Limit the displacement e.g. by using fitting bolts
- Use long and thin bolts
- Use fillers to enlarge the length of the bolt
- Increase the preload
- Use thin or even better no coating in the faying surfaces to reduce embedding
- Use of efficient safety elements
- Increase the friction under the head of the bolt

Loosening and embedding in constructions under cyclic loads are a serious problem that can cause failure and damage. That has to be taken into account in the early construction phase. Only the combination of a good design and frequent inspections can assure the durability of the connection.

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