LOSS OF PRELOAD IN BOLTED CONNECTIONS DUE TO EMBEDDING AND SELF LOOSENING

Roland Friede, Jörg Lange

Institut for Steel Structures and Material Mechanics, Technische Universität Darmstadt, Germany
friede@stahlbau.tu-darmstadt.de, lange@stahlbau.tu-darmstadt.de

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Abstract. *At the Technische Universität Darmstadt, Germany, a research project analyzes the effect of embedding and self loosening of bolted connection. Therefore tests on single bolted lap joints were performed. The amount of static embedding proved to depend mainly on the coating system. If there was a cyclic displacement in the joint, even uncoated connections lost up to 40 % of the preload. Self loosening tests showed the importance of several parameters, especially the clamping length and the amount of displacement. The paper presents the tests and the results.*

1 INTRODUCTION

Bolted connections are more or less preloaded. Especially when the stiffness of the connection is important or a cyclic load can lead to a fatigue problem, it is necessary to fasten the connection with a special amount of preload. But there are some effects that can lead to a decrease of the preload during the lifetime of the construction. The two most important effects are (a) embedding and (b) self loosening.

To protect connections against the loss of preload, several antiloosening devices are 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 Due to that in 2003 all German regulations for these elements were withdrawn [1]. At the moment a research project is running at the Technische Universität Darmstadt, Germany, to analyze the mechanism of embedding and self loosening. The aim is, to find a constructive way to protect bolted connections. Therefore several tests to identify the important parameters were realized. Within this paper the tests and the main results are presented.

2 LOSS OF PRELOAD

After the fastening the preload of bolted connection can be reduced due to embedding and self loosening. Embedding is the result of yield processes in the microstructure of the connecting surfaces. The height of the embedding depends on time, pressure, temperature, material, number of surfaces and the implemented load. In standard steel connections especially the coating system has a large influence. Within different tests the amount of embedding has been earlier assessed for static loads and different coating systems [2]. The reduction of the preload due to embedding depends on the construction. Especially the resilience of the bolt and the clamped material is important. If the bolt and the plates are stiff, embedding leads to a higher loss of preload [3]. When the loss of preload exceeds a tolerable value, the bolts have to be refastened.

Self loosening in lap joints can take place when a cyclic slippage in transverse direction takes place. In this situation the loosening moment in the thread can exceed the holding moment due to friction. The height of the critical slippage can be calculated by equation (1). The equation bases on a model of a beam clamped on both sides (see Fig. 1) [3].

$$a_{ult} \leq \frac{F_v \cdot l_k^3 \cdot \mu}{12 \cdot EI} \qquad (1)$$

If the slippage is below the critical slippage the deformed bolt can follow the displacement. Long and bending flexible bolts have got an advantage. To avoid self loosening there are several possibilities [4]:

- Enlarge the clamping length
- Increase the preload
- Raise the friction
- Use long and thin bolts
- Reduce the displacement, e.g. by using fitting bolts
- Use efficient securing devices

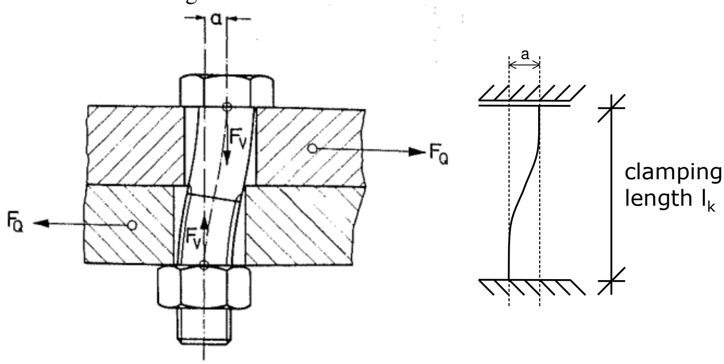

Figure 1: Lap joint with transversal deformation [3] / mechanical model

A dynamic test to assess the self loosening effect was developed by Junker in 1966 [5]. 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 code DIN 65151 [6]. With the Junker test it is not possible to affirm a secure connection but to compare different connections and safety devices. For test specimens hardened surfaces are used generally.

3 RESEARCH PROJECT

At the Technische Universität Darmstadt, Germany, a research project to assess the effects of embedding and self loosening of bolted connections is conducted. The aim is, to create new data about these effects and to find possibilities for designing secure constructions. During the project several tests were run which are presented in the following chapters.

3.1 Embedding tests

Within these tests [7] the embedding of bolted connections with different coating systems was assessed. Therefore static and cyclic tests were run on single bolted connections with bolts M20 10.9. For the test specimens (plate thickness 25 mm, overlapping area 100x100 mm, S235, ø22 mm) different coating systems were used. Table 1 shows the five different coating systems. The systems 0, 1 and 2 are supposed to have a hard surface, the systems 3 and 4 have a soft surface.

Table 1: Coating system of embedding tests

System Number	Coating (thickness)	
System 0	Uncoated	
System 1 (150 µm)	Primer	Epoxy-zinc (70 µm)
	Cover	Epoxy-iron mica + polyurethane (80 µm)
System 2 (230 µm)	Primer	Epoxy-zinc (70 µm)
	Intermediate	Epoxy-iron mica + polyurethane (80 µm)
	Cover	Epoxy-iron mica + polyurethane (80 µm)
System 3 (80 µm)	Coating	Alkyd (80 µm)
System 4 (160 µm)	Coating	Alkyd (80 +80 µm)

In a first step the connections were fully fastened ($M_A = 450$ Nm, $F_P \sim 160$ kN). The preload was measured over the elongation with a micrometer. This method was tested and calibrated in advance. It showed that the preload is reduced after the fastening very quick. After about one day the preload stays constantly, the static embedding came to a halt. At the test specimens with the system 3 and 4 the soft coating is literally squeezed out of the contact surfaces (see Fig. 2).

In a second step the two plates were fixed in a testing machine and a cyclic deformation between the plates was applied (see Fig. 2). In these tests self loosening was avoided by a weld spot. The preload was measured over the load cycles.

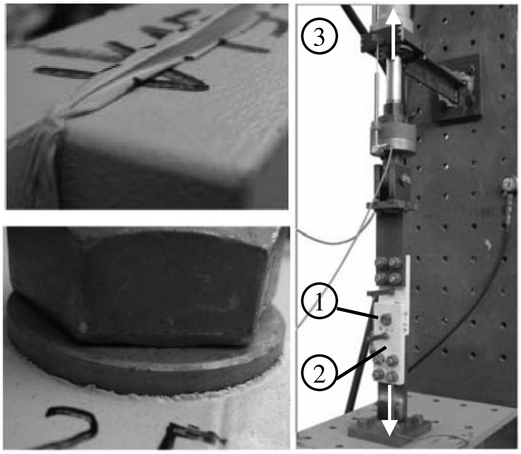

Figure 2: Static test, coating squeezed out (left),
cyclic test with bolt (1), plates (2) and cylinder (3) (right) [7]

The results of these tests (step one and two) are given in Fig. 3. For the four different coating systems the mean values of three tests are shown. On the left side are the results of the static step. It can be seen that in every test at first a declination of the preload takes place which goes over to a constant value. The static embedding is between 8 and 80 % of the initial preload. On the right side the results continue with the load cycles of the second step. The preload is reduced because of the slippage in the contact pairs. The static and cyclic embedding leads to a total loss of preload of about 45 to 95 %.

The results show that embedding can have a big influence on the preload. The amount of static embedding depends on the coating system, in uncoated connections the preload is reduced too. The slippage in the connection leads to an additional loss of preload that is even severe for uncoated systems. Slippage in the connection has to be avoided or additional procedures have to be foreseen. These could be e.g.: use long and thin bolts, use additional elastic devices, use thin and hard or even better no coating, use material with hardened surface, increase the preload.

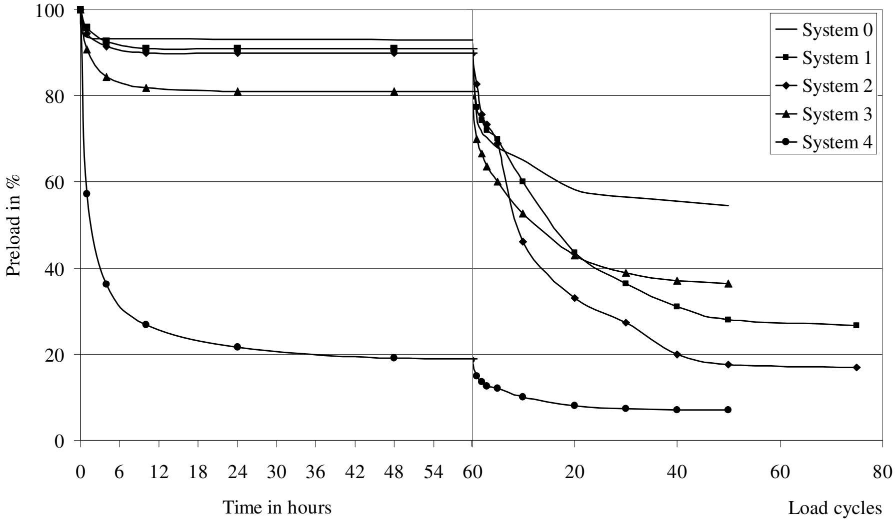

Figure 3: Results of the embedding tests: static test (left), cyclic test (right)

3.2 Self loosening tests

A new test was developed to assess self loosening. The idea was to analyze the effect under realistic conditions. Compared to the Junker test, standard material with a not-hardened surface was used. Within these tests (see also [8] and [9]) different parameters like the clamping length, the amount of the slippage and the effect of coating were assessed. The tests were run with single bolted lap joints with plates (plate thickness 20-60 mm, overlapping area 220x200 mm, S235, Δø2 mm) and bolts M16 to M24 (strength grade of 8.8 and 10.9). The tests were run displacement controlled with a slippage between ±0.3 and ±2 mm and a frequency of 0.2 to 0.4 Hz. The force in the bolts was measured via strain gauges implemented in the bolt shank. Fig. 4 shows a sketch and a picture of the experimental setup.

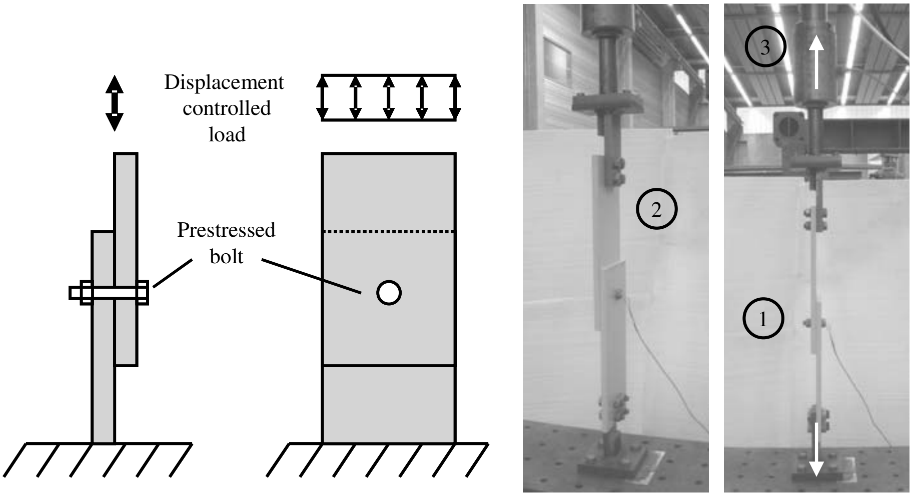

Figure 4: Sketch of the self loosening tests; experimental setup - bolt (1), plates (2), cylinder (3)

Some of the results are presented in diagrams below. The curves are means of at least two tests. The loss of preload can be traced back on a combination of embedding and self loosening. The figures show the number of load/displacement cycles on the horizontal axis and the relative preload on the vertical axis.

In Fig. 5 the results of tests with varying clamping length are shown. A clamping length under 90 mm led to a complete loss of the preload within 200 cycles, a number that is far away from being associated with a fatigue problem. But even a clamping length above 90 mm led to a significant loss of the preload. During the tests with a clamping length of 90 or higher, no slippage of the bolt/nut was measured. Self loosening did not occur.

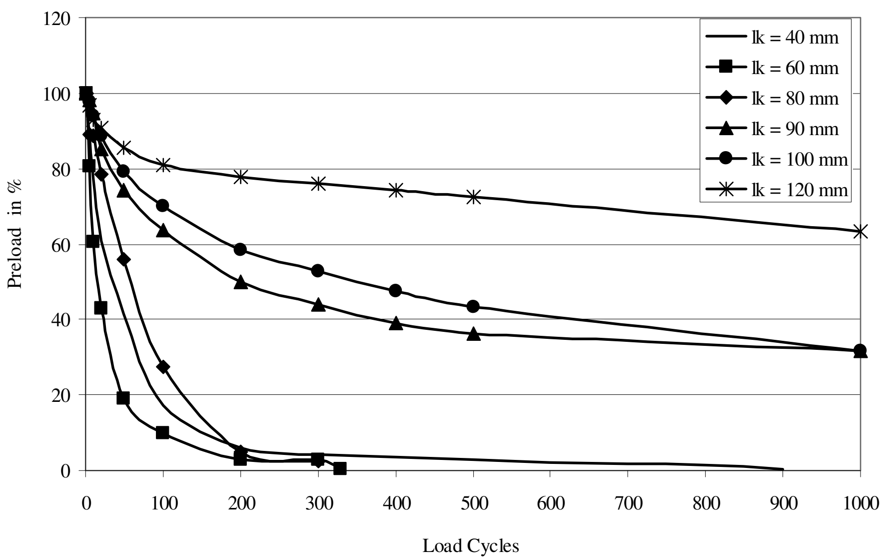

Figure 5: Self loosening of bolts M20 10.9 with different clamping length l_k

In figure 6 results of self loosening tests with a different displacement between the plates are shown. Smaller displacements led to a minor declination of the preload. In the tests with bolts M20 10.9 a displacement of 0.3 led to a constant preload on a high level. The tests with a higher displacement led to slippage of the bolt/nut and self loosening.

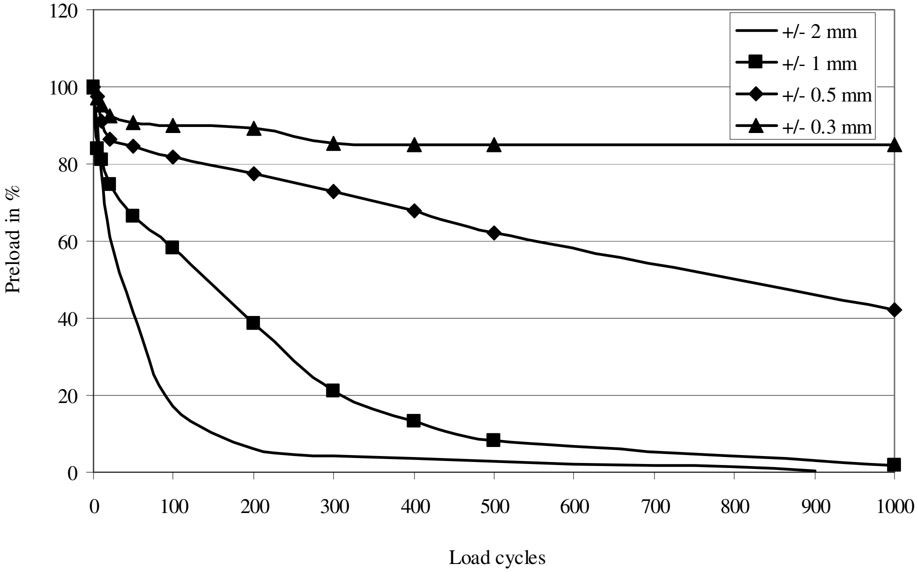

Figure 6: Self loosening of bolts M20 10.9 l_k = 40 mm with different displacements

The parameters tested can be divided into three groups (see table 3): positive influence (slow down the loss of preload), negative influence and no influence.

Table 3: Influence on the self loosening of the tested parameters

Positive influence:	Enlargement of the clamping length Reduction of the slippage Using of the securing device NORD-LOCK
No influence:	Additional axial force Fastening with the combined method (combination of torque and rotation controlled) Producing the clamping length with additional non fixed plates compared to the same clamping length in one peace Bolt diameter
Negative influence	Additional coating 8.8

4 CONCLUSION

Every bolted connection is more or less preloaded. After the fastening the preload can be reduced due to embedding and self loosening. At the Technische Universität Darmstadt, Germany, the effects were assessed.

A first test series assessed the effect of embedding. Static and cyclic tests with single lap joint connections with bolts M20 10.9 were run. The result was that embedding under static load leads to a loss of the preload, in the tests between 8 and 80 % of the starting preload. The coating system has got a major influence. Therefore it is necessary to choose an adequate coating system. Hard coatings, like epoxy-zinc and epoxy-iron mica + polyurethane systems, led to good results. Soft coatings, like alkyd, are pushed out of the connection and led to a higher loss of preload. The thickness must be limited. The results are comparable to earlier tests [2]. Under cyclic loads the reduction of preload grows. Even in uncoated connections the preload is reduced to 55 % of the initial preload. This is a result of abrasion in the contact pairs. In the coated connection the reduction amplifies. In the worst case the preload is gone.

The loss of preload hast to be taken into account during the design process. To secure the connection slippage has to be avoided or an adequate construction is necessary (e.g. use long and thin bolts, use additional elastic devices, use thin or even better no coating, use material with hardened surface, increase the preload, refasten during frequent maintenance).

In a second test series the effect of self loosening was assessed. Therefore single lap joint connections with bolts M16 to M24 8.8 and 10.9 under cyclic loads were assessed. The results are that self loosening can be avoided under the following circumstances:

- Reduce the slippage in the lap joint ($\leq$ 0.3 mm for bolts M20)
- Enlarge the bolt length above the clamping length to diameter ratio of five ($l_k/d > 5$)
- Achieve form fit between the bolt and the nut by additional securing elements or adhesives

Nevertheless the preload will be reduced due to static and cyclic embedding. Additional there is always a risk of fatigue failure when a slippage in the lap joint leads to bending of the bolt. The only enduring protection from self loosening is to avoid the slippage in the joint.

A comparison of the test results with the critical slip showed that eq. 1 leads to conservative results. To improve the calculation of the critical slip it is possible to take the flexibility of the clamped ending of the beam model into account [10]. That leads to eq. 2. For bolts M20 the stiffness C_φ = 1250 kNm/rad fits quite well to the test results.

$$a_{grenz} \leq F_V \cdot \mu \left[\frac{l_k^3}{12 \cdot EI} + \frac{l_k^2}{2 \cdot C_\varphi} \right] \tag{2}$$

Embedding and self loosening reduce the preload and can lead to the complete failure of the bolt. During the design process the reduction of preload in bolted connections has to be taken into account. Although a lot of test results are available, in some cases it is still very difficult to foresee and prevent the reduction of preload with economic solutions. Therefore it is, beside a good design, necessary to develop worst case scenarios and to monitor critical connections frequently.

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