Experimental studies on the clamp length diameter ratio in highly stressed bolted joints

Ch. Denkert[a], F. Kalkowsky[b], W. Flügge[c]

Fraunhofer IGP, Rostock
a. christian.denkert@igp.fraunhofer.de
b. florian.kalkowsky@igp.fraunhofer.de
c. wilko.flügge@igp.fraunhofer.de

Abstract :

Especially in railway vehicles like wagons and locomotives bolted joints are applied in purpose of maintenance or repair. Those bolted joints offer the opportunity to demount and reinstall components and assemblies e. g. accumulators and drive units. The article deals with a significant construction detail for tensioned bolted joints. For such joints clamp length diameter ratios $\frac{l_k}{d} = 3...5$ *are recommended. However the configurations of the bolted joints frequently lead to a ratio between clamp length and diameter of* $\frac{l_k}{d} < 3$*. This fact is caused by the low thickness of the sheet metal and the necessary diameter of the bolt for prestressing with their mandated property class.*

The execution of tensioned bolted joints with such small ratios between clamp length and diameter is prohibited by standards and regulations, e. g. DIN 25201-2. With the presented studies in this article the effect on the slip resistance according to a variation of the $\frac{l_k}{d}$ *ration is determined. For this purpose the resistance against slipping is investigated with a variation of the clamp length diameter ratio as well as the tightening procedure. The results of the experimental studies are not corresponding with the verification against slipping using the actual calculation models of the stated standards and regulations.*

Railway vehicles, bolted joint, preload, slip load, frictional engaged load bearing

1 Introduction

According to DIN 25201-2 [1] the preloaded bolted connection owns the task to prohibit relative movement or a gaping between the joint adherends. The principal of frictional engaged load bearing behaviour is displayed in Figure 1 for a transverse loaded shear joint. It means in effect that the bolted joint fails at the moment the transverse load F_Q exceeds the slip resistance $F_{Q\,zul\,\mu} = F_s$. The slip resistance of bolted joints essentially depends on the residual clamp load $F_{KR\,min}$ which comes along with the assembly preload F_M.

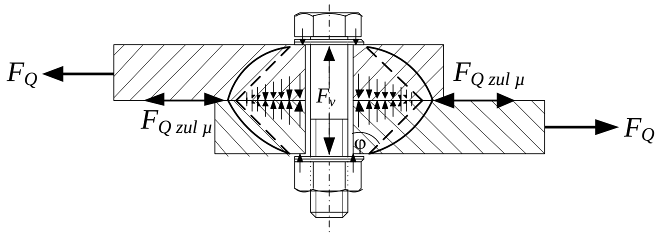

Figure 1 – Principle of frictional engaged load bearing

According to VDI 2230-Part 1 [2] the residual clamp load $F_{KR\,min}$ is calculated by equation (1). This equation is also called the main dimensioning formula and forms the basis for bolt calculation. Within the residual clamp load F_{KRmin} the frictional engaged load bearing effect is activated. The safety verification against slipping is given with equation (2) [2]. As equation (1) displays, the residual clamp load F_{KRmin} depends on several terms. This article focus on the term F_Z in relation to the necessary resiliance.

$$F_{KR\,min} = \frac{F_{M\,zul}}{\alpha_A} - (1 - \phi)F_{A\,max} - F_Z - \Delta F_{Vth} \tag{1}$$

$$F_Q \leq F_{Q\,zul\,\mu} = \mu_{T\,min} \cdot \frac{F_{KR\,min}}{S_G} \tag{2}$$

$$F_z = \frac{f_z}{\delta_S + \delta_P} \tag{3}$$

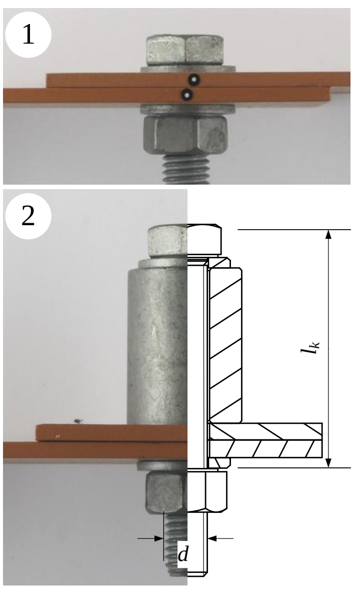

Figure 2 – Expansion Sleeve to increase $\frac{l_k}{d}$

The amount of the item F_z is essentially depends on the resiliance and thereby on the clamp length of the highly stressed bolted joint. The analytical model of the standard [2] computes the preload due to embedding F_z in consideration of resiliance. This correlation is shown by the denominator of the equation (3). With the resiliance of the bolt δ_S and the clamped parts δ_P the loss of preload due to embedding can be calculated. If the denominator of equation (3) increases by extension of the clamp lenght the loss of preload due to embedding F_z decreases. As consequence of equation (3) the ratio between clamp length and diameter of the bolt $\frac{l_k}{d}$ is mandated. For national railway constructions $\frac{l_k}{d}$ is restricted to a value $\geq 3 \ldots 5$. For plenty of bolted joints (Figure 2 - ①) this ratio is not realizable without the help of an expansion sleeve between bolt and sheet metal parts (Figure 2 - ②). Unfortunately the integrated expansion sleeves lead to a significant raise of construction weight and more part diversity in the manufacturing line. For the proof against slipping the determined load is the transverse load F_Q as cutting load out of the load case computation. According to Figure 1 the limiting slip force $F_{Q\,zul\,\mu}$ or slip resistance F_s always has to be greater than the transverse load F_Q to maintain the frictional engaged load bearing. Therefore it is important to find out, how the slip resistance changes if the expansion sleeve is not applied as it is demonstrated in the Figure 2 - ①.

2 Experimental studies

2.1 Design of experiments and test arrangement

An overview over the design of experiments is given by TABLE 1. Two elementary parameters are considered during the experimental studies. First one is the clamp length by the ratio $\frac{l_k}{d}$ which is regulated with a sleeve. Therefore FIGURE 2 displays the variation of the clamp length by omitting the expansion sleeve to decrease the $\frac{l_k}{d}$ ratio. The second parameter varies with the tightening procedure. On the one hand a torque-controlled tightening is applied.

TABLE 1 – Design of experiments

series	$\frac{l_k}{d}$	tightening procedure	sleeve	surface	specimen number
i	1	torque-controlled	no	primer	$1 \dots 6$
ii	4	torque-controlled	yes		$12 \dots 17$
iii	1	yield-controlled	no		$7 \dots 11$
vi	4	yield-controlled	yes		$18 \dots 22$

A yield-controlled tightening is adapted on the other hand. Ahead of the torque-controlled tightening the characteristic friction coefficients in the bearing μ_b and thread μ_{th} were determined in accordance with DIN EN ISO 16047 [3]. In combination with the determined relation of torque and clamp load the friction coefficients help to provide the tightening factor for prediction of a preload level. A more accurate tightening procedure in reference to the scatter of prelaod is the yield-controlled tightening. For this tightening procedure almost no scatter of preload is expected.

Furthermore the value of preload becomes even higher because the strength of the bolt is utilized up to its yield point. The bolt set consists of a bolt ISO 4017 - M10 x 60 - 8.8, GEOMET 500A/5mu together with a nut ISO 4032 – M10 – 8 GEOMET 500A/5mu and a washer ISO 7098 – 10. As TABLE 1 displays the specimen were primed by a railway coating. The losses of preload due to embedding and relaxation processes determined in previous studies [4, 5] and hence are already known. After tightening the bolted joints with the help of a KISTLER analyzing system the specimen were stored for over 72 hrs to await for the main loss of preload due to embedding. To determine the slip load the specimens are loaded with the help of the test machine ZWICK/ROELL 400E according to FIGURE 3 (right). The measuring of the displacement is realized by an optical system VIDEOXTENSE in the axis of the bolt. The tests are performed in a displacement controlled mode with a velocity of $0,05\ mm/min$. The result of the test in FIGURE 3 is a load-displacement-behaviour as shown in FIGURE 4.

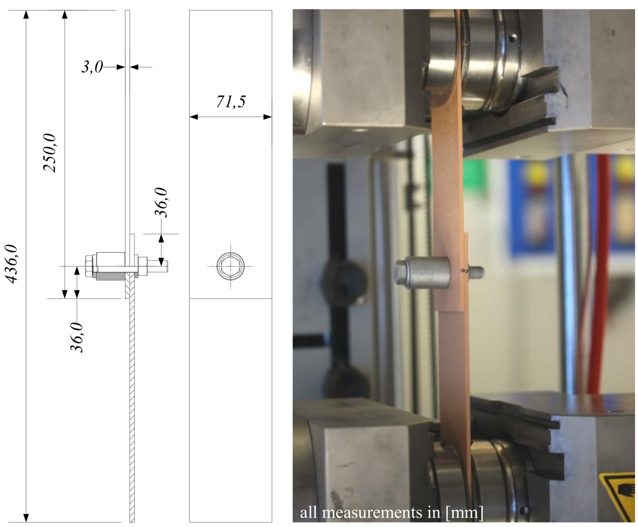

FIGURE 3 – Bolted specimen (left) and arrangement of tensile test (right)

2.2 Results of the slip load test

As result of the slip load test a characteristic graph of load and displacement correlated by the time is obtained. The FIGURE 4 displays this correlation for one specimen as an example. TABLE 2 summarizes the characteristic slip loads referring to the graphs in FIGURE 4.

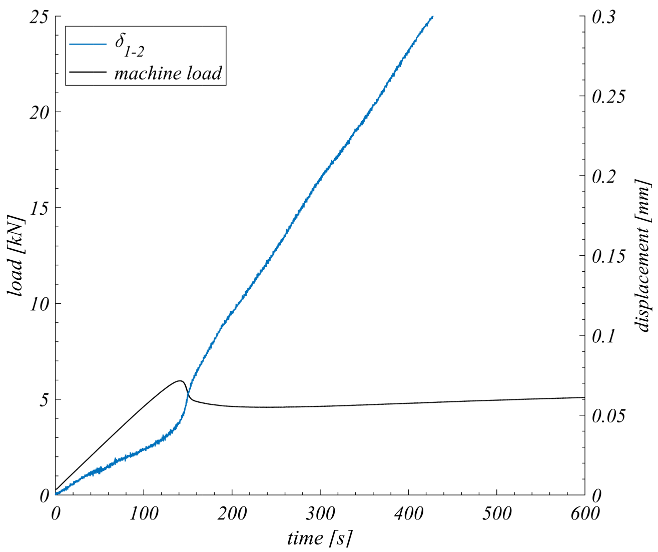

FIGURE 4 – Characteristic graph of load and displacement in correlation to the time

The loads $F_{s,30\mu m}$ and $F_{s,50\mu m}$ in TABLE 2 characterize the slipping for a displacement of $\delta = 30\ \mu m$ respectively $\delta = 50\ \mu m$. For the local maximum of the load $F_{s,max}$ the displacement $\delta_{F_{s,max}}$ is also displayed in TABLE 2. All experimental values are sorted with the statistic of mean value m_x, standard deviation s_x and variation coefficient V_x. A typical displacement in railway industry to analyze the slip load is $\delta = 30\ \mu m$.

In consideration of the necessary sleeve the mean values of the slip loads in series ii and vi are not significantly higher in comparison to the series i respectively ii without sleeve. Also the determined local maximum slip loads $F_{s,max}$ do not increase by application of a sleeve. The slightly higher slip loads in series iii and vi results from origin assembly preload in correlation with the utilization of the bolt by yield controlled tightening. Furthermore the determined variation coefficients of the measured slip loads are interesting. The variation coefficient returns the scatter of the measured values in relation to their mean value.

This becomes especially important if the experimental values should be used for computational proof of bearing capacity. The lower the coefficient of variation, the better the result. At the displacement of $\delta = 30\ \mu m$ the variation coefficients for the bolted joints with sleeve $V_x = 0,14$ (series ii) and $V_x = 0,15$ (series vi) exceed the variation of the specimen without sleeve (series i & iii) nearly twice as much. Also the additional points of evaluation of $\delta = 50\ \mu m$ and the local maximum display a higher scatter for the bolted joints with sleeve according to the variation coefficient. Regarding to the variation coefficients hereby the characteristic values reduces supplementally the slip resistance for the bolted joints with sleeve. Another relationship occurred by reference to TABLE 2. The displacement $\delta_{F_{s,max}}$ for the determined local maximum loads $F_{s,max}$ becomes lower

TABLE 2 – Results of the slip load tests

series		$F_{s,30\mu m}$ [kN]	$F_{s,50\mu m}$ [kN]	$F_{s,max}$ [kN]	$\delta_{F_{s,max}}$ [mm]
i	m_x	4,26	5,04	5,50	0,09
	s_x	0,33	0,66	0,83	0,01
	V_x	0,08	0,13	0,15	0,17
ii	m_x	4,75	5,66	5,04	0,05
	s_x	0,65	1,07	1,14	0,03
	V_x	0,14	0,19	0,23	0,33
iii	m_x	4,68	5,67	6,06	0,10
	s_x	0,36	0,56	0,86	0,03
	V_x	0,08	0,10	0,14	0,36
vi	m_x	5,01	6,53	6,21	0,05
	s_x	0,77	0,94	1,12	0,01
	V_x	0,15	0,14	0,18	0,19

with the application of an expansion sleeve. The load displacement behaviour is significantly influenced by the sleeve. This effect was also observed in studies for applications in steel constructions [6]. So in experimental studies the integration of a sleeve or gauge ring should not be used to measure preloads for determination of the friction coefficient within the shear plane. As an exception count cases of bolted joints which are executed within a sleeve in the industrial practice.

3 Summarization

The expectation of lower slip resistance as consequence of rapidly decreasing residual clamp loads $F_{KR\,min}$ can not be confirmed as a result of these experimental studies. The ratio $\frac{l_k}{d}$ between both configurations with and without a sleeve did not significantly influences the slip load. The predicted slip loads calculated by standard [1] and guideline [2] for bolted joints with a ratio $\frac{l_k}{d} = 1$ (without sleeve) do not correspond with the values of the displayed experimental studies [8]. So loss of prelaod as result of an increasing item F_Z due to embedding could not take place as the calculation model assumes in equation (3). As a consequence for design and construction the wide usage of sleeves has to be questioned regarding the mentioned disadvantages.

4 Acknowledgement

The IGF-research project (Nr. 18546 BR) of the European Research Association for Sheet Metal Working (EFB), Lothringer Straße 1, 30559 Hannover has been funded by the AiF within the programme for sponsorship by Industrial Joint Research (IGF) of the German Federal Ministry of Economic Affairs and Energy based on an enactment of the German Parliament.

Références

[1] DIN 25201-2, Design guide for railway vehicles and their components - Bolted joints - Part 2 : Desing - mechanical applications, Deutsche Norm, Berlin, Dez 2015.

[2] VDI 2230-Part 1, Systematic calculation of highly stressed bolted joints - Joints with one cylindrical bolt, VDI-Richtlinie, Düsseldorf, Nov 2015.

[3] DIN EN ISO 16047, Fasteners – Torque/clamp force testing, Deutsche Norm, Berlin, Jan 2013.

[4] Ch. Denkert : Experimentelle Untersuchungen zum Tragverhalten planmäßig vorgespannter Schraubenverbindungen mit Blindnietmuttern, Prüfbericht Nr. P-Fh-AGP-1410-02, Fraunhofer-AGP, Rostock, 2015.

[5] Ch. Denkert : Experimentelle Untersuchungen zur Ermittlung von Setzbeträgen bei unterschiedlichen Beschichtungen und Schichtdicken, Prüfbericht Nr. P-Fh-AGP-1511-09, Fraunhofer-AGP, Rostock, 2016.

[6] A. Ebert, R. Glienke, M.-C.Wanner : Aktuelle Anforderungen an die mechanische Fügetechnik im Stahl- und Metallleichtbau für Solar- und Windenergieanlagen, in DVS Congress, Große Schweißtechnische Tagung 2014, page 210 - 219, Berlin, Germany 2014.

[7] Finale Report EUR 29527 EN : Execution and reliability of slip resistant connections for steel structures using CS and SS (SIROCCO), Luxembourg, 2019.

[8] EFB-Forschungsbericht Nr. 483 : Ausnutzung planmäßig vorspannbarer Verbindungselemente für dünne Klemmbereiche unter montagegerechten Bedingungen, Düsseldorf, Germany, 2018.