Increasing the load-bearing capacity of slip resistant joints through the use of structural adhesives (pre-loaded hybrid joints)

T. Gerke[a], **T. Valleê**[b], **R. Glienke**[a], **Ch. Denkert**[a], **H. Fricke**[b], **Andreas Ebert**[a]

a. Fraunhofer IGP Rostock, Germany, thomas.gerke@igp.fraunhofer.de
b. Fraunhofer IFAM Bremen, Germany, till.vallee@ifam.fraunhofer.de

Abstract :

Connections in steel constructions exposed to shear stress, in particular if designed for vibration and/or reversal fatigue stresses, are inevitably designed as slip resistant pre-loaded bolted joints. Strong benefit of these joints is the ability to create fatigue resistance by prevention of slip in the shear plane. Typically, the lifespan of common applications such as steel lattice towers or plant- and bridge constructions ranges from 20 up to 50 years. This requires a robust corrosion protection over the course of a long lasting component design. If the corrosion protection for the steel components is realized by hot-dip galvanizing, low static friction coefficients occur. Costly, yet largely inefficient, follow-up treatments are necessary to increase the friction coefficient in order to achieve higher load capacities. In a recently completed research project the enhancement of slip resistant pre-loaded bolted joints in conjunction with structural adhesives was shown. The results of the studies demonstrate a significant increase in load bearing capacity when combining the two latter techniques. The exact mechanisms of action have yet to be resolved. Further scientific research is currently being carried out to address open issues. Presumably, the stress distribution in the adhesive layer is positively influenced by an inhibition of the detrimental transverse tensile stresses at the overlap ends through applied pre-load. Knowledge of the superimposed transverse tensile/compression- and shear strength in the multiaxial stressed adhesive layer is required in order to determine design parameters for the pre-loaded hybrid (bonded/bolted) joint.

hybrid joints, pre-load, slip resistance, bolted/bonded joints, adhesives, steel constructions

1 Introduction

Mechanical joints in steel constructions such as wind turbines must be designed durable and fatigue resistant under operating load over the whole construction life span. This is commonly achieved with pre-loaded slip resistant bolted joints. The load-bearing capacity of pre-loaded slip resistant bolted joints

$$F_{s,Rd(ser)} = \frac{k_s \cdot n \cdot \mu \left(F_{p,C} - 0,8F_{t,Ed(ser)}\right)}{\gamma_{M3,(ser)}} \tag{1}$$

for category B and C (EN 1993-1-8 [1]) primarily results from the product of slip factor μ and pre-load $F_{p,C}$ (eq. (1)).

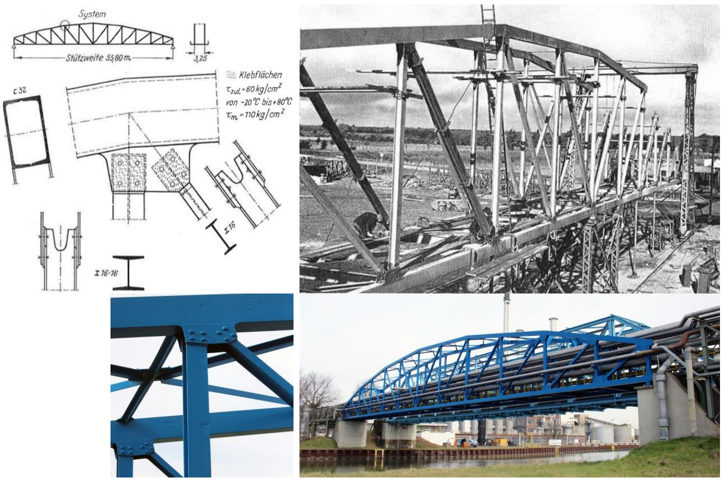

FIGURE 1 – Bonded pipe- and pedestrian-bridge across the Lippe-Seitenkanal in Marl (Germany) in 1955 and 2017 (Pict. : Ch. Denkert)

In a recently completed research project [2] the enhancement of pre-loaded slip resistant bolted joints through the use of adhesive bonding was investigated. Comparative experimental investigations were carried out with pre-loaded bolted, bonded and hybrid (bonded/bolted) specimens. The idea of the pre-loaded hybrid joint was already born in the early 1960s. Trittler and Dörnen [3], [4] identified the positive load-bearing properties of high strength pre-loaded bolted joints in combination with adhesive bonding. In conjunction with research results from [5], static shear tests showed significant increases in load bearing capacity. The increases in bearable shear stress up to failure were proportional to the surface pressure due to pre-loading, but capped by a limit value of the surface pressure, presumably between 12 and 25 MPa. Fig. 1 shows an outcome of the research results. The pipe- and pedestrian-bridge across the Lippe-Seitenkanal in Marl, Germany was constructed in 1955 with bonded connection nodes and is still in proper condition until today. Hybrid joining methods have been established in other industrial fields for some time. For example, combinations of spot welding and bonding, self-pierce riveting and bonding as well as clinching and bonding are successfully applied in automotive constructions. Combining these methods generally pursues the goal to compensate the disadvantages of each joining method [6].

2 Material and methods

2.1 Materials

Adhesive selection was performed with regards to the suitability for steel construction applications. As they are relatively robust to external influencing factors, a two-component epoxy was selected as adhesive system. The chosen adhesive, Scotch-Weld 7240 B/A FR, has a pot time of around 45 minutes and rheological properties which allow for vertical application on a construction site. High strength lockbolt systems M16-10.9 which have received a national technical approval [7] were chosen as mechanical fasteners throughout all experiments.

The adherends were made of steel grade S355J2+N with a hot dip galvanizationion as it is the most common form of corrosion protection for steel constructions. The adherends with a thickness of $10\,\mathrm{mm}$ and $20\,\mathrm{mm}$ showed nominal zinc layers of $195\,\mu\mathrm{m}$ to $236\,\mu\mathrm{m}$. The silicon content amounted to $0{,}22\,\%$ and thus is located within the sebisty area ($0{,}13\,\%$ to $0{,}28\,\%$ silicon) [8].

2.2 Methods

Figure 2 shows the test setup with the servohydraulic testing machine HB 1000 of Zwick/Roell (1) and a sketch of the double-lap specimen (2). The linear displacement measurement is achieved with linear variable differential transformers (LVDT's) which are positioned at the overlap end (3a) and centered

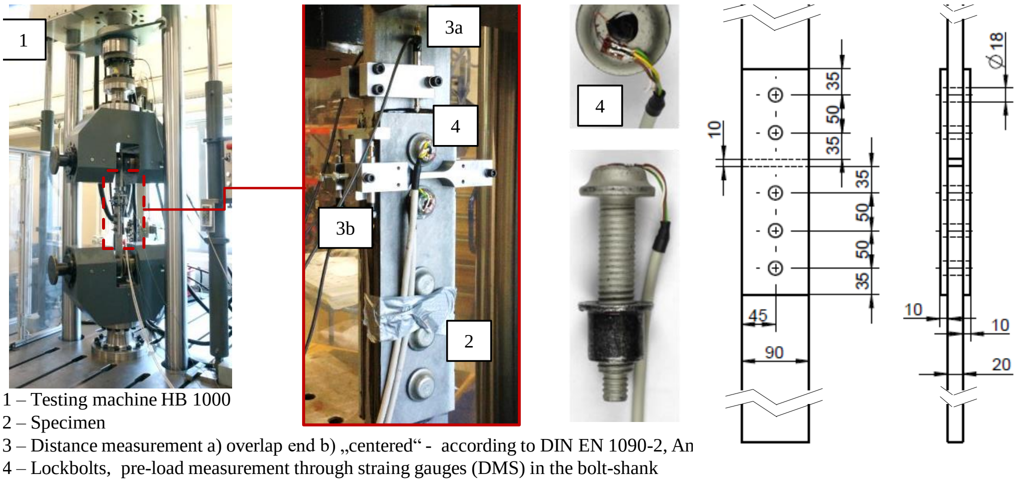

FIGURE 2 – Test arrangement (left) and specimen with measurement equipment together with lockbolt for pre-load measuring (middle)

between two bolts (3b). To measure the pre-load during the tests, calibrated linear strain gauges (BTM6C of Preusser Messtechnik GmbH) were applied centrically in axial direction of the lockbolt (4) with a shielded four-wire connection hooked up to a measurement system of HBM.

To evaluate and compare the load bearing capacity of each joining method, tests were carried out for bonded, pre-loaded bolted and pre-loaded hybrid (bonded/bolted) joints. Since the main focus of the investigation is to enhance the load bearing capacity of slip resistant connections, tests are performed according to EN 1090-2 Annex G "Determination of slip factor" [9]. The test comprises three test sequences. All tests are executed in a displacement controlled mode. At first, four quasi-static slip load tests are performed. The machine speed is being set so that the slip load is reached within 10 to 15 minutes. The individual slip load values F_{Si} are assigned to the machine force which occurs at displacement values of $\delta_i = 150\,\mu\text{m}$ of each respective position sensor (LVDT positions at (3a) and (3b) in Fig. 2). The mean slip load value F_{Sm} is obtained from the individual values F_{Si}. As a second step, creep tests with $90\,\%$ of F_{Sm} are performed. Commonly, according to the authors [2], those creep tests are going to fail if the adherends underwent any kind of surface treatments such as hot dip galvanizing. Further elaboration of the creep tests can be found in [2]. If the creep test fails, three extended creep tests must be carried out to secure permanent load resistance. A load level as utilization of F_{Sm} must be found at which excessive creep ($\delta \geq 300\,\mu\text{m}$) in the service life of the steel structure can be excluded. With the creep test a displacement log(time) curve is recorded to show that the selected load does not exceed the displacement criteria. The curve may be linearly extrapolated to the estimated service life as soon as a tangent can be determined with sufficient accuracy. The individual slip factors result as following by eq. (2) :

$$\mu_i = \frac{F_{Si}}{n \cdot (F_{p,C,1} + F_{p,C,2})} \tag{2}$$

with n as the number of load transmitting faying surfaces and $F_{p,C,i}$ as the lockbolt pre-load. If extended creep test are necessary, individual values of the slip factors need to be reduced according to the ratio between the extended creep test load level to the mean slip load values. More information on the test procedure from EN 1090-2 Annex G can be found in [10] and [11]. Further information on the used materials and methods can be found in [2].

3 Results

At first, five slip load tests with bolted double lap specimen were performed (2). Fig. 3 shows the load-displacement curves of each of the five specimen. The abscissa represents the displacement δ while the corresponding machine force F is plotted on the ordinate. As stated in [9], the individual slip load values $F_{Sm,i}$ are defined as either the maximum machine force at $\delta = 150\,\mu\text{m}$ or before. The load-displacement curves have a degressive slope until the slip load is reached. The subsequent drop of the curves is associated with a failure of the joint, resulting in sliding/slipping of the faying surfaces. Based on the average value of $F_{Sm} = 242{,}4\,\text{kN}$, a lower $5\,\%$-quantile of $X_{k(n)} = 210\,\text{kN}$ with a variance of $V_x = 6\,\%$ could be determined for the five slip load test with bolted joints. This resulted in a nominal slip factor of $\mu = 0,47$. Pre-load measurement was omitted purposefully since pre-load monitoring was done with specimen and lockbolts from the same batch before hand. It could be shown that the variance of the applied pre-load was only $V_x = 1{,}2\,\%$. Eight individual slip load test were performed with hybrid (bolted/bonded) double lap specimen. Fig. 4 shows the load-displacement curves of each of the eight specimen. A sudden failure of the hybrid joints was detected which is ascribed to a failure of the adhesive rather than slipping of the faying surfaces. Due to barely measurable displacements at position 3b, Fig. 4 shows the mean displacement measurements at the overlap edge (position 3a). An average value of $F_{Sm} = 402{,}4\,\text{kN}$ resulted in a lower $5\,\%$-quantile of $X_{k(n)} = 373{,}0\,\text{kN}$ with a variance of $V_x = 4\,\%$ for the hybrid joints. Thus, a nominal slip factor of $\mu = 0,82$ was achieved. Pre-load measurement was performed in half of the slip load tests with two strain gauge - prepared lockbolts for each test.

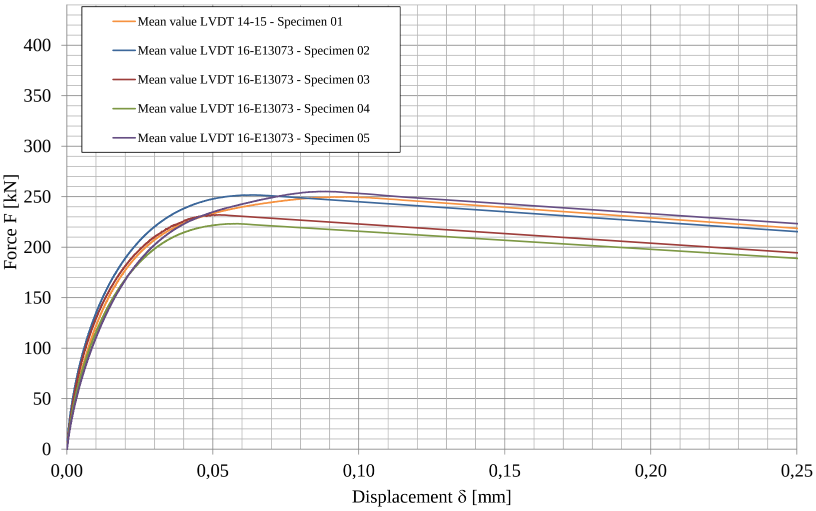

FIGURE 3 – Slip load test results - bolted specimen

As described in section 2.2, extended creep tests are usually necessary for surface-treated adherends to ensue permanent load resistance over the construction life span. A load level of $80\,\%$ of F_{Sm} which amounts to $194\,\text{kN}$ could be obtained for the bolted specimens. This resulted in a secured slip factor of $\mu = 0,42$. On the contrary, the hybrid joined specimen did not pass the extended creep test at a load level of $80\,\%$ of F_{Sm} ($322\,\text{kN}$) and exceeded the threshold of $\delta = 300\,\mu\text{m}$ in roughly $3{,}5\,\text{h}$. Hence the load level was lowered to $65\,\%$ ($262\,\text{kN}$) and a slip factor of $\mu = 0,59$ has been secured. Further results, including the tests of adhesively bonded specimen can be found in [2].

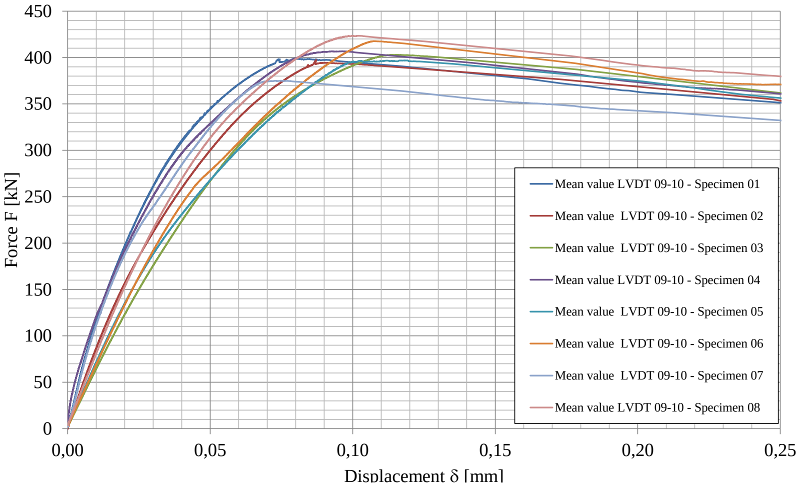

FIGURE 4 – Slip load test results - hybrid specimen

4 Discussion and lookout

Steel composition, temperature of the zinc bath, bath duration among others have an effect on the composition of the zinc layer which leads to varying attainable slip factors in slip resistant bolted connections between $\mu = 0,18 \dots 0,52$ [12, 13]. The presented experimental results determined slip factors of $\mu = 0,42$ for the bolted- and 0,59 for the hybrid specimen with hot-dip galvanized adherends. This means an increase in load-bearing capacity by $40\,\%$ under permanent load. With reference to the characteristic resistance for short term loads it would lead to an increase by up to $78\,\%$ between the bolted- ($F_{5\%} = 210\,\mathrm{kN}$) and hybrid ($F_{5\%} = 373\,\mathrm{kN}$) specimen. As of now, there is no satisfactory scientific explanation for the resistance enhancing effect through the use of structural adhesives in conjunction with pre-loaded bolted connections. Presumably, the stress distribution in the adhesive layer is positively influenced by an inhibition of the detrimental transverse tensile stresses at the overlap ends through applied pre-load. Similar effects regarding an enhancement of the shear strength due to superimposed transverse compressive stresses could be observed in adhesively bonded hub/shaft press fits [14]. Against the background of considerable increases in load bearing capacity, the pre-loaded hybrid connection seems to be a potent joining technology. Possible cost savings reside in lower manufacturing expenses (shorter connection lengths, reduced amount of drill holes and fasteners) and due to elimination of costly friction surface treatments after hot-dip galvanizing.

Further research on this topic is being performed in an ongoing research project (AiF/IGF-project nr. 20036BG) to make use of the full potential of pre-loaded hybrid joints. Based on an optimized adhesive selection to increase the bond strength, investigations on the influence of temperature as well as tests on creep resistance will be carried out. In addition, common effects in practical applications, such as imperfections from sheet thickness jumps or varying pre-load levels when using classic HV bolts need to be addressed. In the course of determining design parameters for the pre-loaded hybrid joint, knowledge of the superimposed transverse tensile/compression- and shear strength in the multiaxial stressed adhesive layer is essential. In this context, off-axis tests are used to achieve different combinations of simultaneously acting shear τ_{xz}, transverse tensile- and compressive stresses σ_z^+, σ_z^- [15].

Acknowledgment

The IGF-projekt (Nr. 20036BG) of the European Research Association for Sheet Metal Working (EFB), Lothringer Straße 1, 30559 Hannover has been funded by the AiF within the program 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 EN 1993-1-8 :2010-12 : Eurocode 3 Design of steel structures - Part 1-8 : Design of joints, German version EN 1993-1-8 :2005 + AC :2009 2010.

[2] M.-C. Wanner et al., Pre-loaded hybrid (bonded/bolted) joints with lockbolts, AiF final report 17596BR/1, EFB research report 434, EFB e.V., Hannover, 2016.

[3] G. Trittler, Kombinierte Eisenbahn- und Straßenbrücke über den Lippte-Seiten-Kanal der chemischen Werke Hüls A.G. Marl, Der Stahlbau, 27 (1958) Nr. 1 S. 7 –9.

[4] G. Trittler, K. Dörnen, Die vorgespannte Klebverbindung (VK-Verbindung) - eine Weiterentwicklung der Verbindungstechnik im Stahlbau, Der Stahlbau, 33 (1964) Nr. 9 S. 257 –269.

[5] G. Trittler, Klebverbindungen im Ingenieurbau, VDI-Z, 105 (1963) Nr. 8 S. 325 –364.

[6] G. Habenicht, Kleben - Grundlagen, Technologien, Anwendungen, Springer Verlag, Berlin, Heidelberg, 2006.

[7] Z-14.4-591 : release date 04.11.2016. National technical approval : Lockbolts without pin-break Berlin : DIBt, 2016.

[8] W.-D. Schulz, M. Thiele, Feuerverzinken von Stückgut, Eugen G.Lenze Verlag KG, Bad Saulgau, 2012.

[9] DIN EN 1090-2 :2018-09 : Excecution of steel structures and aluminium structures - Part 2 : Technical requirements for steel structures, German version EN 1090-2 :2018,

[10] N. Stranghöner et al. Gleitfeste Verbindungen nach Eurocode 3 und DIN EN 1090-2. Nordic Steel Construction Conference 2015, Stahlbau, 2015.

[11] N. Stranghöner et al. Influence of different testing criteria on the slip factor of slip-resistant connections. Nordic Steel Construction Conference 2015, Tampere (Finland), 2015.

[12] G. Valtinat, F. Albrecht, P. Dangelmeier, Gleitfeste Verbindungen mit feuerverzinkten Stahlteilen und reibfesten Beschichtungen oder anderen reibbeiwerterhöhenden Maßnahmen. Forschungsbericht Nr. 122, Gemeinschaftsausschuss Feuerverzinken Hamburg, 1993.

[13] ECCS - European Convention for Constructional Steelwork : Slip factors of connections with H.S.F.G. Bolts. Bd. no. 37, 1984.

[14] H. Schürmann, Konstruieren mit Fast-Kunststoff-Verbunden, Springer Verlag, Berlin, Heidelberg, 2007.

[15] M. Albiez, T. Vallêe, T. Ummenhofer, Adhesively bonded steel tubes - Part II : Numerical modelling and strength prediction, International Journal of Adhesion and Adhesives, 90 (2019) 211 –224.