

## ORIGINAL ARTICLE



# Experimental Investigations on load-bearing Capacity and characteristic Preload of Lockstud Systems

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## Abstract

The joining technology Lockstud System combines the advantages of a bolt thread for making a tapped thread joint and the advantages of a lockbolt. On the tapped thread joining side, the bolt has a metric ISO thread. On the assembly side, the bolt has a grooved geometry like lockbolts of type A, B and C. This article publishes results on the mechanical-technological properties, the assembly process with the initial preload, the preload losses due to embedding under long period of time and the load-bearing capacity subjected to static and fatigue normal stress for Lockstud systems of nominal diameters M12, M16 and M20 (strength grade 10.9) compared to conventional bolt assemblies and lockbolt systems.

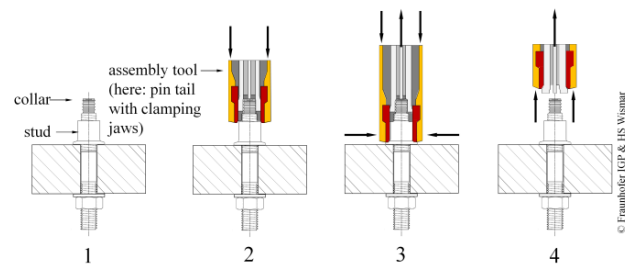
## Keywords

Lockstud, detail category, fatigue resistance, Eurocode 3, assembly preload, initial bolt preload, preload loss

## 1 Introduction

Although high-quality connections can be realised with the conventional bolted joint as a through-bolt or tapped thread joint, their use is associated with some significant disadvantages. The main disadvantage is the process-related scattering of the preload in torque-controlled assembly, which, combined with fluctuations in the thread and under head coefficients of friction, leads to assembly uncertainties. Due to insufficient initial preload and subsequent subject to normal stress ranges, self-loosening of the bolted joint can occur, which often results in damage to bolts in practice. [1–5] Therefore maintenance intervals are prescribed immediately after commissioning as well as during the use of bolted joints subjected to normal stress ranges in various areas of application in structural and mechanical engineering [6; 7]. Lockbolt systems according to Technical Bulletin DVS/EFB 3435-1 [8] and Technical Bulletin DVS/EFB 3435-2 [9] consist of a lockbolt made of carbon steel and an associated collar. Compared to classic bolted joints, these are characterised by a special suitability for maintaining the preload over the service life, [10–12] by a high level of assembly safety due to the friction- and torsion-free tightening process [13–15], a higher fatigue strength under concentric and eccentric load compared to structural steel bolts (system HV according to EN 14399-4 [16]) [17–19] and an effective securing effect for transverse loads above the theoretical threshold [20; 21]. Responding to the mentioned requirements, a stud-bolt is presented which combines the advantages of a bolt

thread for making a tapped thread or through-bolt joint and the advantages of a lockbolt system. This is called the Lockstud System (LoS). On the threaded side, the bolt has a metric ISO thread according to DIN 13-1 [22]. On the assembly side, the bolt has a groove geometry, as is known from lockbolts of types A, B and C according to Technical Bulletin DVS/EFB 3435-2 [9].



**Figure 1** Schematic assembly process for the Lockstud system (type C) for a through-bolt joint

This characteristic offers the potential for a mechanically maintenance-free joint. Due to the torsion-free tightening process of the Lockstud systems, a preload level with low scatter is achieved. Together with the formed collar, mechanically joined connections can be secured against self-loosening during service life. Therefore, the fatigue limit of constructions over their service life can be guaranteed.

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Figure 1 schematically shows the assembly process of a Lockstud system as a through-bolt joint. After the nut with washer and the collar are screwed on the respective part (1), the assembly on the groove side begins with the steps as shown (2-4). For this purpose, the installation tool is applied to the pin tail of the Lockstud. The Lockstud is tensioned by the installation tool while the collar is simultaneously formed into the lock grooves. It results a pre-loaded high strength joint.

There is no knowledge about the preload losses and load-bearing capacity of Lockstud systems and the decisive failure mechanism under the influence of nominal stress (quasi-static, fatigue). A transfer of the existing design rules for tension connections with threaded bolts/studs or lockbolt systems to Lockstud systems is not sufficiently clarified due to the unknown failure mechanisms. As part of the current public funded EFB research project "Tragverhalten Lockstud" (21540 BR) [23] the preload-time as well as the load-bearing capacity of Lockstud systems are being investigated experimentally and numerically. Based on the investigations, the determined preload-time curves and load-bearing capacities are analysed and evaluated to enable a more economical assembly and design. In the research project, recommendations for the design and execution of connections with Lockstud systems will be developed and the fundamentals for normative regulations for the implementation of the results in the Technical Bulletin DVS/EFB 3435-2 [9] will be established. Design rules are derived based on VDI 2230 - Part 1 [24] and Eurocode 3 (EC3) [25]. This allows small to medium sized enterprises (e.g. engineering offices) in particular to avoid cost- and time-intensive individual investigations.

## 2 Experimental investigations

The subject of the current investigations are two bolt assemblies, three lockbolt systems and 14 Lockstud systems. Figure 2 shows an example of the investigated fasteners under variation of the nominal diameter (3/8", M12, M16, M20), strength grade (8.8, 10.9), surface and coating conditions as well as the use of a nut according to EN ISO 4032 [26] or EN 14399-4 [16] (system HV). The coating conditions are black, hot-dip galvanised (hdg) and zinc-flake.



Figure 2 Representation of the investigated fasteners

### 2.1 Mechanical-technological properties

Each series has been tested for normative deviations and imperfections according to EN ISO 898-1/-2 [27; 28] for metric bolt assemblies or according to Technical Bulletin

DVS/EFB 3435-1 [8] for lockbolt systems. For this purpose, the mechanical-technological properties, such as chemical structure, impact strength, core hardness, microhardness profile as well as the coating and surface condition were characterised.

The core hardness (VICKERS) of the fasteners was determined in the cross-section according to EN ISO 898-1 [27]. The measurements of the Lockstud systems are carried out in the lock groove and thread cross-sections. Figure 3 shows the averaged core hardness for the respective strength grade of the bolts (blue), lockbolts (orange) and Lockstuds (green) in the thread cross-section. The core hardness of the fasteners (strength grade 10.9) are within the specified tolerance of 320 - 380 HV10. The EN ISO 898-1 [27] distinguishes between nominal diameters  $d \leq M16$  and  $d > M16$  for the tolerances of the core hardness of strength grade 8.8. The hardness values of the Lockstud systems M16 and M20 strength grade 8.8 were determined between 342 - 344 HV10 and exceed the required tolerances. The core hardness of the two Lockstud systems M12 strength grade 8.8 reach the upper range of the tolerance limit.

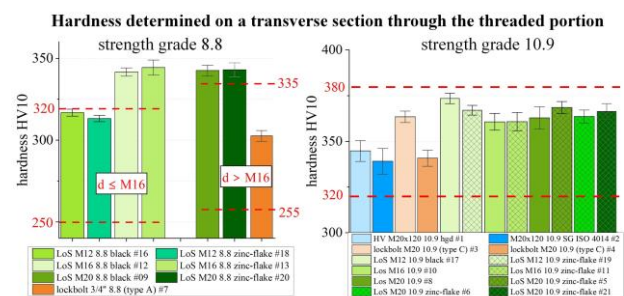


Figure 3 Core hardness of the fasteners strength grade 8.8 (left) and strength grade 10.9 (right)

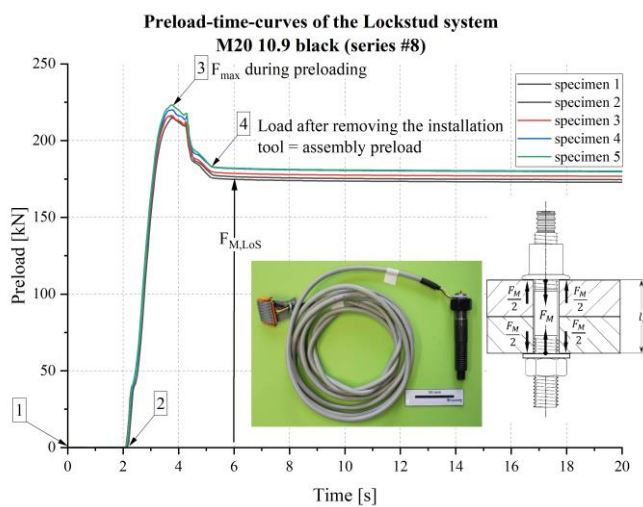
After conversion to the tensile strength according to EN ISO 18265 [29], the hardness values of Lockstud systems M16 and M20 strength grade 8.8 corresponds to an overstrength that is equal to strength grade 10.9. For this reason, only Lockstud systems of strength grade 10.9 are investigated in this article.

### 2.2 Assembly process

The determination of the assembly process is used to define the initial preload of the Lockstud systems after completion of the assembly process as well as the tightening factor  $\alpha_A$  required for the design of a connection according to VDI 2230 - Part 1 [24]. In addition, the assembly process of the Lockstud systems is described in the form of a preload-time curve. According to the current state of the research project, three Lockstud systems of nominal diameter M16 and M20 with strength grade 10.9 (type C) in black and zinc-flake conditions of series #8, #10 and #11 with a grip length ratio of  $l_k/d = 2.8$  were investigated. The joint was designed as a through-bolt joint with the corresponding nut according to EN ISO 4032 [26] and washer according to EN ISO 7089 [30]. The assembly process was carried out based on Figure 1 in components made of uncoated structural steel S355JR with one interface and medium-sized through-holes according to EN 20273 [31].

Figure 4 shows an example of the preload-time-curve of a Lockstud system (M20, 10.9, black) during the assembly process. In accordance with the Technical Bulletin DVS/EFB 3435-1 [8], this process can be described as follows:

1. After arranging the components, the assembly process begins with inserting the Lockstud into the through hole with screwing on the nut with washer on the threaded side and loosely fitting or screwing on the collar on the lock grooves (assembly side).
2. The Preloading begins when the installation tool is activated.
3. The preload increases until its maximum value  $F_{\max}$  is reached. This value marks the end of the collar being swaged into the lock grooves.
4. The remaining preload after removing the installation tool is now described as the initial Lockstud assembly preload  $F_{M,LoS}$ .



**Figure 4** Characteristic preload-time-curves during the assembly process

The investigations demonstrated that the maximum preload  $F_{\max}$  is below the nominal minimum yield strength  $R_{p0.2 \min}$  of the bolt material. This means that 94 – 97 % of the yield strength of the bolt material  $R_{p0.2 \min}$  is utilized during preloading. The tightening factor  $\alpha_A$  varies between 1.02 and 1.05, reflecting the advantage of the tightening process. The initial preload  $F_{p,C}$  reached the calculation value as well as for the design as a bolt according to EN 1993-1-8 [32] and as a lockbolt according to Technical Bulletin DVS/EFB 3435-2 [9].

### 2.3 Characteristic preload

The preload losses  $F_z$  due to embedding is caused by the time-dependent plastic flattening of surface roughness at the bearing areas and relaxation of coatings. Pulling tightening techniques can increase preload losses compared to torsional tightening techniques. [1; 24] For the design of preloaded fasteners according to EC3, preload losses of 10 % are included [33]. The preload losses were determined on three Lockstud systems of nominal diameter M16 and M20 strength grade 10.9 without additional load (static, fatigue). The Lockstud systems and components were applied from the assembly process tests. The preload

was recorded for eight specimens per series after the assembly process and measured again after defined time intervals (7 days, 42 days). The preload losses due to embedding were extrapolated to 20 and 50 years and are shown in Table 1 after statistical evaluation.

**Table 1** Extrapolated preload losses due to embedding

Series #	10	11	8
Nominal diameter [mm]	M16	M16	M20
Strength grade	10.9	10.9	10.9
Coating	-	zinc-flake	-
Number of specimens	8	8	8
Assembly Preload <sup>1)</sup> [kN]	121.34	118.12	184.49
time interval [days]	42	42	7
$k_n$	2.00	2.00	2.00
<b>Preload losses [%] - Extrapolation 20 years</b>			
Mean value	7.73	7.91	5.88
Standard deviation	1.54	1.90	1.24
Coefficient of variation	0.02	0.04	0.02
95% Quantile	10.81	11.70	8.35
<b>Preload losses [%] - Extrapolation 50 years</b>			
Mean value	8.11	8.31	6.13
Standard deviation	1.64	2.03	1.32
Coefficient of variation	0.03	0.04	0.02
95% Quantile	11.38	12.38	8.78

<sup>1)</sup> 5%-Fractile

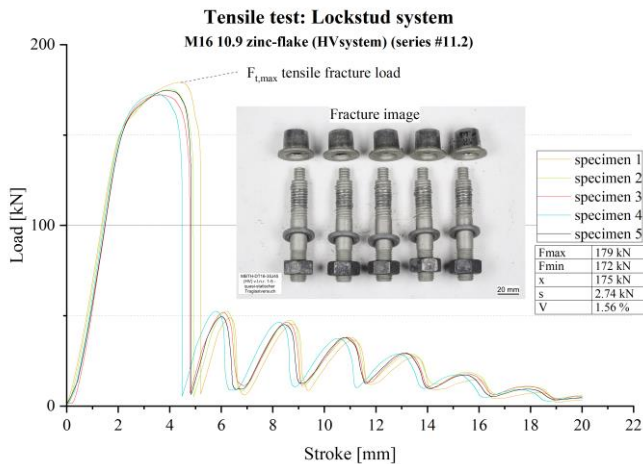
The assembly preload reach the minimum preload according to EN 1090-2 [33]. The highest losses are observed in the zinc-flake-coated Lockstuds systems (series #11) with 12.38 % extrapolated to 50 years. The series #8 has the lowest preload loss at 8.78 % extrapolated to 50 years.

### 2.4 Load-bearing capacity

The static load-bearing capacity of the fasteners under concentric load was investigated on five different Lockstud systems strength grade 10.9. For the test procedure, the investigated Lockstud systems were assembled in an adjusted test fixture according to installation instructions based on Technical Bulletin DVS/EFB 3435-1 [9]. The test was stroke controlled over a traverse stroke of up to 20 mm with a test speed of  $v = 5$  mm/min until failure of the respective Lockstud systems on a static tension/compression testing machine. In order to investigate the influence of the nut height as well as the degree of flank coverage, nuts and washers according to EN ISO 4032 [26] and EN ISO 7089 [30] as well as HV nuts and washers according to EN 14399-4/-6 [16; 34] were used. The strength grades of the nuts are compatible with those of the Lockstuds. The assembly condition of the nut on the threaded and the collar on the grooved side corresponds to common assembly principles [1; 8].

All Lockstud systems achieved the specified minimum fracture load according to EN ISO 898-1 [27] or the characteristic value of the limiting tensile load  $F_{t,Rk}$  according to Technical Bulletin DVS/EFB 3435-2 [9] in accordance with the respective strength grade and nominal diameter. The majority of the Lockstud systems strength grade 10.9 failed by stripping the collar over the lock grooves. The experimentally determined load-stroke curve of the Lockstud system M16 10.9 zinc-flake (series #11.2) is shown as an example in Figure 5.

A linear increase of the test load can be seen until a maximum load  $F_{t,max}$  is reached, followed by a sudden drop in load and failure of the Lockstud system. In the further curve of the diagram, the test load increases until the second maximum load is reached and then decreases again after repeated stripping of a collar groove. This process repeats until the complete collar grooves are stripped off. The stripping of the collar under quasi-static concentric load is already known from completed research activities [13; 15] and is interpreted as a design principle of lockbolt systems.



**Figure 5** Static load-bearing capacity of a concentric loaded Lockstud system with collar stripping

## 2.5 Fatigue strength of non-preloaded systems

The fatigue tests were carried out in accordance with DIN 969 [35] at constant mean load  $F_m$  on the servo-hydraulic dynamic testing machine in load-controlled mode. The test stopped with the fracture of the fastener into two

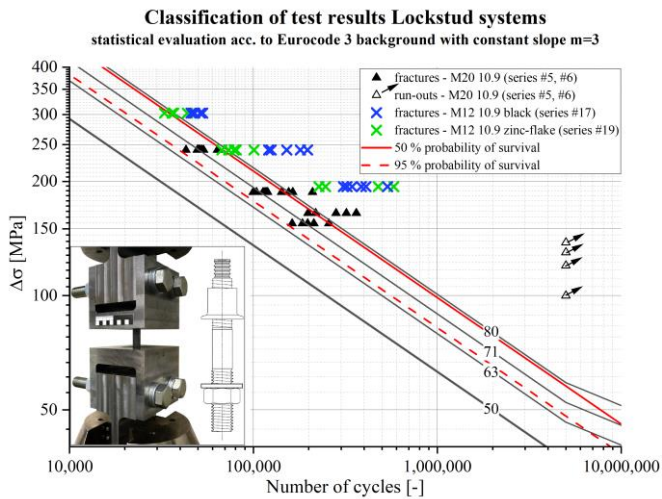
parts or by reaching a limit number of load cycles  $N = 5 \cdot 10^6$  (= run out). The stress ratio varies between  $0.42 \leq R < 0.89$ . The mean load  $F_m$  is calculated by utilizing the minimum yield strength  $R_{p0.2 \min}$  of the bolt material in the tensile stress area  $A_s$  of the respective fastener in the ratio of 70 % according to DIN 969 [35]. The tensile stress area  $A_s$  of the Lockstud system in the threaded part is considered more critical and is used for the calculations. The assembly position of the fasteners in the test fixture corresponds to the normative specifications of DIN 969 [35], whereby the nut and collar were assembled to four free loaded thread and lock grooves. According to DIN 969 [35], the fastener must be installed in the test fixture without preload. When assembling a Lockstud system, it is first initially preloaded. Therefore, an installation procedure according to Technical Bulletin DVS/EFB 3435-1 [8], Glienke [15] and Schwarz [36] must be considered, which allows testing on preload-free Lockstud systems.

Figure 6 shows the classification of the fracture results of the Lockstud systems strength grade 10.9 series #5 and #6, as well as the common statistical evaluation with the S-N curves of the 95 % and 50 % probability of survival. The reference value of the fatigue strength at 95 % probability of survival is  $\Delta\sigma_{C,Ps=95\%} = 65.1$  MPa. In addition, the fracture points of the M12 series #17 and #19 were added. These are not included in the common statistical evaluation. The individual Lockstud systems M20 as well as the result after common statistical evaluation are to be assigned to detail category (DC) 63 up to the current state of the research project. The variable slope after common evaluation was determined with  $m_{var.} = 3.55$ . After statistical evaluation, the nominal diameter M12 strength grade 10.9 black reached DC 80. The failure mode occurred mainly in the first load-bearing thread. Series #5 and #6 failed more frequently in the transition from high cycle fatigue (HCF) to very high cycle fatigue (VHCF) in the first load-bearing lock groove.

**Table 2** Test results of the fatigue tests subject to normal stress acc. to the background document to EN 1993-1-9 [37]

	# Series	Fastener	#Data	Slope [-]		$\Delta\sigma_{C,Ps=95\%}$ [MPa]		Detail category
				$m_{var.}$	$m_{const.}$	$m_{var.}$	$m_{const.}$	
<b>Bolt</b>	1	HV-M20x120-10.9/10 - hdg	1) <sup>1)</sup> 31	2.80	3	54.5 (60.1)	57.9 (63.5)	<b>56</b>
	2	M20x120-10.9/10 -black	2) <sup>2)</sup> 38	3.99	3	96.6 (112.5)	73.5 (93.1)	<b>71</b>
<b>Lockbolt</b>	3	M20 10.9 type C - zinc-flake	1) <sup>1)</sup> 31	3.43	3	126.8 (138.6)	103.2 (120.1)	<b>100</b>
	4	M20 10.9 type C - zinc-flake	1) <sup>1)</sup> 18	3.55	3	88.5 (101.8)	77.5 (89.0)	<b>71</b>
	7	3/4" 8.8 type A - black	1) <sup>1)</sup> 15	3.32	3	129.2 (147.8)	121.9 (137.5)	<b>112</b>
<b>Lockstud</b>	17	M12 10.9/10 type C - black	1) <sup>1)</sup> 15	4.65	3	125.7 (137.3)	81.4 (100.4)	<b>80</b>
	19	M12 10.9/10 type C - zinc-flake	1) <sup>1)</sup> 15	4.79	3	109.5 (129.0)	67.4 (88.5)	<b>63</b>
	5	M20 10.9/10 type C - zinc-flake	1) <sup>1)</sup> 18	4.48	3	92.6 (107.2)	64.5 (79.7)	<b>63</b>
	6	M20 10.9/10 type C - zinc-flake	1) <sup>1)</sup> 18	3.16	3	66.7 (75.4)	66.2 (71.5)	<b>63</b>
						(101.5)	(81.8)	

1) Thread rolled before heat treatment  
2) Thread rolled after heat treatment  
 $\Delta\sigma_{C,Ps=95\%}$  Reference value of fatigue strength with 95 % probability of survival  
(...) 50 % probability of survival



**Figure 6** Statistical evaluation of the fatigue strength tests of the Lockstud systems according to background document to EN 1993-1-9 [37]

To verify the fatigue strength of Lockstud systems (type C) strength grade 10.9 without hot dip galvanising, a DC 63 is proposed according to the current state of the research project. According to current knowledge, the first load-bearing thread is decisive for failure mode in the HCF.

### 3 Conclusions

The results from the current research project [23] provide new knowledge on the load-bearing capacity of Lockstud systems under the influence of quasi-static and fatigue loads. In addition, the assembly process of the Lockstud system was described by using a preload-time curve. They build the fundamentals and contribute to the design of connections with Lockstud systems. The previous research results on the Lockstud systems of strength grade 10.9 can be summarised in the following results:

1. Suitability for the realisation of a preloadable high strength joints of strength grade 10.9
2. Assembly process equivalent to lockbolt assembly with low tightening factor  $\alpha_A = 1.05$  due to the torsion-free tightening process
3. 94 – 97 % utilisation of the bolt material yield strength  $R_{p0.2 \min}$  through initial preload
4. Extrapolated to 50 years, the preload losses  $F_z$  due to embedding are higher for zinc-flake Lockstud systems with 12.38 % than for black Lockstud systems
5. Failure mode due to stripping of the collar under quasi-static load, whereby the characteristic value of the limiting tensile load  $F_{t,Rk}$  according to Technical Bulletin DVS/EFB 3435-2 [9] has been reached
6. Failure mode due to fracture in the first load-bearing thread subject to normal stress ranges in the HCF, whereby DC 63 is recommended for the fatigue resistant design

Further investigations of the current research project include numerical simulation of the assembly process and calculations of the elastic resilience. In addition, the maintenance-free characteristics of preloaded Lockstud systems subject to shear stress ranges are being investigated by fatigue tests.

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### References

- [1] Wiegand H., Kloos K.-H. und Thomala W. (2007) *Schraubenverbindungen - Grundlagen, Berechnung, Eigenschaften, Handhabung*. Heidelberg, Berlin, Germany: Springer Verlag.
- [2] Stranghöner, N. et al. (2018) *Vorspannkraftverluste geschraubter Verbindungen infolge beschichteter Kontaktflächen*. Bd. Stahlbau 87, Berlin, Germany: Ernst & Sohn Verlag für Architektur und technische Wissenschaften GmbH & Co. KG.
- [3] Friede, R. (2010) *Vorspannkraftverluste durch Setzen und selbsttätiges Losdrehen planmäßig vorgespannter Schraubenverbindungen*. Dissertation, Darmstadt, Germany: Technische Universität Darmstadt.
- [4] Hasselmann, U.; Valtinat, G. (2002) *Geschraubte Verbindungen - Beitrag in Stahlbaukalender*. pp. 343-421, Berlin: Ernst & Sohn Verlag für Architektur und technische Wissenschaften GmbH & Co.KG.
- [5] Glienke, R. et al. (2015) *Anforderungen an die mechanische Fügetechnik für Türme von WEA in Stahlbauweise für große Nabenhöhen*. . Stahlbau 84, H. 8, pp. 556-570, Berlin: Ernst und Sohn Verlag für Architektur und technische Wissenschaften GmbH & Co. KG.
- [6] Deutsches Institut für Normung e. V. (2019) *DIN 18088-3 - Structures for wind turbines and platforms - Part 3: Steel structures*. Berlin, Germany: Beuth Verlag GmbH.
- [7] DNV GL SE (2021) *Support structures for wind turbines. DNVGL-ST-0126 (Standard)*. Norway: DNV GL AS.
- [8] German Welding Society and European Research Association for Sheet Metal Working (2021) *Technical Bulletin DVS/EFB 3435-1 - lockbolt systems*. Düsseldorf, Germany: DVS Media GmbH.
- [9] German Welding Society and European Research Association for Sheet Metal Working (2017) *Technical Bulletin DVS/EFB 3435-2 - Lockbolt systems - calculation of connections according to Eurocode 3 and VDI 2230-Part 1*. Düsseldorf, Germany: DVS Media GmbH.
- [10] Ebert, A.; Glienke, R.; Dörre, M. (2017) *Behaviour of lockbolts in slip-resistant connections for steel structures*. Bd. Steel Construction Vol. 4/2017, Berlin, Germany: Ernst & Sohn Verlag für Architektur und technische Wissenschaften.
- [11] Matos, R.; Shah Mohammadi, M. R.; Rebelo, C.

- (2017) *A year-long monitoring of preloaded free-maintenance bolts - Estimation of preload loss on BobTail bolts*. Renewable Energy 116, pp. 123 - 135.
- [12] Mohammadi, M. R. S.; Matos, R.; Rebelo, C. (2017) *Bobtail bolt preload loss in wind turbine tower prototype*. Copenhagen: EUROSTEEL, Ernst & Sohn Verlag für Architektur und technische Wissenschaften GmbH & Co. KG.
- [13] Glienke, R.; Wanner, M.-C. (2012) *EFB-Forschungsbericht Nr. 355: Bemessungskonzept für SRB-Verbindungen in Stahl- und Aluminiumblechen*. Hannover, Germany: Europäische Forschungsgesellschaft für Blechverarbeitung e.V.
- [14] Stranghöner, N. et al. (2019) *Forschungsvorhaben P1091 / IGF-Nr. 18711: Entwicklung eines Konzeptes zur Erfassung von Vorspannkraftverlusten in vorgespannten Schraubverbindungen unter Ermüdungsbeanspruchung*. Düsseldorf, Germany: Forschungsvereinigung Stahlanwendung e.V. Verlag und Vertriebsgesellschaft mbH.
- [15] Glienke, R. (2013) *Beitrag zur Bemessung von Verbindungen mit Schließringbolzen im Stahl- und Maschinenbau*. Dissertation, Rostock, Germany: Universität Rostock.
- [16] European Committee for Standardization (2015) *EN 14399-4 - High-strength structural bolting assemblies for preloading - Part 4: System HV - Hexagon bolt and nut assemblies*. Berlin, Germany: Beuth Verlag GmbH.
- [17] Missoum, A. et al. (1997) *Testing of swaged bolts for steel connections*. Lissabon: International Conference on New Technologies in Structural Engineering.
- [18] Glienke, R. et al. (2015) *Bemessung und Ausführung von Verbindungen mit Schließringbolzen im Stahlbau*. Stahlbau 84, H. 12, pp. 980-997, Berlin: Ernst und Sohn Verlag für Architektur und technische Wissenschaften GmbH & Co. KG.
- [19] Schwarz, M. et al. (2018) *EFB-Forschungsbericht Nr. 480: Steigerung der Tragfähigkeit in exzentrisch beanspruchten Verbindungen durch den Einsatz von Schließringbolzensystemen*. Hannover: Europäische Forschungsgesellschaft für Blechverarbeitung e.V. (EFB).
- [20] Schwarz, M. et al. (2017) *Bemessung von Verbindungen mit Schließringbolzen im Maschinenbau - Teil 1: Schließringbolzentechnologie und -tragverhalten*. Konstruktion H. 10, pp. 84-90, Düsseldorf, Germany: Springer VDI Verlag.
- [21] Schwarz, M. et al. (2020) *Calculation of lockbolt joints in mechanical engineering*. Volume 51, Issue 3, pp. 267-283, Berlin, Germany: Materials Science & Engineering Technology.
- [22] Deutsches Institut für Normung e. V. (1999) *DIN 13-1 - ISO general purpose metric screw threads - Part 1: Nominal sizes for coarse pitch threads; nominal diameter from 1 mm to 68 mm*. Berlin, Germany: Beuth Verlag GmbH.
- [23] European Research Association for Sheet Metal Working (2021-2023) *Tragverhalten von zugkraftbeanspruchten Lockstud-Systemen zur Herstellung wartungsfreier Verbindungen - IGF 21540 BR / 1*. Hannover, Germany.
- [24] Verein Deutscher Ingenieure e.V. (2015) *VDI 2230 - Part 1 - Systematic calculation of highly stressed bolted joints - Joints with on cylindrical bolt*. Düsseldorf, Germany.
- [25] European Committee for Standardization (2010) *EN 1993-1-9 - Eurocode 3: Design of steel structures - Part 1-9: Fatigue*. Berlin, Germany: Beuth Verlag GmbH.
- [26] European Committee for Standardization (2013) *EN ISO 4032 - Hexagon regular nuts (style 1) - Product grades A and B*. Berlin, Germany: Beuth Verlag GmbH.
- [27] European Committee for Standardization (2013) *EN ISO 898-1 - Mechanical properties of fasteners made of carbon steel and alloy steel - Part 1: Bolts, screws and studs with specified property classes - Coarse thread and fine pitch thread*. Berlin, Germany: Beuth Verlag GmbH.
- [28] European Committee for Standardization (2012) *EN ISO 898-2 - Mechanical properties of fasteners made of carbon steel and alloy steel - Part 2: Nuts with specified property classes - Coarse thread and fine pitch thread*. Berlin, Germany: Beuth Verlag GmbH.
- [29] European Committee for Standardization (2014) *EN ISO 18265 - Metallic materials - Conversion of hardness values*. Berlin, Germany: Beuth Verlag GmbH.
- [30] European Committee for Standardization (2000) *EN ISO 7089 - Plain washers - Normal series, Product grade A*. Berlin, Germany: Beuth Verlag GmbH.
- [31] European Committee for Standardization (1992) *EN 20273 - Fasteners; clearance holes for bolts and screws*. Berlin, Germany: Beuth Verlag GmbH.
- [32] European Committee for Standardization (2010) *EN 1993-1-8 - Design of steel structures - Part 1-8: Design of joints*. Berlin, Germany: Beuth Verlag GmbH.
- [33] European Committee for Standardization (2011) *EN 1090-2 - Ausführung von Stahltragwerken und Aluminiumtragwerken - Teil 2: Technische Regeln für die Ausführung von Stahltragwerken*. Berlin, Germany: Beuth Verlag GmbH.
- [34] European Committee for Standardization (2015) *EN 14399-6 - High-strength structural bolting assemblies for preloading - Part 6: Plain chamfered washers*. Berlin, Germany: Beuth Verlag GmbH.
- [35] Deutsches Institut für Normung e. V. (2020) *DIN 969 - Threaded fasteners - Axial load fatigue testing - Test methods and evaluation of results*. Berlin, Germany: Beuth Verlag GmbH.
- [36] Schwarz, M. (2021) *Beitrag zur Beurteilung der Schwingfestigkeit von Verbindungen mit Schließringbolzen ohne Abrissteil unter Berücksichtigung von Biegeeinflüssen*. Dissertation, Rostock, Germany: Universität Rostock.
- [37] Background Information on Fatigue Design Rules (2018) *Statistical Evaluation (2nd Edition) - Technical Committee 6 Fatigue and Fracture - No 140, ECCS*. - European Convention for Constructional Steelwork.