A nyomaték-előfeszítő erő összefüggéseiben szereplő nyomaték és súrlódási tényezők kísérleti meghatározása csavarkötéseknél

Experimental determination of torque and friction coefficients in the torque–preload relationships of bolted connections

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Abstract

This study examines the torque–preload relationship in bolted connections with deeply embedded anchor bolts used in precast concrete structures. It evaluates torque and friction coefficients under different lubrication and tightening torque levels. Lubrication notably reduces friction, while higher torque flattens surfaces, further lowering friction. Connection type and size had minimal impact. Findings highlight the need for precise, case-specific analysis in structural applications.

Keywords: bolted connections, nut factor, torque-preload relationship, lubrication, friction coefficients

Kivonat

A tanulmány a nyomaték–előfeszítő erő kapcsolatát vizsgálja mélyen beágyazott csavarkötéseknél előregyártott beton szerkezetekben. A nyomaték- és súrlódási tényezőket különböző kenési állapotok és meghúzási nyomatékok mellett értékelték. A kenés jelentősen csökkenti a súrlódást, a nagyobb nyomaték pedig a felületek kisimulása révén tovább mérsékli azt. A kötés típusa és mérete csekély hatással volt. Az eredmények hangsúlyozzák az egyedi, pontos vizsgálatok fontosságát szerkezeti alkalmazásokban.

Kulcsszavak: csavarkötések, anya tényező, nyomaték–előfeszítő erő összefüggés, kenés, súrlódási tényezők

1. INTRODUCTION

Bolted connections are widely utilized in prefabricated concrete structures because they facilitate rapid and efficient assembly and disassembly. This makes them particularly advantageous for construction, as well as for maintenance and repair operations. In general, these joints consist of two main components: anchor bolts with deep embedment depths and a column shoe, which is simply a steel plate fixed by a group of reinforcing bars. Once assembled, the bolted connection is capable of resisting tension, shear, and bending stresses, contributing to the overall structural performance. When using these connections in high-rise buildings or for assembling slender structural members, it is crucial to apply the optimal tightening torque to ensure their safe and effective performance, as the reliability of these connections is essential for the overall stability of the assembled structure. In the majority of manufacturing applications, bolt tension (preload) is typically applied using a torque wrench on either the bolt head or the nut. The tribological conditions during the tightening process play a key role in determining the actual relationship between the applied torque and the resulting tension [1, 2]. A high percentage of the applied tightening torque is used to overcome two primary sources of friction: underhead (or bearing) friction, caused by the sliding of the bolt head against the washer surface, and thread friction between the male and female threads. The remaining portion of the torque contributes to generating bolt tension by creating the clamping force within the joint. Inaccurate estimation of these friction components can result in either overestimating or underestimating the performance of the bolted joint [3]. The relationship between torque and preload is commonly simplified using Eq. (1), a constant K referred to as the torque coefficient or nut factor. While some standards and authors [4, 5] suggest an approximate value of 0.20 for this coefficient, caution is advised when applying it to critical joints.

$$T = K \times F_V \times d \qquad \ldots (1)$$

T is the applied tightening torque of the bolt head, F_v is the preloading force, and d is the nominal thread diameter. More accurate formula was proposed by the other researchers; Motosh [6] and VDI2230 [7] proposed an equation Eq.(3), that consider three different contributions: the pitch T_p, the thread T_t and the underhead T_h torque as shown in Eq.(2) as a general form:

$$T_{input} = T_{Pitch} + T_{Threads} + T_{Head} \qquad \ldots (2)$$

$$T = T_p(F_v, p) + T_t(F_v, \mu_t, d_m) + T_h(F_v, \mu_h, d_h)$$

$$T = F_v[0.16 \times p + 0.58 \times \mu_t \times d_m + 0.5 \times \mu_h \times d_h] \qquad \ldots (3)$$

Where p is the thread pitch, μ_t friction coefficient among threads, d_m is the mean diameter *(d_m=d-0.649. p)*, μ_h is the underhead friction coefficient and d_h is the under head mean diameter. Most studies in the existing literature [8–14] have concentrated on identifying the friction factors in conventional bolted connections, such as the one illustrated in Figure 1A. In this setup, a bolt, nut, and washers are used to clamp multiple components together, and the joint's effectiveness depends on achieving the proper clamping force. This force is generated by applying the appropriate tightening torque to the nut, which stretches the effective length of the bolt shank. In contrast, very few—if any—studies have explored the friction coefficients in bolted connections that involve anchor bolts with deep embedment lengths, like the configuration shown in Figure 1b, where measuring the effective length is not as straightforward. This paper aims to address that gap by focusing on determining the nut factor and friction coefficients for this less-explored type of bolted connection because its initial stiffness significantly impacts the prefabricated concrete structures; moreover, establishing a universal value for the K factor is not feasible, as it is highly dependent on the frictional conditions and the geometric characteristics of the considered joint [15]. In both types of bolted connections, numerous common factors influence the achievement and retention of the desired preload in a bolt. These include phenomena such as relaxation, self-loosening, temperature fluctuations, tool accuracy, tightening sequences, and the material grade of the bolt. The internal forces within a bolted joint—particularly the clamping force—are subject to change over time, and the behavior during the assembly process plays a critical role in the joint's long-term performance [16]. However, the specific type of connection examined in this study introduces additional complexities, such as slip between the embedded portion of the anchor bolt and the surrounding concrete. This interaction can lead to further preload losses, both in the short term and throughout the service life of the bolted connection.

2. EXPERIMENTAL PROGRAM

Each connection consists of two main parts: the anchor bolt and the column shoe; the connections included in this study are manufactured by PFEIFER company [17]. In the experimental setup, full-scale assembled beams were deployed to replicate the actual configuration of the bolted connection. Each assembled beam has three bolted connections at the joint zone, two at the lower part and one at the middle upper part, as shown in Figure 2. Three connection types were tested; the geometry and dimensions of each type are shown in Figure 3 and Table 1, respectively. In such multi-bolt joints, the sequence of bolt tightening significantly influences the resulting preload distribution unless all bolts are tightened simultaneously. When bolts are tightened sequentially, the preload applied to earlier bolts can be partially lost due to relaxation effects induced by the tightening of subsequent bolts. In the current study, where the joint is clamped by three bolted connections, after tightening the first bolt to the desired preload, tightening the second bolt causes a reduction in the preload of the first. Similarly, tightening the third bolt results in additional relaxation in the first and second bolts. As a result, despite applying the same initial preload to each bolt, the final residual preloads differ

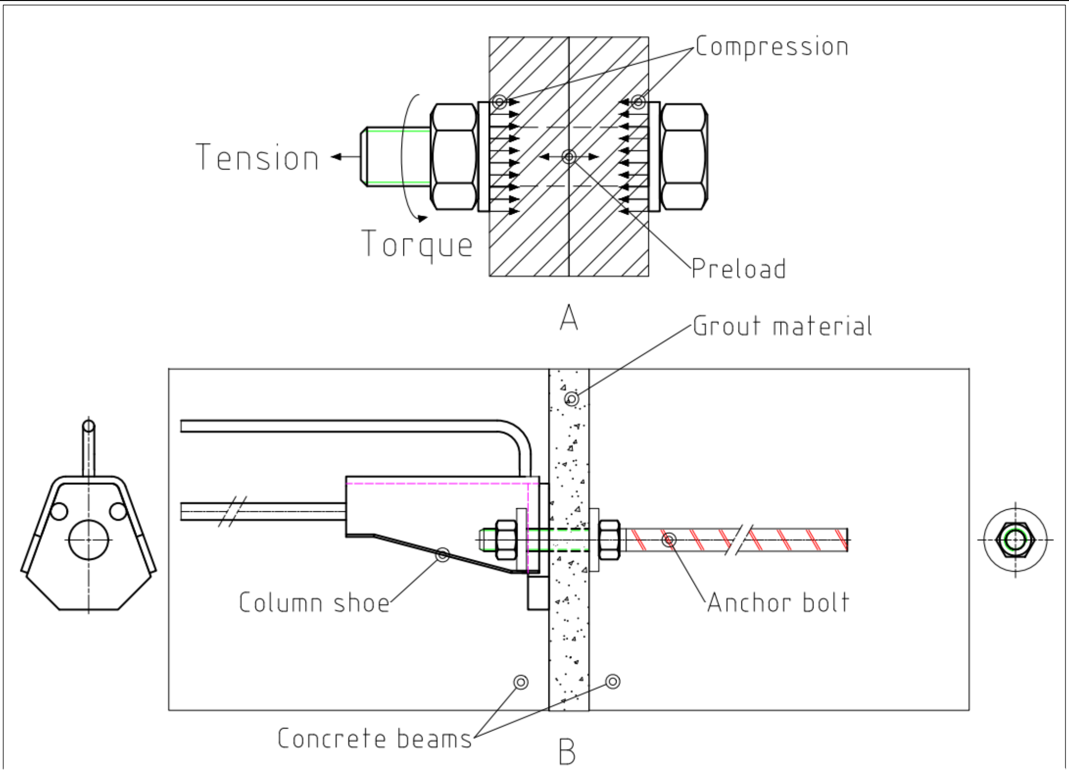

Fig.1 *Bolted connection types (A) conventional connection (B) bolted connection with anchor bolt of deep embedment length*

among them. To minimize this effect, each measured preload was represented by the average preload value of the two lower connections, while the upper connection was excluded from the measurements.

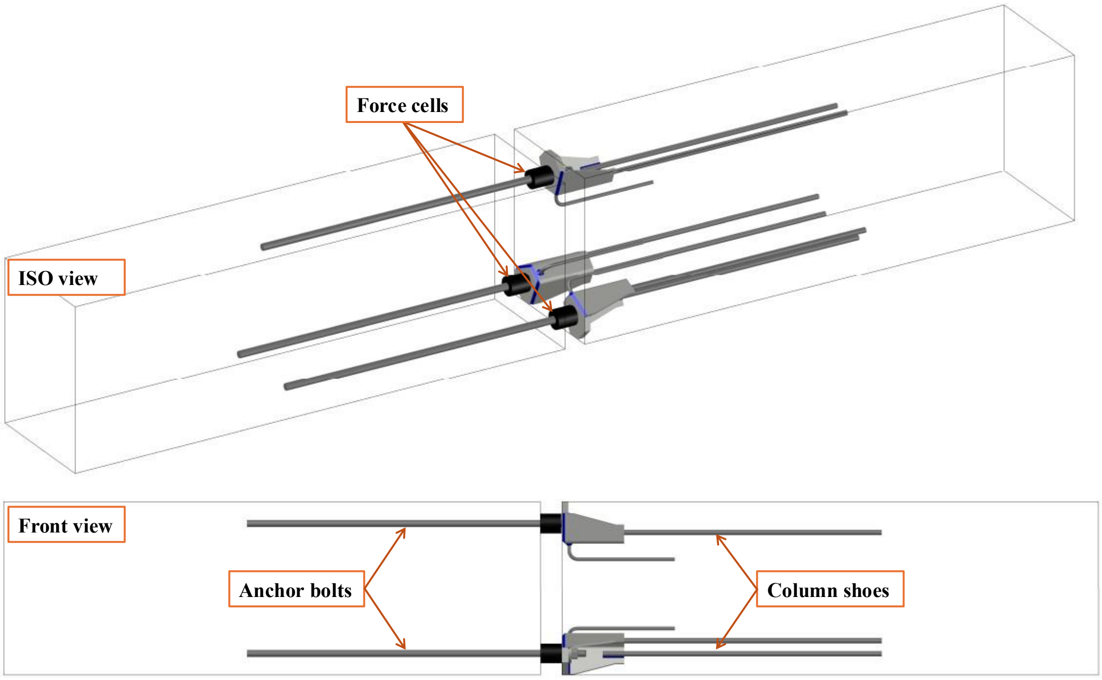

Fig.2 *3D visualization of bolted connection positions embedded inside RC beams*

To investigate the influence of lubrication on bolted connections, three distinct lubrication conditions were evaluated for each connection type. In the first condition, referred to as “Wiped,” the bolts were throughly cleaned using a dry, lint-free cloth to remove any residual grease or contaminants from the contact surfaces. In the second condition, designated as “Dry,” all mating surfaces were treated with a degreaser (Loctite SF 7061) prior to the initial tightening to ensure the absence of lubricants. The third condition, termed “Oiled,” involved the application of a substantial amount of mineral-based 15W-40 motor oil (MOL MSE) to all contact surfaces within the bolted joint. New washers were employed in all cases to minimize variability due to surface wear or deformation, particularly under high-tightening torques. However, the same bolts and nuts were retained throughout the testing process. For each lubrication scenario, five tightening levels 15%, 20%, 25%, 30%, and 35% of the maximum permissible torque for each bolt type—were applied. Two torque-controlled wrenches, with maximum torque capacities of 210 Nm and 400 Nm respectively, were employed in the tests. In total, 216 individual tests were performed.

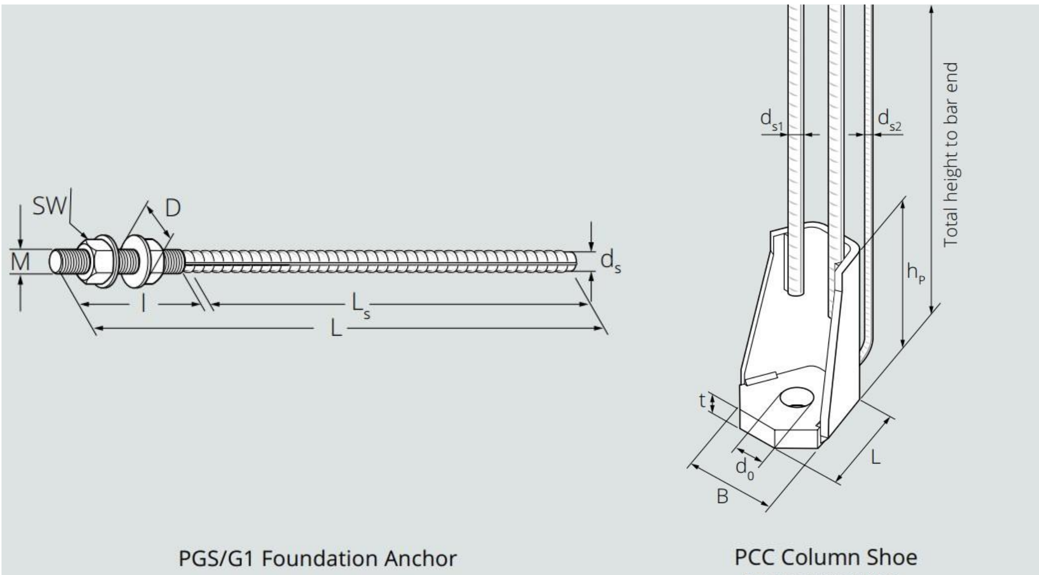

Fig. 3 *Geometry of bolted connection components [17]*

Table 1 Dimensions of bolted connection components [17]

PGS/G1 Foundation anchor					
Type designation			PGS-16/G1-790	PGS-20/G1-970	PGS-24/G1-1110
Thread type			M 16	M 20	M 24
Overall length	L	mm	790	970	1110
Reinforcing steel diameter	d_s	mm	16	20	25
Overlap length	L_s	mm	690	860	990
Thread length	l	mm	100	110	120
Wrench size	SW	mm	24	30	36
Washer diameter	D	mm	45	45	55
PCC Column shoe dimensions					
Type designation			PCC 16	PCC 20	PCC 24
Overall height	h	mm	745	910	1125
Reinforcing steel diameter	d_{s1}	mm	12	14	16
Reinforcing steel diameter	d_{s2}	mm	8	8	10
Plate thickness	t	mm	15	20	25
Bore diameter	d_0	mm	28	30	35
Profile height	h_p	mm	145	170	190
Foot width	B	mm	89	97	100
Foot length	L	mm	90	95	100
Overlap length	L_s	mm	650	800	1000

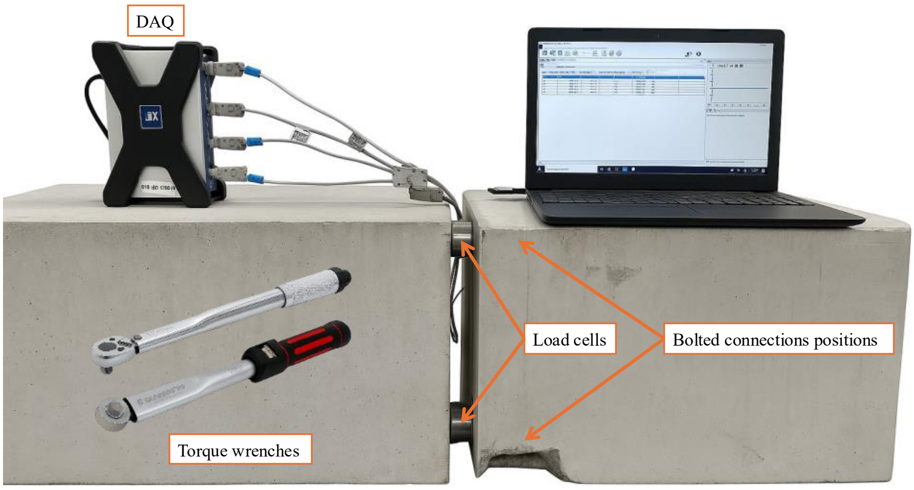

Fig. 4 *Experimental setup layout*

3. RESULTS AND DISCUSSION

To experimentally determine key coefficients such as the torque coefficient (*K*), the thread friction coefficient (μ_t), and the underhead friction coefficient (μ_h), Eq.(3) was reformulated into Eq.(4). In this reformulation, the thread and underhead friction coefficients were assumed to be equal, represented by a unified mean friction coefficient (μ_m). The torque coefficient (*K*) was calculated using the general expression provided in Eq.(1).

$$\mu_m = \frac{T/F_v - 0.16 \times p}{0.58 \times d_m + 0.5 \times d_h} \qquad \dots (4)$$

According to the experimental results that listed for each connection type in Tables 2,3,4, variations in the type of bolted connection do not significantly influence either the mean friction coefficient or the torque coefficient. The slight variations observed are likely due to sampling limitations rather than any systematic trend. Furthermore, the observation that the anchor bolt diameter does not affect the torque coefficient is consistent with theoretical expectations. This is because, in the equation describing the relationship between torque and tension, the anchor bolt diameter is treated as a separate variable from the torque coefficient, and thus should not influence its value.

Table 2 Experimental results of connection type [(PGS-16/G1-790)+(PCC 16)]

ID	Lubrication	Torque %	*Fv (N)*	μ_m	*K*
1	Wiped	15	5650	0.260	0.353
2	Wiped	20	7250	0.271	0.367
3	Wiped	25	10450	0.233	0.318
4	Wiped	30	13550	0.214	0.295
5	Wiped	35	16050	0.211	0.29
6	Wiped	50	23700	0.203	0.281
7	Dry	15	3400	0.442	0.587
8	Dry	20	4950	0.404	0.538
9	Dry	25	6600	0.377	0.504
10	Dry	30	8950	0.332	0.446
11	Dry	35	10750	0.322	0.433
12	Dry	50	17400	0.283	0.383
13	Oiled	15	7100	0.204	0.281
14	Oiled	20	8850	0.219	0.301
15	Oiled	25	11650	0.207	0.286
16	Oiled	30	16150	0.177	0.247
17	Oiled	35	22100	0.149	0.211
18	Oiled	50	29900	0.158	0.223

As anticipated, lubrication leads to a reduction in both the mean friction and torque coefficients. It is evident that the dry condition exhibits the highest coefficient values, while the oiled condition yields the lowest. The coefficients for the wiped condition generally fall between these two extremes. However, an exception is observed in the third type of bolted connection, where the wiped condition results in higher coefficients than the dry condition. This anomaly is likely due to inconsistent wiping and the presence of debris trapped between the larger threads, which may have increased surface roughness. With respect to the influence of tightening torque on friction coefficients, a clear trend is observed: as the applied torque increases, both the mean and torque friction coefficients tend to decrease. This behavior can be attributed to the higher clamping force generated by increased torque, which promotes the flattening of contact surfaces, thereby reducing surface roughness. As a result, the sliding friction between the mating surfaces is diminished.

Table 3 Experimental results of connection type [(PGS-20/G1-970)+(PCC 20)]

ID	Lubrication	Torque %	*Fv (N)*	μ_m	*K*
19	Wiped	15	9900	0.230	0.315
20	Wiped	20	14530	0.208	0.286
21	Wiped	25	14900	0.256	0.349
22	Wiped	30	21400	0.212	0.292
23	Wiped	35	25400	0.208	0.287
24	Wiped	50	38050	0.197	0.273
25	Dry	15	7500	0.309	0.416
26	Dry	20	11450	0.268	0.363
27	Dry	25	15350	0.248	0.339
28	Dry	30	19100	0.239	0.327
29	Dry	35	22250	0.239	0.327
30	Dry	50	31100	0.245	0.334
31	Oiled	15	12350	0.181	0.253
32	Oiled	20	21050	0.138	0.198
33	Oiled	25	25150	0.146	0.207
34	Oiled	30	29050	0.152	0.215
35	Oiled	35	32300	0.160	0.225
36	Oiled	50	44450	0.167	0.234

Table 4 Experimental results of connection type [(PGS-24/G1-1110)+(PCC 24)]

ID	Lubrication	Torque %	*Fv (N)*	μ_m	*K*
37	Wiped	15	15000	0.218	0.300
38	Wiped	20	20250	0.215	0.296
39	Wiped	25	26100	0.208	0.287
40	Wiped	30	31950	0.204	0.281
41	Wiped	35	37000	0.205	0.283
42	Wiped	50	49600	0.220	0.302
43	Dry	15	22700	0.139	0.198
44	Dry	20	29850	0.141	0.201
45	Dry	25	34680	0.153	0.216
46	Dry	30	42500	0.149	0.211
47	Dry	35	48250	0.154	0.217
48	Dry	50	63700	0.168	0.235
49	Oiled	15	21000	0.151	0.214
50	Oiled	20	31600	0.132	0.190
51	Oiled	25	38450	0.136	0.195
52	Oiled	30	47050	0.133	0.191
53	Oiled	35	55050	0.133	0.190
54	Oiled	50	72750	0.145	0.206

4. CONCLUSIONS

This study presents an experimental evaluation of friction-related parameters in bolted connections involving deeply embedded anchor bolts, a configuration prevalent in prefabricated concrete systems. The following key conclusions were drawn:

1. Lubrication has a significant impact on both the mean friction coefficient and torque coefficient. Dry conditions produced the highest coefficients, while oiled conditions yielded the lowest, with wiped conditions falling in between.

2. Increasing the tightening torque consistently decreased the friction coefficients, a trend attributed to higher clamping forces that reduce surface roughness through micro-level deformation of contact interfaces.
3. The type of bolted connection, including the size and geometry of the connected components, did not notably influence the friction or torque coefficients. Minor variations observed are likely due to sampling effects rather than systematic differences.
4. The anchor bolt diameter did not affect the torque coefficient, aligning with theoretical models that treat diameter and torque coefficient as independent variables in the torque–preload equation.
5. The observed behavior underscores the need for project-specific calibration of the torque–preload relationship, especially in structural applications where standard assumptions may introduce significant inaccuracies.

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REFERENCES

[1] Nassar, S. A., El-Khiamy, H., Barber, G. C., Zou, Q., Sun, T. S., *An Experimental Study of Bearing and Thread Friction in Fasteners*, Journal of Tribology, 127(2), pp. 263–272, 2005.

[2] Nassar, S. A., Ganeshmurthy, S., Ranganathan, R. M., Barber, G. C., *Effect of Tightening Speed on the Torque-Tension and Wear Pattern in Bolted Connections*, Journal of Pressure Vessel Technology, 129(3), pp. 426–440, 2007.

[3] Croccolo, D., De Agostinis, M., Vincenzi, N., *Failure analysis of bolted joints: Effect of friction coefficients in torque–preloading relationship*, Engineering Failure Analysis, 18(1), pp. 364–373, 2011.

[4] Nassar, S. A., Matin, P. H., Barber, G. C., *Thread Friction Torque in Bolted Joints*, Journal of Pressure Vessel Technology, 127(4), pp. 387–393, 2005.

[5] Robert C. Juvinall, K. M. M., *Fundamentals of Machine Component Design* (3rd ed.), 2000.

[6] Motosh, N., *Development of Design Charts for Bolts Preloaded up to the Plastic Range*, Journal of Engineering for Industry, 98(3), pp. 849–851, 1976.

[7] VDI Handbuch Konstruktion 2230. *Systematic calculation of high duty bolted joints – joints with one cylindrical bolt*, 2001.

[8] Alsardia, T., *Bolt Preload Variations During Repeated Tightenings*, Acta Polytechnica Hungarica, 21(2), pp. 133–150, 2024.

[9] Zou, Q., Sun, T. S., Nassar, S. A., Barber, G. C., Gumul, A. K., *Effect of Lubrication on Friction and Torque-Tension Relationship in Threaded Fasteners*, In Part A: Tribomaterials; Lubricants and Additives; Elastohydrodynamic Lubrication; Hydrodynamic Lubrication and Fluid Film Bearings; Rolling Element Bearings; Engine Tribology; Machine Components Tribology; Contact Mechanics (pp. 591–602). ASME, 2006.

[10] Jiang, Y., Zhang, M., Park, T.-W., Lee, C.-H., *An Experimental Investigation on Frictional Properties of Bolted Joints*, In Analysis of Bolted Joints (pp. 59–66). ASMEDC, 2002.

[11] Güler, B., Gürsel, K. T., *Experimental analysis of the friction coefficient effect of the zinc-lamella coated fasteners on bolt preload and tightening moment*, Materialwissenschaft und Werkstofftechnik, 50(6), pp. 696–705, 2019.

[12] Grabon, W. A., Osetek, M., Mathia, T. G., *Friction of threaded fasteners*, Tribology International, 118, pp. 408–420, 2018.

[13] Liu, Z., Zheng, M., Yan, X., Zhao, Y., Cheng, Q., Yang, C., *Changing behavior of friction coefficient for high strength bolts during repeated tightening*, Tribology International, 151, pp. 106486, 2020.

[14] Morgan, R. C., Henshall, J. L., *The Torque–Tension Behaviour of 22 × 1.5 mm Bolts for Fixing Spigot-Located Wheels on Heavy Commercial Vehicles*, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 210(3), pp. 209–214, 1996.

[15] Finnish Standards Association, SFS-EN ISO 16047, Fasteners. Torque/clamp force testing. Helsinki, 2005.

[16] VILLE PALVANEN, TORQUE MOMENT – TENSION FORCE RELATION FOR ANCHOR BOLTS. Tampere University of technology, 2018.

[17] PFEIFER connections, (n.d.), from https://www.pfeifer.info/en/home/ (Retrieved April 10, 2025).