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An Experimental and Comparative Study of the Self-Loosening of Bolted-Joints Under Cyclic Transverse Loading

Umut İNCE*[1], Mustafa GÜDEN[2]

Abstract

The capabilities of analytic models in predicting the experimental critical displacements of the self-loosening of bolted-joints were investigated experimentally and numerically. The experimental loosening rates were determined in a Junker test bench at a constant transverse displacement amplitude (0.45 mm) and under varying initial clamp force and clamp length and controlled bearing and thread friction coefficients. The analytic critical displacements were then calculated using experimental parameters. In addition, a three-dimensional accompanying finite element (FE) model was developed in order to calculate the ratio of spring constants engaging the thread to spring. The results showed relatively low capabilities of present analytic model in the prediction of the critical displacements of the self-loosening of bolted-joints. The efforts to modify the nut reaction moment and the inclination compliance of bolt head portion in the investigated equations however resulted moderate increase in the appropriate predictions. On the other side, the use of the reaction moment determined by FE model increased the appropriate prediction from 58.3 to 73.4%. The accuracy of the equations was further increased by the use of an appropriate k_w value, but the increase in this case was only ~4%.

Keywords: bolted-joints, self-loosening, numerical simulation, Junker test, analytic model.

1. INTRODUCTION

Bolted-joints are widely used in engineering structures as they are relatively easy to implement, offer relatively low cost and generate comparatively high clamping forces. Nevertheless, they are prone to catastrophic failure, particularly at prolonged service durations, making them one of the most critical structural parts. The well-known failure mode of bolted-joints is self-loosening which is primarily caused by vibrational forces. The gradual decrease of preload with the increase of dynamic load on a bolt leads to the initiation of self-loosening. Self-loosening plays a pivotal role in the initiation of fatigue failure, causing not only material and financial losses but also fatal accidents. The crash of a Tupolev 154M type passenger jet in 1999, an example to fatal

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accidents, resulted in the death of 61 persons. The officially reported cause of the accident was the self-loosening of a self-locking nut connecting the pull rod and bell crank in the elevator control system [1]. A United States Air Force reconnaissance airplane caught fire in 2015 as a result of the self-loosening of a fastener, which led to damages in the aircraft control and mission-related systems. The repair cost was declared $62.4 million [2]. A high-speed train derailed in the United Kingdom in 2007, resulted from the self-loosening of a fastener according to the report published by RAIB [3]. There have been many other reports on the causalities resulted from the self-loosening of bolts. The existent analytic equations developed for the self-loosening of bolted-joints under transverse vibrational loads were reviewed in section 2. The applicability of these equations to the experimental results of the self-loosening of bolted-joints, according to authors' knowledge, has not been completely investigated so far. Hence, this study aimed at determining the capabilities of the existent self-loosening analytic models in predicting the experimental critical displacements. For that purpose, extensive transverse vibration experiments were performed under varying initial clamp force and length, controlled bearing and thread friction coefficients and a constant transverse displacement amplitude of 0.45 mm. The transverse vibration experiments were conducted in a Junker bench on the bolted-joints in conjunction with a Finite Element (FE) model. The critical transverse displacements were then calculated for each equation using the experimental parameters. Finally, the experimentally determined loosening rates were drawn as function of analytically calculated critical transverse displacements. The percentages of the correct or appropriate and wrong or inappropriate predictions of the critical displacement of self-loosening were shown in the graphs for each equation. In addition, a three-dimensional simplified accompanying FE model of the bolted-joint was used to calculate the ratio of spring constants engaging the thread to spring which was used in the equations.

2. PREVIOUS EXPERIMENTAL AND NUMERIC STUDIES ON THE SELF LOOSENING OF BOLTED-JOINTS

Early studies on the self-loosening of bolted-joints merely focused on the effect of axial dynamic loads along fastener.

Goodier and Sweeney [4] developed an equation for the loosening of nuts caused by axial vibrational forces. In the same study, the radial micro slips under axial tension, both at the bolt-nut thread interface and the bearing surface, were reported to vary with the radial contraction of bolt and the radial expansion of nut.

Sauer [5] showed that when the ratio of the amplitude of axial dynamic load to mean bolt axial tension was less than 0.7, the axial vibrational forces resulted in no loosening.

Gambrell [6] investigated the effect of fine and coarse thread size, lubrication and frequency on the loosening of fasteners under axial vibrational forces. No effect of fastener thread size and frequency was reported when the dynamic to static load ratio and frequency were less than 1 and between 3.3 and 22 Hz, respectively. When the dynamic to static load ratio was above 1, the fine threaded bolts were shown to loosen less than the coarse threaded bolts. Also, lubrication was shown to be a critical factor in the loosening of coarse threaded bolts.

Junker [7] showed experimentally that the transverse vibrational forces were much more effective than the axial vibrational forces in the self-loosening. The loosening rate expressed as the loss of clamp load per cycle (N/cycle) increased with increasing the amplitude of transverse displacement and thread pitch. An experimental testing device used in the same study, called the Junker tester, was standardized as DIN 65151 in 2002 [8]. DIN 25201 superseded DIN 65151 was published in 2010 [9].

Finkelston [10] showed that the increase of friction and preload enhanced the loosening resistance of fastener.

Yamamoto and Kasei [11, 12] introduced a parameter called the critical relative slippage (S_{cr}) which determines the upper transverse displacement limit for the initiation of loosening. The schematic of threaded fastener deformation subjected to a transverse external force is shown in Figure 1(a). In the same figure, the nut bearing surface is subjected to a shear force (F_s) and a nut reaction moment (M_t). The critical relative slip proposed by Yamamoto and Kasei [11, 12] is

$$S_{cr} = 2\delta = \frac{2l_n F\mu_b(l_n^2 + 3k_w l_n EI)}{3EI} - \frac{3l_n M_t(l_n + 2k_w EI)}{3EI} \tag{1}$$

In Eqn. 1, δ is the critical slip distance, μ_b is the friction coefficient of bearing surface, F is the clamping force, I is the moment of the inertia of the cross-sectional area of bolt, E is the longitudinal elastic modulus of bolt, k_w, is the inclination compliance of bolt head portion and l_n is the length of bolt.

Based on an FE analysis, Izumi et. al. [13] refined the Yamamoto and Kasei's equation as

$$S_{cr} = 2F\left[\mu_b\left(\frac{l_g^3}{3EI_g} + \frac{l_s^3}{3EI_s} + \frac{l_g l_s l_n}{EI_g} + k_w l_n^2\right) - \frac{m}{4}\frac{\mu_t}{Cos^2\alpha}\left(\frac{l_g^2}{2EI_g} + \frac{l_s^2}{2EI_s} + \frac{l_g l_s}{EI_g} + k_w l_n\right)\right] \tag{2}$$

where, l_g and l_s are sequentially the length of bolt and bolt thread and I_g and I_s are the moment of inertia of cross-sectional area of bolt and bolt thread, respectively (Figure 1(b)). The reaction moment on the thread is given as

$$M_t = \left(\frac{m}{4}\right)\left(\frac{\mu_t F}{Cos^2\alpha}\right) \tag{3}$$

where, m is the height of nut, μ_t is the friction coefficient of threaded interface and α is the half-thread angle. Nakamura et. al [14] proposed an equation for the inclination compliance of bolt head portion (k_w) as

$$k_w = 0.168\left(\frac{1}{d}\right)^3 \left[\frac{1}{kN\,mm}\right] \tag{4}$$

where d is the bolt diameter.

Blume and Illgner [15] proposed the following equation for the critical slip distance based on a beam model fixed on both sides,

$$\delta = \frac{F\mu_b l_n^3}{12EI} \tag{5}$$

Friede and Lange [16] performed experiments on the critical slip distance of transversely loaded fasteners including M16 and M24. Comparison of test results with the Blume and Illgner's equation [15] showed conservative results. They proposed an equation for the critical slip distance as

$$\delta = F\mu_b\left(\frac{l_n^3}{12EI} + \frac{l_n^2}{2C_\varphi}\right) \tag{6}$$

where C_φ (kNm/rad) is rotational stiffness of bolt. Nassar and Housari [17-20] investigated the self-loosing of fasters and proposed a mathematical model for the loosening under cyclic transverse loads. The loosening rate was shown to be sensitive to the thread and bearing friction coefficients of fasteners. In the same study, the loosening rate of fine threaded fasteners decreased with the initiation of loosening; a larger clearance between bolt and pilot increased the loosening rate almost exponentially and the number of cycles for complete loosening was directly proportional to initial clamp force.

Yokoyama et. al [21] presented an analytic model for the bolts subjected to transverse loads. The model well agreed with the FE modelling results. In the same study M_t was proposed as

$$\Delta M_t = \frac{K_t}{K_b + K_t}\Delta F_s l_n \tag{7}$$

where K_t and K_b are the spring constant of engaged thread and the spring constant of bolt head, respectively. The spring constant of bolt head is given as

$$K_b = \frac{EI}{0.6d} \tag{8}$$

where d is the nominal thread diameter.

Although the use of numerical simulation method for the investigation of the loosening behavior of bolt-nut joints with the development of computer and allowing comprehensive analysis in a short time, the number of studies combining experimental - analytical and numerical simulation methods is quite few [22-25].

3. EXPERIMENTAL STUDY

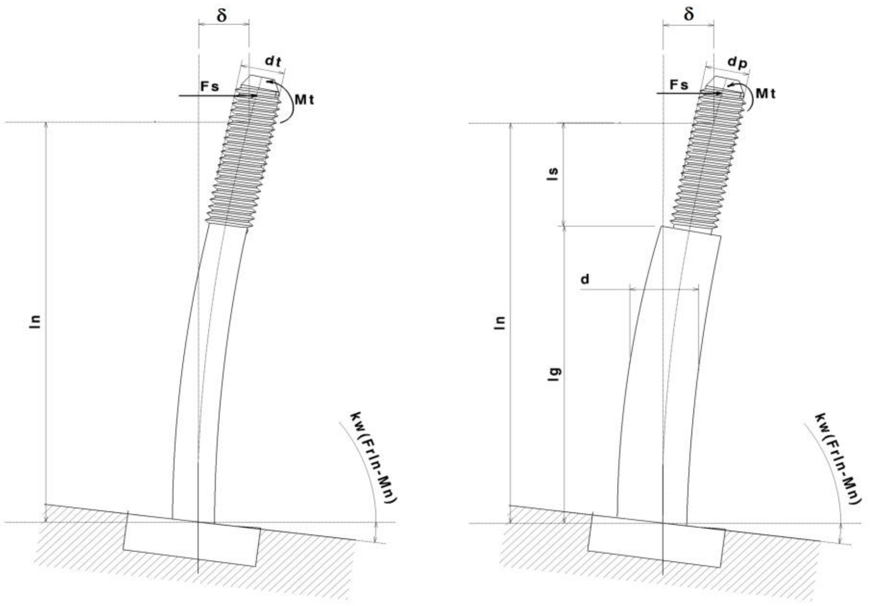
M8x1.25 8.8 ISO 4017 [26] carbon steel bolts and M8x1.25 8 DIN 934 [27] carbon steel nuts were selected for the Junker tests. The thread forming and heat-treatment of bolts and nuts were performed sequentially according to ISO 898-1 [28] and ISO 898-2 [29]. Before testing, the bolts and nuts were coated with Delta Protekt® KL100 + VH301 GZ zinc flake by a dip-spin process in a single batch. Delta Protekt® KL100 + VH301 GZ zinc flake coating induces a friction coefficient between 0.09 and 0.14 and widely preferred by the automotive industry. Thread and bearing friction coefficients of five bolt/nut specimens were measured according to ISO 16047 [30] using SCHATZ® friction coefficient tester. Transverse vibration tests were performed in a Junker test bench shown in Figure 2(a) and Figure 2(c).

In a typical test, the test bench applies a transverse dynamic vibrational force with variable frequency and amplitude on a glider plate. The glider top plate is driven by an eccentric cam. The bolted joint being tested is clamped together the glider plate and fixed plate as shown in Figure 2(b). The clamp force is measured by means of load cells as function of time. The clamp force-cycle data are then exported for the analysis.

The parameters used in transverse vibration tests are tabulated in Table 1. The tests were performed at three different initial clamp forces, six different clamp lengths, four different bearing-thread friction coefficients and a constant transverse displacement amplitude of 0.45 mm and a frequency of 5 Hz. Total 360 vibration tests were performed for 72 test conditions and at least five tests were performed for each test condition. In order to improve the reliability of data, maximum allowable standard deviation of loosening rates was accepted as %20 of average loosening rate value of five test results. If the standard deviation is bigger than the allowed, additional tests performed until the allowable standard deviation value was reached.

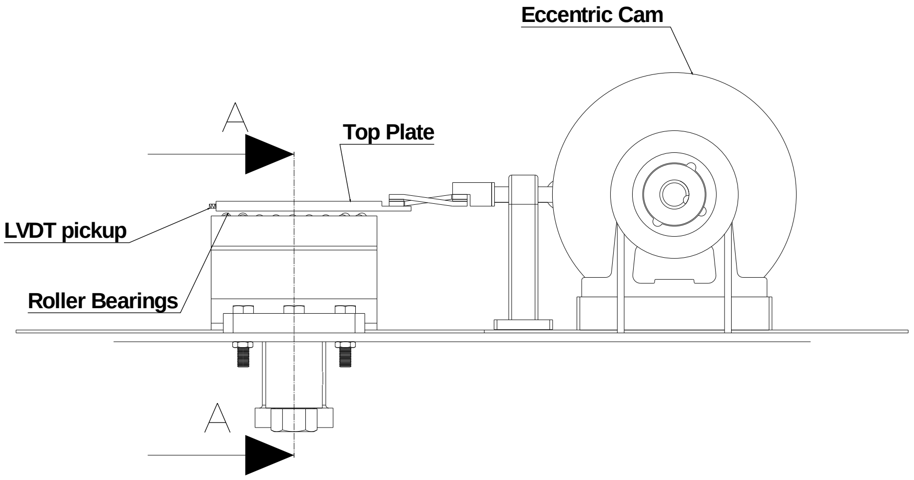
An average value for loosening rate for each test condition was the calculated using 5 tests. The loosening rate (kN/cycle) was determined from the slope of a linear fit to the average clamping force–cycle curve. For the experimental test conditions resulting in self-loosening, the critical transverse displacements were then calculated using the analytic equations elaborated in section 2. These equations are also listed in Table 2 and numbered from 1 to 3 as equation sets numbers. The corresponding parameters and the equations (section 2) used to calculate the critical transverse displacements are also listed in the same table. For example, for the equation set number 1 (Eqn. Set Nr-1) of Table 2, the critical transverse displacement (δ) was calculated using Eqn.1 (Yamamoto and Kasei, 1977) and k_w was calculated using Eqn. 4 (Nakamura et. al, 2001) given in section 2.

Finally, the experimentally determined loosening rates were drawn as function analytically calculated critical transverse displacements for comparison.

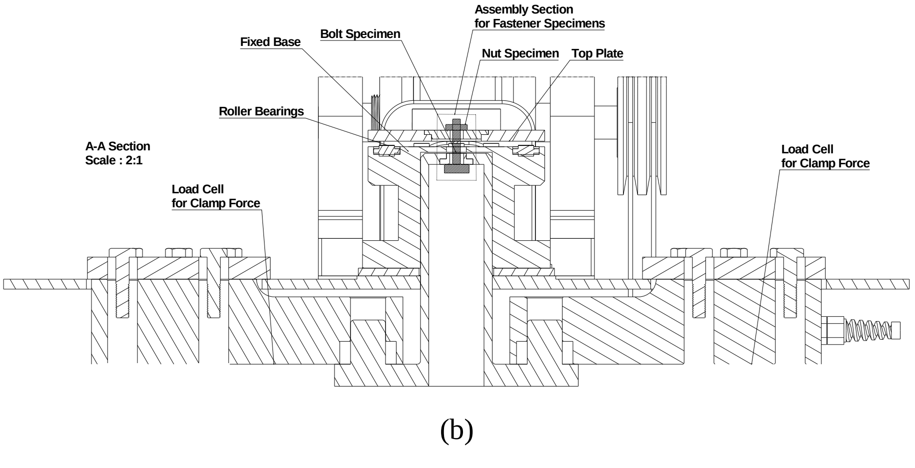


(a) (b)

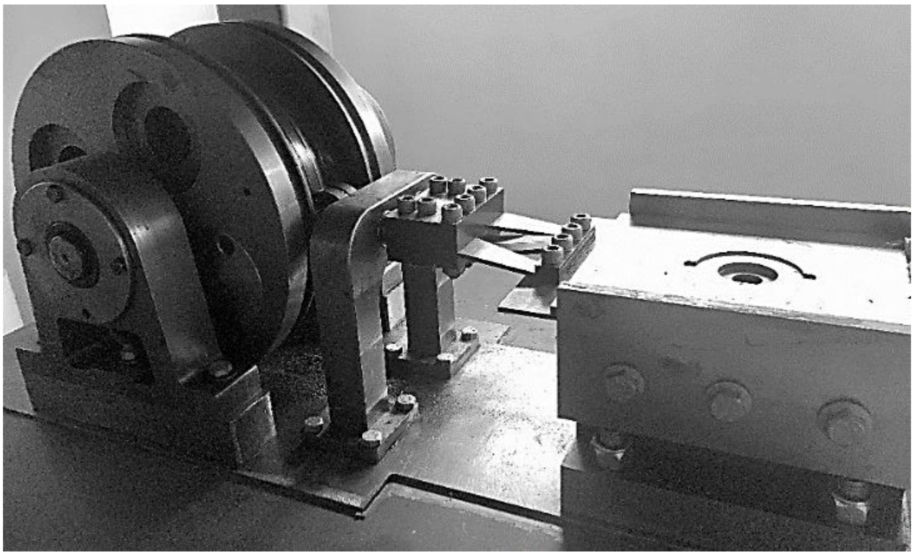
Figure 1 (a) Deflection of a bolt caused by a transverse external force and (b) deflection of multi sectioned bolt caused by transverse external force



(a)



(b)



(c)

Figure 2 (a) Transverse vibration experimental set-up and (b) cross-section view of A-A showing the fixture used in the experimental setup (c) image of Junker test bench

Table 1
Parameters used in the transverse vibration tests

Initial Clamping Force (kN)	Clamp Length (mm)	Bearing Friction Coefficient	Thread Friction Coefficient	Transverse Displacement Amplitude (mm)	Frequency (Hz)
17.6	23	0.121	0.113	0.45	5
14.3	31	0.153	0.125		
10.27	44.5	0.172	0.137		
	53	0.204	0.146		
	65				
	85				

Table 2
Equation set numbers used to calculate the critical displacement (Eqn. Set Nr-1 through Eqn. Set Nr-3)

Number	δ	M_t	K_t	k_w
1	Yamamoto and Kasei [1977]			Nakamura et. al [2001]
2	Blume and Illgner [1988]	NA		NA
3	Friede and Lange[2010]	NA		NA

4. NUMERICAL STUDY

A three-dimensional simplified FE model of the bolted-joint shown in Figure 3 was used to determine the proportion of M_t to $F_s l_n$ to find the ratio of spring constant ratio in Eqn. 7. The finite element simulation was performed in commercial simulation software Simufact®. The elastic modulus and Poisson's ratio were taken 210 GPa and 0.3, respectively, for all deformable steel parts. All geometrical properties of bolt and nut joint model including helical thread (comply with DIN 13 [31]) and the tolerances given for 6h/6H, were kept the same as the experiments. The clamping force was applied by moving up "rigid nut washer" element in z-direction (Figure 3). After creating clamping force, the transverse excitation with 5 Hz frequency and 0.45 mm transverse displacement amplitude was applied to the moving "rigid nut washer" element through Y direction for 10 cycles (Figure 3). The numerical simulation was implemented with 23 mm clamp length and 17.6 kN initial clamping force. 0.121 bearing friction coefficient and 0.113 thread friction coefficient. Coulomb friction model was used and friction coefficients assigned to bearing and thread sides as 0.121 and 0.113 respectively. The numbers of tetrahedral 134 elements that are used at bolt and nut models, were 31041 and 25911 respectively. Segment to segment contact algorithm, mixed-direct iterative solver and adaptive time stepping based on automatic displacement change parameters were used.

5. RESULTS AND DISCUSSION

The variations of experimentally measured thread and bearing friction coefficient as function of the number of tightening-loosening (1st, 3rd, 5th, and 7th tightening-loosening) are shown given in Figure 4. All thread and bearing friction coefficients were measured according to ISO 16047 Fasteners-Torque/clamp force testing. At least 5 friction coefficient measurements were taken and the values were then averaged for each tightening-loosening number. The average friction coefficients of 1st, 3rd, 5th, and 7th tightening-loosening are sequentially 0.121, 0.153, 0.172 and 0.204 for bearing friction coefficient and 0.113, 0.125, 0.137 and 0.146 for friction thread coefficient. As the tightening-loosening number increases the friction coefficients increase as seen in Figure 4. Note in the same figure that the increase of bearing friction coefficient with the tightening-loosening number is higher than that of thread friction coefficient. The increase in friction coefficients with the increase of tightening-loosening number is also noted to show nearly a linear dependence. Hence, the experimental bearing and threat friction coefficients tabulated in Table 1 were average values of these measurements and determined by applying tightening-loosening prior to the transverse vibration experiments.

The critical transverse displacement prediction was taken correct or appropriate if the calculated critical transverse displacement of the equation sets numbered from 1 to 3 in Table 2 was less than 0.45 mm in the experimentally self-loosened bolts or if the calculated critical transverse displacement was higher than 0.45 mm in the experimentally no self-loosened bolts. Otherwise, the prediction was taken wrong or inappropriate. Figures 5(a-c) show the experimentally measured loosening rates as function of calculated critical displacement of the equation sets listed in Table 2. The experimental displacement amplitude (0.45 mm) is also shown as a vertical dotted line in Figures 5(a-c). As noted in Figures 5(a) and (c), the appropriate predictions of critical displacements of the Eqn. Set Nr-1 and Eqn. Set Nr-3 of Table 2 are 50 and 36.1%, respectively. The highest appropriate predictions of critical displacements are found in the Eqn Set Nr-2 of Table 2 as seen in Figures 5(b). This equation set predicts appropriately 58.3% of the critical displacements. The value of k_w is reduced from $3.28x10^{-4}$ to $1x10^{-8}$ in order to determine its effect on the correctness of the critical displacement prediction of Eqn. Set Nr-1. Note that Eqn. Set Nr-2 and Eqn. Set Nr-3 do not use the inclination compliance of bolt head portion. The results of the calculations are shown in Figure 6 as the appropriate prediction percentage versus log k_w curve. As seen in Figure 6, the reduction of k_W is effective in increasing the appropriate prediction of the critical displacements down to 1x10^{-5} and further reduction is noted to have no significant effect on the appropriate prediction percentages of the equations investigated. Until this critical k_w value, 1x10^{-5}, the appropriate prediction percentages increase to ~57% for the Eqn. Set Nr-1 (Figure 6). This critical value of k_w ,1x10^{-5}, is noted to be much smaller than kw values specified by Nishumira [32]. The finite element model variations of M_t and F_s with transverse displacement are shown in Figures 7(a) and (b), respectively. The ratio of spring constant ($\frac{K_t}{K_b+K_t}$) in Eqn. 7 was then calculated using numerical M_t and F_s values revealing pure bolt bending behavior during transverse loading. The ratio was determined 0.628. In order to compare the loosening rate of numerical simulation with those of experiments, the loosening rate of numerical simulation was numerically extended to higher cycles. Initially a linear fit lto the FE model clamp force-cycle curve was applied within 100 cycles; then, using the slope of this linear fitting the FE model clamp force-cycle curve was extended to 850 cycles. Figure 7(c) shows the variation of the extended FE model clamp force with the number of cycle at an initial clamp force of 17.6 kN. In the same figure, the variations of experimental clamp forces of five tests with the number of cycle at an initial clamp force of 17.6 kN are shown together with the variation of the experimental average clamp force. Note that the average experimental clamp force-cycle curve shows well agreements with the FE model clamp force-cycle curve especially at low cycles. The slope of the experimental average clamp force-cycle curve shown in Figure 7(c) yields a loosening rate of approximately 0.01256 kN/cycle. Finally, a new set of equations was developed using the FE model M_t values. This new equation is coded as Eqn. Set Nr-4 and tabulated in Table 3. Using the numerically calculated spring constant ratio and reaction moment, the critical transverse displacement amplitude was calculated for Eqn. Set Nr-4. Initially, the effect of value of k_w on the critical transverse displacement predictions of Eqn. Set Nr-4 was determined. The variation of the appropriate prediction percentage of Eqn. Set Nr-4 of Table 3 with the value of k_w is shown in Figure 8(a). The appropriate prediction percentage increases from 73.4 to 77.7% with the increase of k_w from 7.5x10^{-5} to 5x10^{-5} thereafter the appropriate percentage values saturate. Figure 8(b) shows the experimentally measured loosening rate as function of calculated critical displacement amplitudes with k_w value of 5x10^{-5}. The use of FE model determined reaction moment increases the accuracy from 50.0 to 73.4%. The accuracy of the equations further increased with the use of appropriate k_w value, while the increase is only ~4%. The total increase in the appropriate prediction percentage is 27.7%.

6. CONCLUSIONS

The capabilities of the analytic models in predicting experimental self-loosening of bolted-joints was investigated both experimentally and numerically. The experimental loosening rates were determined in a Junker test bench at a constant transverse displacement amplitude (0.45 mm) and under controlled thread and bearing friction coefficient. The experimental test parameters were then used to calculate the critical displacement for self-loosening for each equation investigated. In addition, a three-dimensional accompanying FE model of bolted-joint was developed to calculate the ratio of spring constants engaging the thread to spring. The results indicated relative low capabilities of present analytical models in the prediction of the critical displacements of bolted-joint for self-loosening. The efforts to modify the nut reaction moment and the inclination compliance of bolt head portion in the equations investigated however resulted in moderate increase in the predictions of the critical displacements for self-loosening. On the other side, the use of the reaction moment determined through the FE model was found to increase the prediction capabilities of the equations significantly.

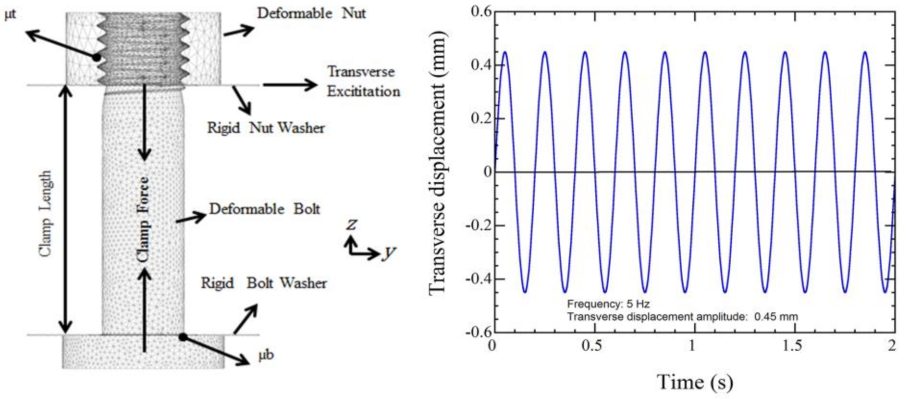


Figure 3 Finite element model of bolted-joint and applied transverse displacement versus time curve

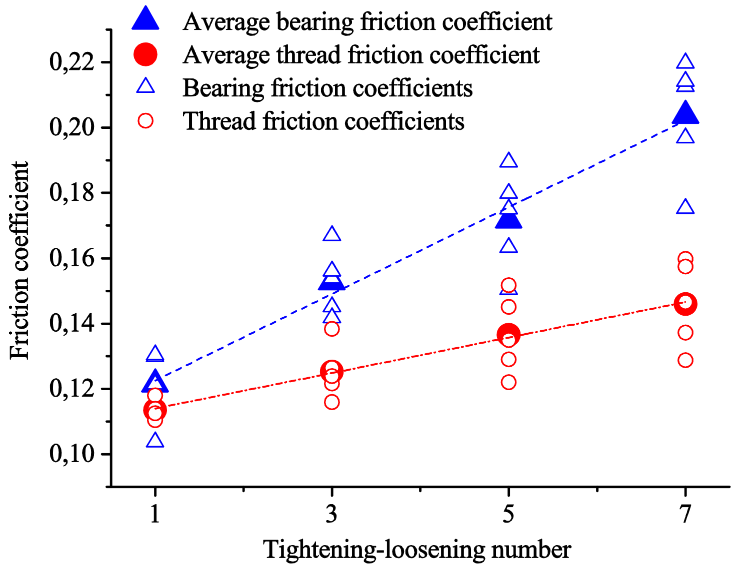
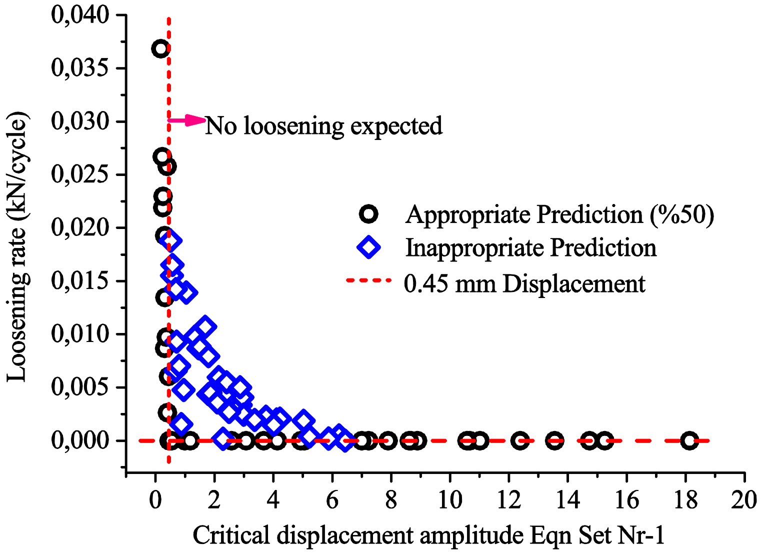
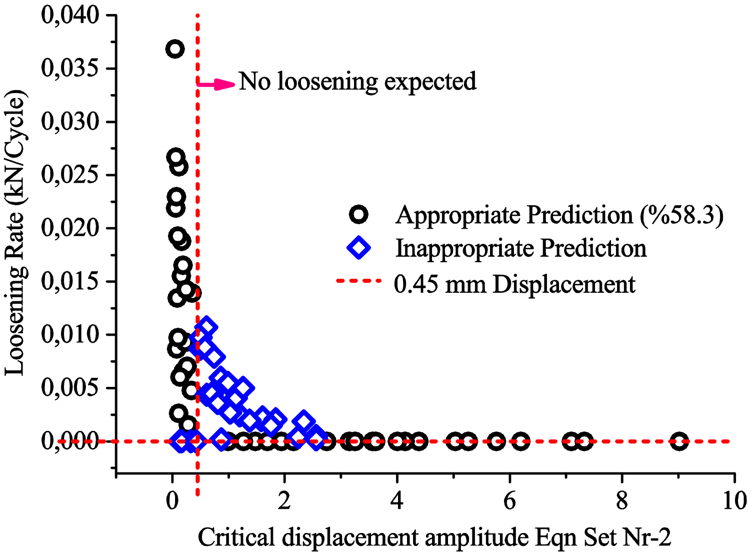


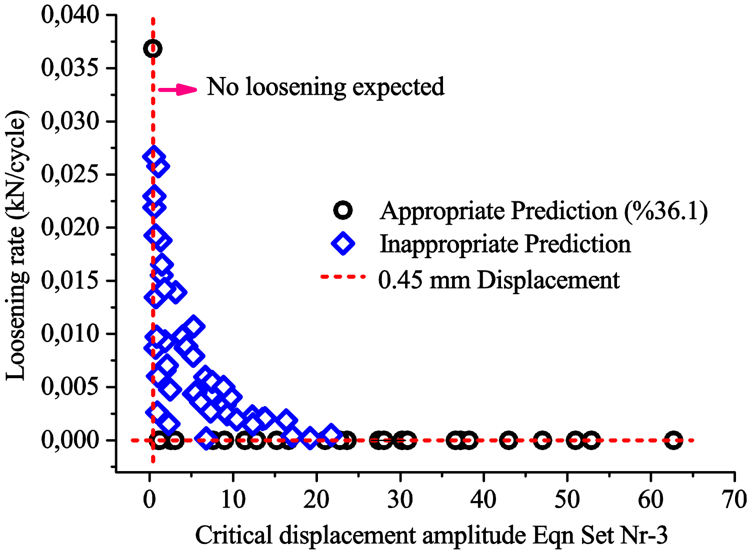
Figure 4 The variations of the thread and bearing friction coefficients with the number of tightening-loosening


Loosening rate (kN/cycle)
0,040
0,035
0,030
0,025
0,020
0,015
0,010
0,005
0,000
No loosening expected
Appropriate Prediction (%50)
Inappropriate Prediction
0.45 mm Displacement
0
2
4
6
8
10
12
14
16
18
20
Critical displacement amplitude Eqn Set Nr-1

(a)


Loosening Rate (kN/Cycle)
0,040
0,035
0,030
0,025
0,020
0,015
0,010
0,005
0,000
No loosening expected
Appropriate Prediction (%58.3)
Inappropriate Prediction
0.45 mm Displacement
0
2
4
6
8
10
Critical displacement amplitude Eqn Set Nr-2

(b)



(c)

Figure 5 Comparison of experimental and analytical results of Eqn. Set Nr (a) 1, (b) 2, (c) 3 of Table 2

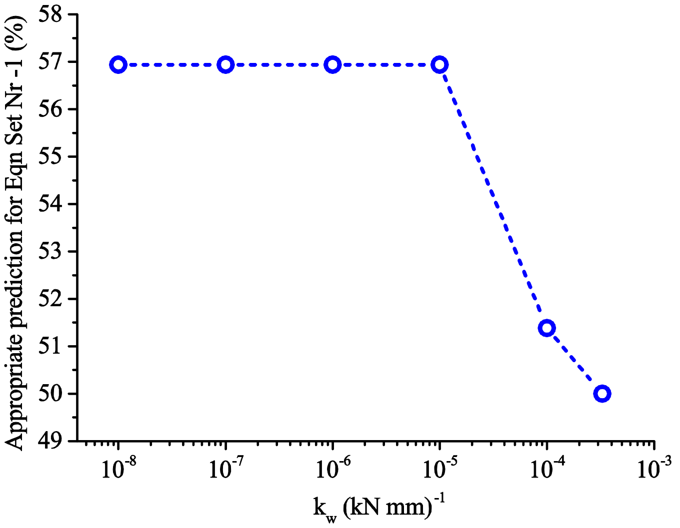
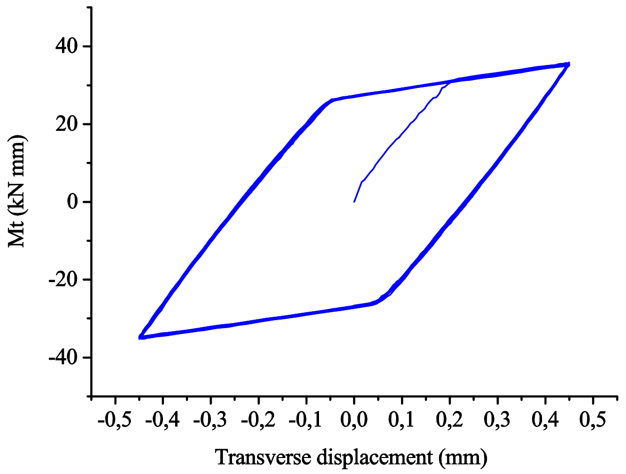
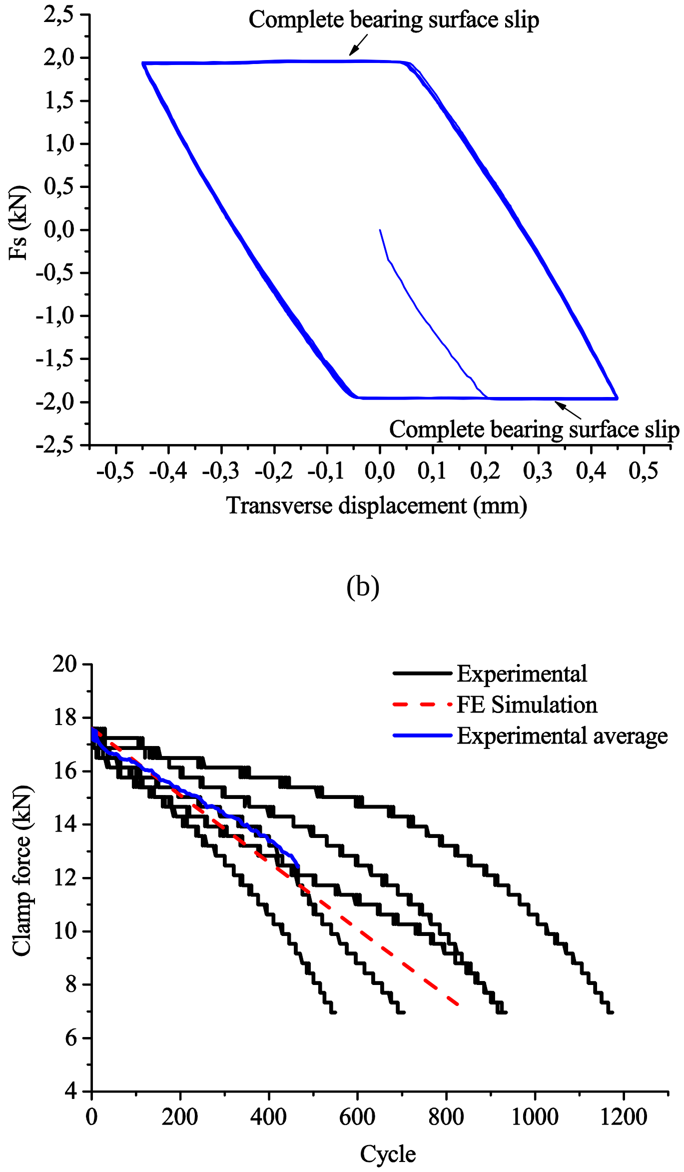


Figure 6 Change of appropriate prediction percentage with k_w for Eqn. Set Nr-1 of Table 2



(a)



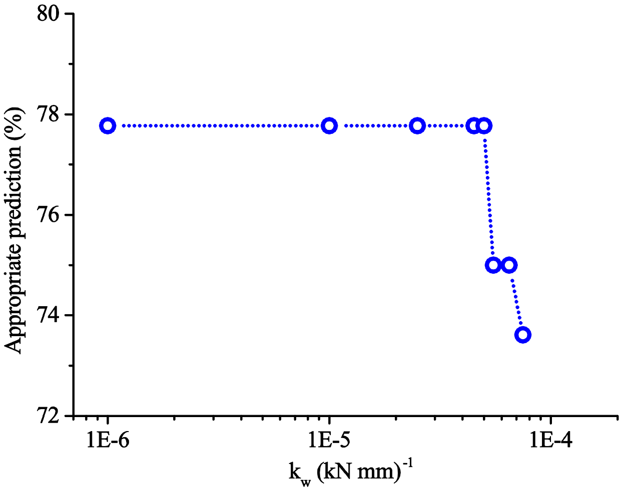
(b)

(c)

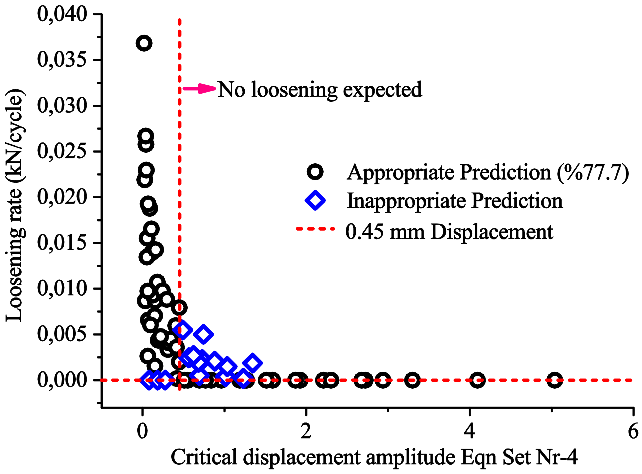
Figure 7 The curves of numerical simulation results of (a) M_t versus transverse displacement and (b) F_s versus transverse displacement and (c) the experimental and FE model clamp force versus cycle

Table 3
Equation set for Eqn Set Nr-4 for the critical displacement

Number	δ	M_t	$Kt/(Kb+Kt)$	k_w
4	Yamamoto and Kasei [1977]	Yokoyama et. al [2010]	Using Yokoyama et. al [2010] equation, derived from simulation : 0.628	Various



(a)



(b)

Figure 8 (a) variation of appropriate prediction percentage with k_w and (b) comparison of experimental and analytical results of Eqn. Set Nr-4 of Table 3

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

Authors' Contribution

Umut İnce : Literature research, data collection, data processing, organize the execution of the study, contribution to article writing and study.

Mustafa Güden : Contribution to article writing and study, literature research

The Declaration of Ethics Committee Approval

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REFERENCES

[1] (1999, March of 3rd). *Aviation Safety Network - Accident Description*. Available: https://aviation-safety.net/database/record.php?id=19990224-0

[2] W. M. Evans, "United States Air Force Aircraft Accident Investigation Board Report," 2015.

[3] R. A. I. Branch, "Rail Accident Report - Derailment at Grayrigg," 2011.

[4] J. Goodier and R. Sweeney, "Loosening by vibration of threaded fastenings," *Mechanical Engineering,* vol. 67, pp. 798-802, 1945.

[5] J. Sauer, D. Lemmon, and E. Lynn, "Bolts: How to prevent their loosening," *Machine Design,* vol. 22, pp. 133-139, 1950.

[6] S. C. Gambrell, "Why bolts loosen?," *Machine Design,* vol. 40, pp. 163-167, 1968.

[7] G. H. Junker, "New Criteria for Self-Loosening of Fasteners Under Vibration," *SAE Transactions,* vol. 78, pp. 314-335, 1969.

[8] "DIN 65151:2002-08 Aerospace series - Dynamic testing of the locking characteristics of fasteners under transverse loading conditions (vibration test)," ed. 2002-08, 2002.

[9] "DIN 25201-1:2015-12 Design guide for railway vehicles and their components " in *Bolted joints - Part 4: Securing of bolted joints* ed, 2015.

[10] R. J. Finkelston, "How much shake can bolted joints take," *Machine Design,* vol. 44, pp. 122-128, 1972.

[11] A. Yamamoto and S. Kasei, "Investigation on the self loosening of threaded fasteners under transverse vibration - A solution for self-loosening mechanism," *Journal of the Japan Society of Precision Engineering,* vol. 43, pp. 470-475, 1977.

[12] A. Yamamoto and S. Kasei, "A solution for self-loosening mechanism of threaded fasteners under transverse vibration," *Journal of the Japan Society of Precision Engineering,* vol. 18, pp. 261-266, 1984.

[13] S. Izumi, T. Yokoyama, A. Iwasaki, and S. Sakai, "Three-dimensional finite element analysis of tightening and loosening mechanism of threaded fastener," *Engineering Failure Analysis,* vol. 12, pp. 604-615, Aug 2005.

[14] M. Nakamura, T. Hattori, S. Tsujimoto, and T. Umeki, "Estimation of back-off loosening limit for bolted joints under transverse cyclic loading," *Transactions of the Japan Society of Mechanical Engineers,* vol. 67, pp. 2976-3056, 2001.

[15] Araki.H and Pereyra.J., "Safely Secure Fasteners in Critical Applications," presented at the 2014 FAA Worldwide Airport Technology Transfer Conference, Galloway, New Jersey, USA, 2014.

[16] R. Friede and J. Lange, "Loss of Preload in Bolted Connections Due to Embedding

and Self Loosening," presented at the Stability and Ductility of Steel Structures, Rio, Brazil., 2010.

[17] S. A. Nassar and B. A. Housari, "Study of the effect of hole clearance and thread fit on the self-loosening of threaded fasteners," *Journal of Mechanical Design,* vol. 129, pp. 586-594, Jun 2007.

[18] B. A. Housari and S. A. Nassar, "Effect of thread and bearing friction coefficients on the vibration-induced loosening of threaded fasteners," *Journal of Vibration and Acoustics-Transactions of the Asme,* vol. 129, pp. 484-494, Aug 2007.

[19] S. A. Nassar and B. A. Housari, "Effect of thread pitch and initial tension on the self-loosening of threaded fasteners," *Journal of Pressure Vessel Technology-Transactions of the Asme,* vol. 128, pp. 590-598, Nov 2006.

[20] S. A. Nassar, B. A. Housari, and Asme, *Self-loosening of threaded fasteners due to cyclic transverse loads* vol. 2. New York: Amer Soc Mechanical Engineers, 2005.

[21] T. Yokoyama, S. Izumi, S. Sakai, and Asme, *Analytical Modeling Of The Transverse Load-Displacement Relation Of A Bolted Joint With Consideration Of The Mechanical Behavior On Contact Surfaces*. New York: Amer Soc Mechanical Engineers, 2009.

[22] D. Yasui, T. Fukuoka, and M. Nomura, "Finite Element Analysis of Loosening Phenomena of Bolted Joints with Washers," *The Proceedings of Conference of Kansai Branch,* vol. 2018.93, p. 417, 09/25 2018.

[23] S. Borawake and S. Naik, "An Investigation of Loosening Phenomenon in Bolted Joint by Finite Element Method," *SSRN Electronic Journal,* 01/01 2018.

[24] M. Zhang, D. Zeng, L. Lu, Y. Zhang, and J. Xu, "Finite element modeling and experimental validation of bolt loosening due to thread wear under transverse cyclic loading," *Engineering Failure Analysis*, vol. 104, 05/01 2019.

[25] V. Rafik, C. Bertrand, A. Daidié, and C. Chirol, *Experimental and Numerical Study of the Self-loosening of a Bolted Assembly*. Advances on Mechanics, Design Engineering and Manufacturing II, 2019.

[26] "DIN EN ISO 4017 "Fasteners – Hexagon head screws – Product grades A and B", 2015/05," ed, 2015.

[27] "DIN 934 "Hexagon nuts ,with metric coarse and fine pitch thread ,product grades A and B", 1987/10.," ed, 1987.

[28] "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", 2013/01.," ed, 2013.

[29] "ISO 898-2 “Mechanische Eigenschaften von Verbindungselementen aus Kohlenstoffstahl und legiertem Stahl – Teil 2: Muttern mit festgelegten Festigkeitsklassen – Regelgewinde und Feingewinde”, 2012/08.," ed, 2012.

[30] "DIN EN ISO 16047:2013-01 Fasteners - Torque/clamp force testing ", ed, 2013.

[31] "DIN 13-1:1999-11 ISO general purpose metric screw threads - Part 1: Nominal sizes for coarse pitch threads; nominal diameter from 1 mm to 68 mm " 1999.

[32] N. Nishimura, T. Hattori, M. Yamashita, and N. Hayakawa, "Self loosening behavior of metal thread joints under transverse cyclic loading," in *Engineering Plasticity and Its Applications from Nanoscale to Macroscale, Pts 1 and 2.* vol. 340-341, N. Ohno and T. Uehara, Eds., ed Stafa-Zurich: Trans Tech Publications Ltd, 2007, pp. 1467-1472.