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# Loosening Lifetime and Residual Clamping Force Prediction Method on Bolted Joints and Evaluation Criterion of Clamping Force Level for Prevention of Loosening Failure

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## Abstract

To secure the reliability of bolted joints, high clamping force (axial tension) is required to prevent fatigue breakage or loosening failure, and so on. In this paper, at first, we observe the behavior of the initial clamping force decrease tendency (loosening phenomenon) obtained by tightening the bolt used in the actual machine (large forklift) during operation. Based on our previous research, there is a strong linear relationship on log-log paper of loosening phenomenon between decrease tendency of clamping force and distance travelled (or passage of time). By utilizing its properties, we show estimation method of residual clamping force such as "How much the clamping force is remaining after the tens of thousands of hours (kilometers)?" Also, a method for estimating loosening lifetime with respect to residual clamping force level is shown. Finally, we examine evaluation criteria such as "Is the residual clamping force sufficient for prevention of loosening failure?" The limit surface pressure is examined as the upper limit clamping force. As the lower limit clamping force, the allowable value of the external transverse force is examined.

## Introduction

Gadget, automobile, machine, railroad and spacecraft may not even exist without bolted joints (screw thread), either. Bolted joints have played an important role as the machine part and is made based on the simple principle of a wedge and a spiral. Although it is a machine element used for more than 2000 years, problems such as poor bolting, self-loosening, and insufficient strength occur even today. These problems appear to be due to their usage as shown in Table 1.

The optimum tightening condition of bolted joints used in a machine is defined as the state in which it is tightened with sufficiently high clamping force (axial tension) to be free from breakage and loosening by any external force during machine operation [1,2,3]. We also showed methods of load analysis and lifetime evaluation to fatigue failure in bolted joints [4].

We conducted a fundamental observation and analysis of the loosening phenomenon [5], and also performed measurements and analyzed the loosening of bolted joints of components and industrial machines [6,7]. Although these papers treated self-loosening as clamping force, Nassar and coworkers treated self-loosening as a loss of clamp load in several papers [8,9]. Various studies have been conducted on the problems of bolted joints and the elucidation of the self-loosening mechanism as outlined below.

In particular, Junker's research gives many suggestions on the mechanism and a laboratory loosening test method [10,11]. Figure 1 shows example of the Junker's style loosening test machine. And Figure 2 shows one of the results of loosening test by Sase et al. [12], for example.

Many papers have described the principle of self-loosening, the evaluation of the loosening test method and some locking devices, such as that of by Kasei [13]. Sanclemente and Hess [14] investigate the influence on resistance to loosening of several parameters (preload, elastic modulus, etc.). Zhang et al. [15] investigate the effect of clamped length and loading direction on self-loosening. Shoji and Sawa [16] show the mechanism of bolt loosening by several finite element analyses. Manoharan and Friedrich [17] investigate the self-loosening behavior of multi bolted joint. However, they cannot be used to perform an absolute evaluation on whether a bolted joint meets a specified performance and maintains its initial performance after a certain period of time during actual machine operation. Zhao et al. [18] applied a logarithmic equation to the problem of loosening, similarly to in the current paper. However, research on this type of absolute estimation method can only be found in our papers [5,6,7].

Major accidents caused by self-loosening and metal fatigue of bolted joints frequently occur. A tendency to observe a decrease in the initial clamping force is considered to indicate the occurrence of loosening. For judgment of self-loosening, as mentioned above, a relative evaluation (comparison) of locking devices and methods is performed in the current study by using test equipment similar to that of Junker. The basic questions we wish to answer in this study are as follows.

**TABLE 1** Bolted joints subjects and problems

| Problems | Details |
|---|---|
| 1. How to analyze and measure the bolted joint load (Feedback to design and experimental stage) | 1. An axial force, bending moment, or torsional torque is often applied to bolted joints.<br>2. How to measure and obtain the bolted joints loads.<br>3. Establish a load analysis method.<br>4. How to feedback the load measurement and analysis results to design and experimental stage. |
| 2. How to prevent loosening failure | 1. Self-loosening easily occurs owing to the spiral shape and is affected by the depression of the bearing surface.<br>2. Fundamental study of loosening phenomenon is so important.<br>3. Establish a method for predicting lifetime to loosening failure and residual clamping force (Axial tension) estimation.<br>4. Establish a method for design basis of judgement criteria for self-loosening |
| 3. How to prevent breakage (Fatigue breakage, etc.) | 1. Bolted joints are often under high stress and subjected to a vibrational force and repeated external forces.<br>2. Areas of high stress concentration exist in the under-head fillet part and threaded portion.<br>3. As a result, fatigue breakage and hydrogen embrittlement may occur during machine operation.<br>4. Establish a method for predicting lifetime to fatigue failure and embrittlement failure.<br>5. Establish a method for design basis of judgement criteria for infinite lifetime design and finite lifetime design. |
| 4. How to maintain tightening reliability | 1. High initial clamping force is required, therefore plastic tightening methods have been developed. However, applying a high initial clamping force is not straightforward, and even today a calibrated wrench method must be used in many cases.<br>2. Turn-of-nut method, torque gradient control method and plastic-region tightening, etc. are improved as the methods of getting high initial clamping force.<br>3. The breakage of screw threads and damage through deformation (cross-sectional reduction) may be caused by tightening.<br>4. Establish a clamping force level for tightening reliability. |
| 5. Other comments | 1. There are also many types of bolts and screws (coarse/fine screw threads with different strengths and electroplated coatings).<br>2. Many bolted joints are used in a single product.<br>3. Suitable maintenance is required to maintain the initial performance of bolted joints and long-term safety. |



**FIGURE 1** Junker's Style Loosening Test Machine

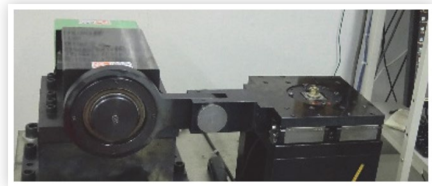
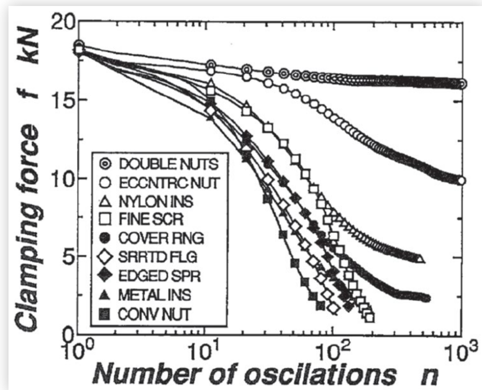




**FIGURE 2** Example results by loosening test machine [12]






1. Several locking device manufacturers have proposed new locking devices, and our question is for how many tens of thousands of operations (distance travelled) do the locking devices maintain their initial clamping force?
2. In actual machines, is it possible to use a locking device with low performance on loosening test machines?

This absolute evaluation is indispensable for the prediction of the lifetimes to loosening failure for machine development.

At first, this paper describes lifetime estimation method. According to the observation results for loosening in an industrial vehicle, there is a strong linear relation between the decrease in the clamping force ratio and the number of operations since the last tightening when both are plotted on logarithmic axes. The loosening lifetime is analyzed from the linear relation obtained by the proposed regression formula. On the basis of this relation, in the early stages of the newly developed test, the rate of decrease in the clamping force can be estimated accurately after prolonged operation by measuring the clamping force behavior. On the other hand, this paper describes evaluation criterion of clamping force level for prevention of loosening failure. Kasei [19] and JFRI [20] introduce the clamping force level for prevention to loosening failure. Jiang et al. [21] show the loosening phenomenon as 3 stages. Paper shows that loosening is caused by material deformation (depression type) as stageI. StageIIis material deformation and backing-off of the nut. Last stage is characterized by the backing-off of the nut and rapid loosening of the clamping force. Amir et al. [22] also shows preload history as the evaluation criterion.

## Basic Idea and Outline of Absolute Evaluation Method for Self-Loosening

Based on our previous research, there is a strong linear relationship on log-log paper of loosening phenomenon between decrease tendency of clamping force and distance travelled (or passage of time). In this chapter, at first, the effectiveness of the concept proposed for static bolt-loosening (in the case of depression-type loosening) is investigated. Second half, we describe the residual clamping force behavior in the case of dynamic bolt-loosening (working-load-type loosening).

Loosening phenomenon is defined as follows [19]. The depression-type loosening is caused by the initial loosening, the permanent deformation of the sealing material, the excessive external force, and the thermal cause when the bolted joints is not subjected to any external force. It is said that the bolt and nut are loosened without relative rotation and the phenomenon is occurred as static behavior. On the other hand, working-load-type loosening is regarded as loosening that occurs when an external force such as a circumferential direction of the shaft, a direction perpendicular to the axis, and an axial direction is applied to the bolted joint. It is said that the bolt and nut are loosened relative to each other and the phenomenon is occurred as dynamic behavior.

## Depression Type Loosening (Static)

Figure 3 shows the detail of the forklift truck (2 tons capacity) used for measuring the loosening phenomenon of the hub bolt and the disc wheel tightening part. A bench test was carried out at this disk wheel. Clamping force (axial tension) of hub bolts was measured by strain gauges attached to the shank of the bolts as shown in Figure 4. A disk wheel was tightened with 8 hub bolts to a hub fixed to a test stand as shown in Figure 5. Clamping force was measured in two hub bolts among eight of them. Strain was measured statically by two gauges method using a universal digital instrument (UCAM -8BLr, Kyowa Electric Instrument Co., Ltd.). The relation of clamping force and strain of each hub bolt was calibrated by a tension test in advance to the experiment (Figure 5). The bolt-loosening was measured as clamping force change by time immediately after tightened with specified torque (dry,715N·m).

**FIGURE 3** Forklift truck and disk wheel fitting configuration

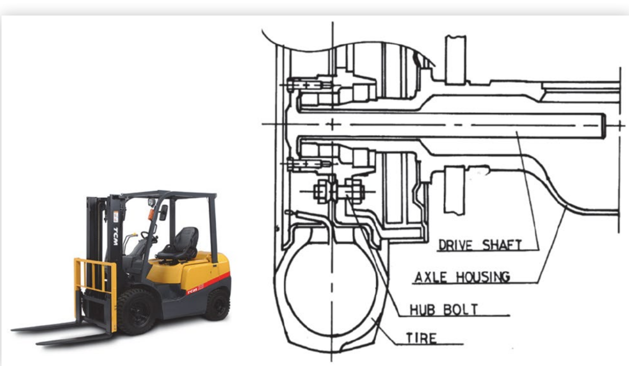





**FIGURE 4** Strain gauges attached to the shank of the bolts

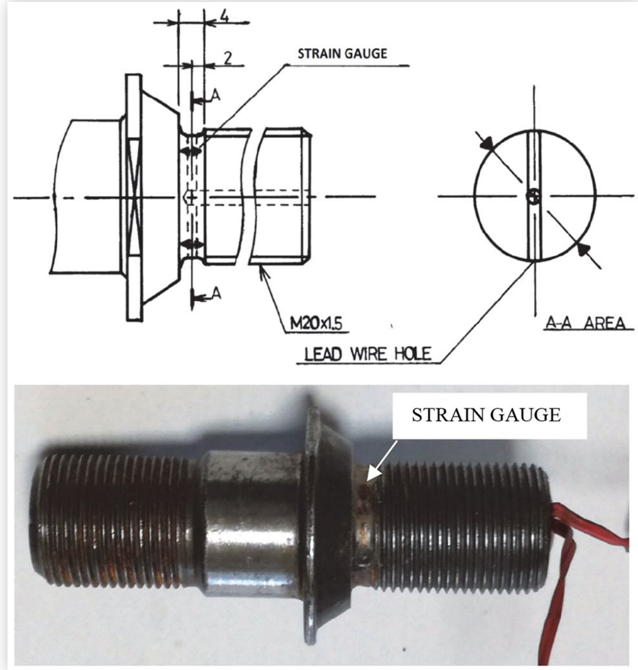





**FIGURE 5** Tension test and test stand for hub bolts fixed to hub

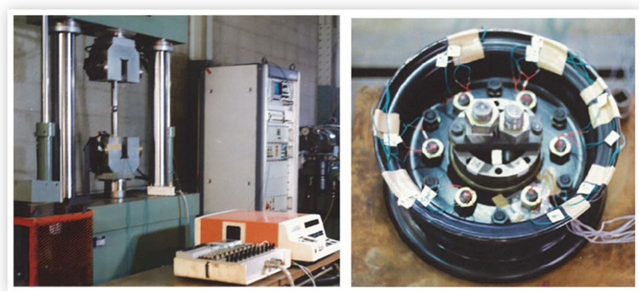




Figure 6 shows the measured result of clamping force change by time immediately after initial tightening as linear coordinates and logarithmic coordinates. We observe that there is a strong linear relationship on log-log paper of depression type loosening phenomenon.

## Working Load Type Loosening (Dynamic)

Figure 7 shows a wheel loader which is a kind of construction machine and the axle housing assembly of the wheel loader are secured by many kinds of bolts. Figure 8 shows the linearity of the observation results for the loosening tendency (decrease in clamping force) during short-term(4 hour), middle-term (1 month), and long-term operation (6 months) at several bolted joints of an axle of the wheel loader [7]. Thus,

**FIGURE 6** Measured results of clamping force behavior

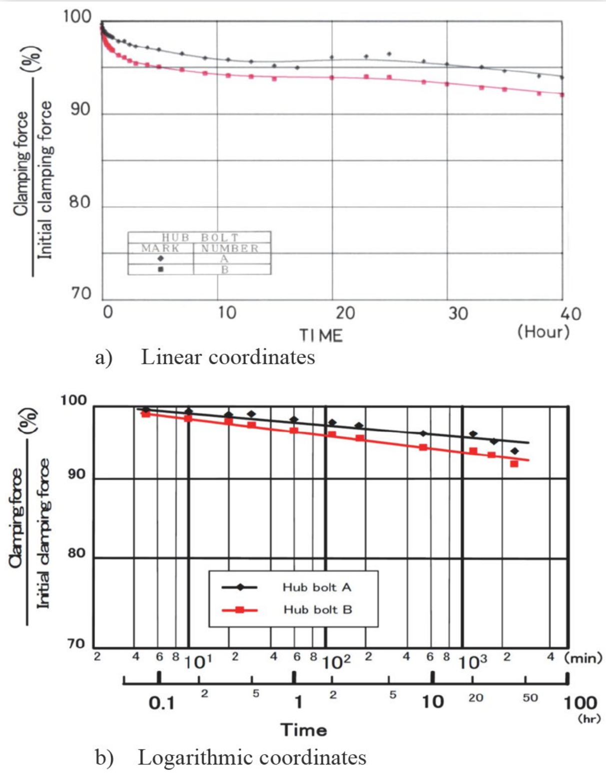





**FIGURE 7** Wheel loader and several bolts in use of the axle housing

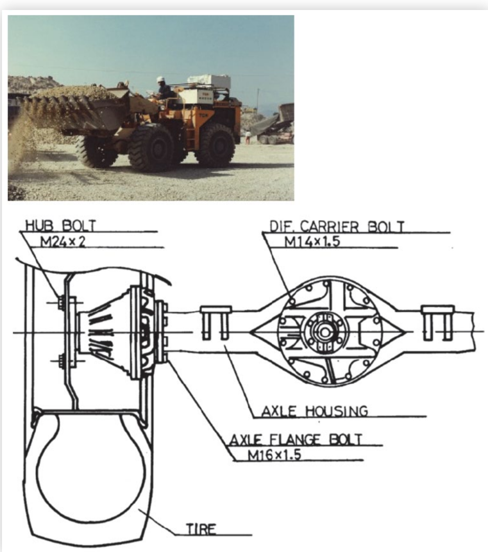
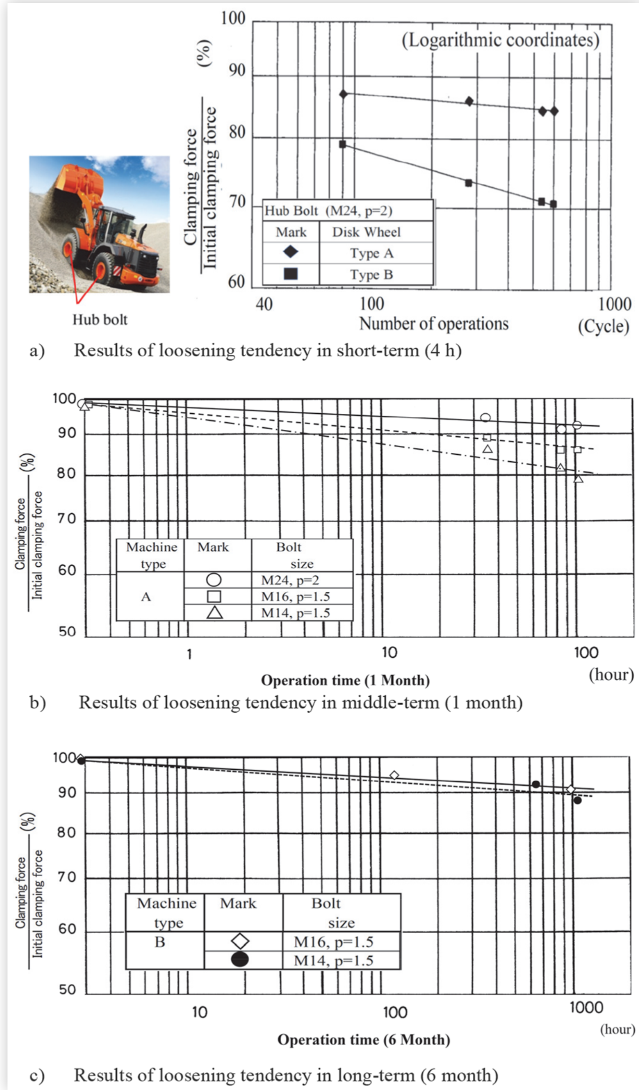





**FIGURE 8** Measurement result of loosening tendency under actual machine operations as working load type loosening






the possibility of estimating the residual clamping force and predicting the lifetime to loosening failure using our fundamental idea has been demonstrated.

(on logarithmic coordinates) [5]

The diagram in Figure 8 can be expressed by the following regression equation.

$$\log r = a + b \times \log h \quad (1)$$

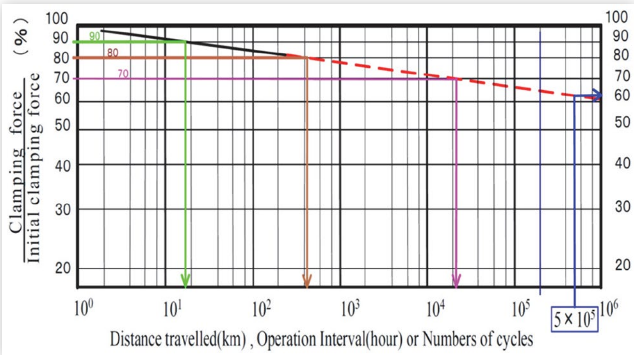
Here, h: Operation Interval (hour)
r : (Measured Clamping Force)/(Initial Clamping Force)
a, b : Constants

Equation (1) can be applied to the regression line of loosening phenomenon as shown in Figure 8.

# Fundamental Concept for Lifetime Prediction to Loosening Failure and Residual Clamping Force Estimation

From these results of experimental loosening observation, we considered that the amount of loosening after long-term operation can be predicted, as shown in Figure 9 for example,

**FIGURE 9** Basic idea of absolute evaluation method for self-loosening






by plotting the measurement results for relatively short-term loosening in the early stages of operation on a log-log graph, and extrapolating the results. When the clamping force residual ratio is 70%, for example, the corresponding value on the horizontal axis obtained with the regression line gives the predicted lifetime. When the distance travelled is 500,000 km, for example, the corresponding value on the vertical axis gives the residual clamping force.

How to estimate the predicted lifetime and the residual clamping force in the sum of depression type and working-load-type loosening. In the development phase of an actual machine, data for both types of loosening may be collected simultaneously or separately at different times. A method of presuming the loosening lifetime is proposed. We describe the grade of residual clamping force estimation method also. From Figure 9, the relation between predicted lifetime and residual clamping force is formulated as Equation (2).

$$\log T_p' = \frac{\log T_t - \log T_1}{\log R_t - \log R_1}\left(\log R_p - \log R_1\right) + \log T_1 \qquad (2)$$

Here,
*T'p* : predicted lifetime by Regression Formula
*Rp* : Residual clamping force (%) for predicted lifetime
*T1*: Start time of loosening observation
*Tt* : Finish time of loosening observation
*R1* : Residual clamping force ratio at *T1 (%)*
*Rt* : Residual clamping force ratio at *Tt (%)*

Equation (2) is a formula for calculating the regression line of loosening phenomenon obtained from experimental results. Table 5 (later) shows the data table when the formula is applied to the regression line shown in Figure 19.

## Fundamental Concept for Evaluation Criterion of Clamping Force Level for Prevention to Loosening Failure

As mentioned above, for the judgment of self-loosening, relative evaluation (comparison) of locking devices and methods is performed using the Junker-style test equipment shown in Figure 1. As shown in Figure 10, the locking effect is evaluated by this loosening test machine for an eccentric nut and a normal nut. Eccentric nuts have good performance in the prevention of loosening. Figure 11 shows the result of a loosening test for a normal nut. A normal nut maintains most of the clamping force for a certain period.

When presenting this kind of test result, the vertical axis shows the residual clamping force (residual axial tension) in many cases. Figures 10 and 11 show that catastrophic loosening takes place for a normal nut, and this transition point should never be reached during actual machine operation. Then, the loosening of bolted joints is classified into the initial loosening region 0, gradual loosening region 1, and catastrophic loosening region 2 as shown in Figure 12. Locking devices and methods for bolted joints of actual machines should only be used up to loosening region 1. The next topic in investigation of loosening should be to determine the characteristics of the transition point shown in Figure 12. A permissible rate of decrease in the clamping force with respect to time (distance travelled or the number of operations) from the initial clamping force should also be determined.

**FIGURE 10** Results of loosening test at two types nut

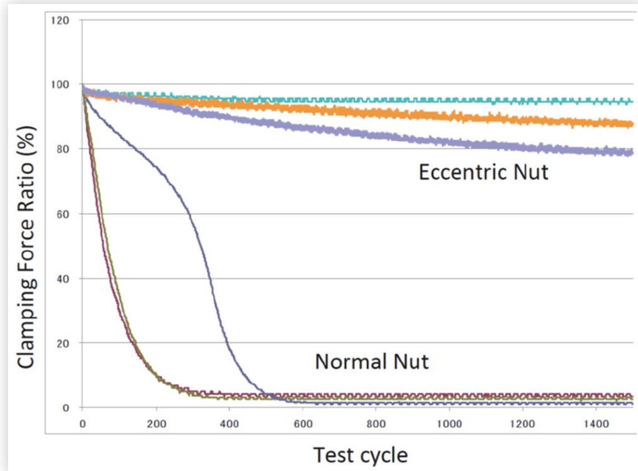





**FIGURE 11** One of the results of loosening test at normal type nut

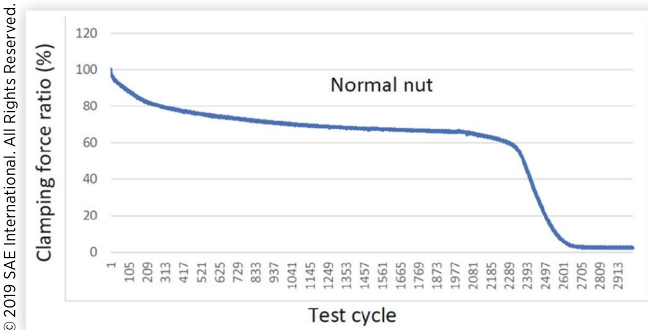


**FIGURE 12** Typical loosening diagram

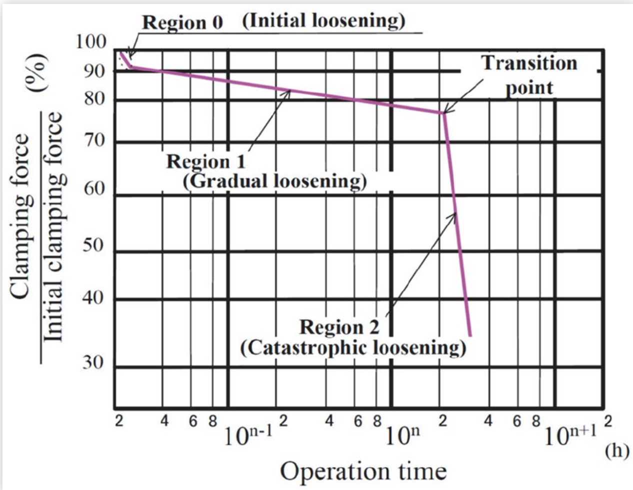
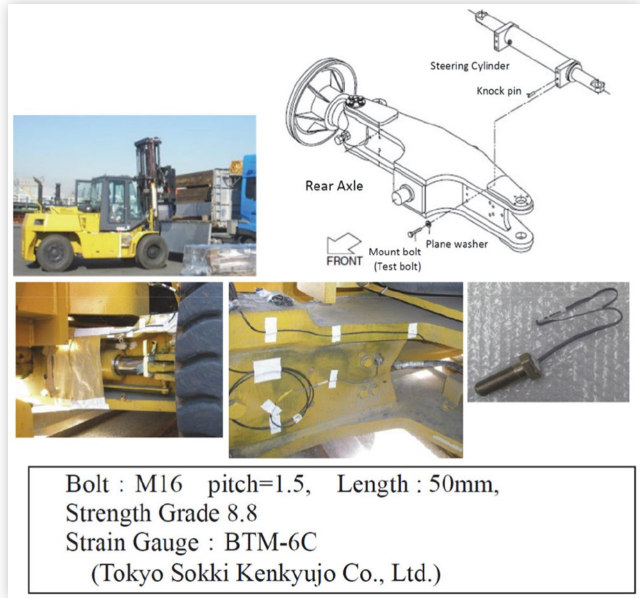





**FIGURE 13** Test fork-lift axle and test bolt specification [5]






# Observation of Loosening Behavior [5]

Observation of loosening phenomenon is conducted as the depression-type loosening as machine is stopped and working-load-type loosening as machine is in operation. The depression-type loosening is caused by the initial loosening, the permanent deformation of the sealing material, the excessive external force, and the thermal cause when the bolted joints is not subjected to any external force. On the other hand, working-load-type loosening is regarded as loosening that occurs when an external force such as a circumferential direction of the bolt axis, a direction perpendicular to the axis, and an axial direction is applied to the bolted joint.

## Test Machine and Initial Clamping Condition

The loosening tendency of a bolted joint used in a machine is measured at the actual operation site. Figure 13 shows test machine, test axle component, test bolted joints, and bolt specification. Test machine is the industrial vehicle (a large forklift truck with 16-ton stacking capacity) used in a loosening measurement at a customer's site. The forklift truck has cylinder mount bolts for steering, which are subjected to a repeated external force in the direction of the bolt axis during operation. Test bolts are shown in the schematic diagram in the figure. Since a knock (dowel) pin is used, the pin is subjected to an external transverse force. The axial force and bending moment mainly act on the test bolts. It is important to investigate the loosening phenomenon for every load situation. The issues are the theme of the research in the following study. In this paper, we observe the tendency of the clamping force of the test bolts to decrease (loosening behavior). This tendency is measured by a strain gauge (bolt gauge) attached to the axis passing through the center of the bolt as shown in Figure 13.

One test bolt is tightened by machine oil lubrication. Another one is tightened by anaerobic adhesive. The test bolts are tightened with the predetermined tightening torque shown in Table 2. The table also shows the tightening conditions and initial clamping force (tension).

**TABLE 2** Tightening condition [5]

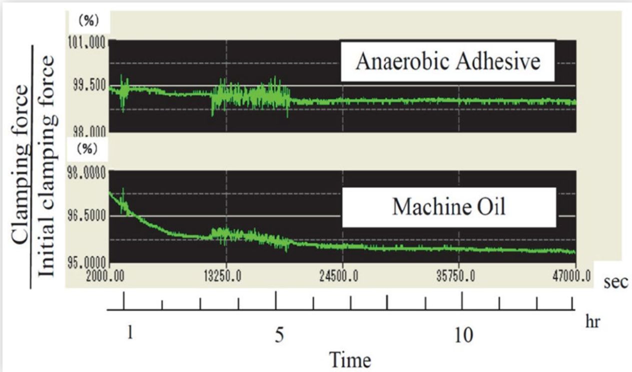
| Tightening method | Calibrated wrench method | |
|---|---|---|
| Tightening condition (Lubrication) | Anaerobic adhesive (LOCTITE #262) | Machine oil (Equivalent to ISO Viscosity Grade 46) |
| Tightening torque (Nm) | 268 | 233 |
| Initial clamping force (kN) | 55.2 | 63.6 |



## Waveform of Decrease Tendency of Clamping force (Loosening Phenomenon) in Depression type Loosening

Clamping force decrease tendency of the test bolts as loosening phenomenon is measured from the initial stage of tightening work in the factory to the transportation to a customer's site. Figure 14 shows the phenomenon in early stages of self-loosening. As an early phenomenon, the clamping force decrease tendency is measured from about 18 minutes after test bolt tightening for 13 hours. Although the relatively large clamping force decrease in about several percent of initial clamping force is observed in the early stages of tightening, it is a gradual decrease tendency after that. After tightening, the truckload work of the test forklift is done and the oscillatory waveform is observed about 1 hour later. And the oscillatory waveform while being conveyed on the track is also observed about from 3 h to 6 h.

**FIGURE 14** Early stage of depression type loosening (Linear coordinates) [5]






# Waveform of Decrease Tendency of Clamping force in External Working Load Type Loosening

Figure 15 shows the observation data in the morning (AM) and afternoon (PM) for the continuous loosening phenomenon of the bolt clamping force ratio *R* from bolt tightening to the end of actual machine operation at the customer's site. Observation of decrease tendency of initial clamping force is conducted through three days. The lapsed time is also shown in the figure. The total time from the initial tightening is 86.5 h. The waveform in the upper row is a working waveform of the clamping force of test bolt tightened by anaerobic adhesive and the lower is that of a test bolt tightened by lubrication tightening. The vertical axis with a linear scale shows the clamping force normalized by initial value. Both waveforms show all the data during the operation of the test forklift truck, and the total net number of operation (working) hours is about 15.5 h. The data from the nighttime when the machine was not in operation are omitted. The clamping force of the bolt repeatedly fluctuates when subjected to an external force. The first and last plotted points show the clamping force ratio when the machine has been stopped on a flat road and are measured by the test staff before and after the operation, respectively.

In Figure 16, shock-induced loosening (an abrupt decrease in clamping force decrease) can be observed at several places in the waveform. Figure 16 is an enlarged view of part of Figure 15. Typical shock-induced loosening occurred in the ellipse in the figure. The waveform captures the state in which the clamping force of the bolt markedly fluctuates in the case of lubrication tightening. In particular, a bolt axis receives an impact load, and the clamping force changes momentarily. The bolt nut is considered to rotate momentarily in the direction in which it loosens by an amount depending on the impact load. On the other hand, in the case of the anaerobic adhesive tightening (LOCTITE #262), although there is a momentary decrease in clamping force, it immediately recovers to its previous value.

Figure 17 shows the clamping force during the entire waveform in Figure 15 including periods when the machine is stopped between operations. Because the operator used the

**FIGURE 15** Actual analog data of working load type loosening (Linear coordinates) [5]

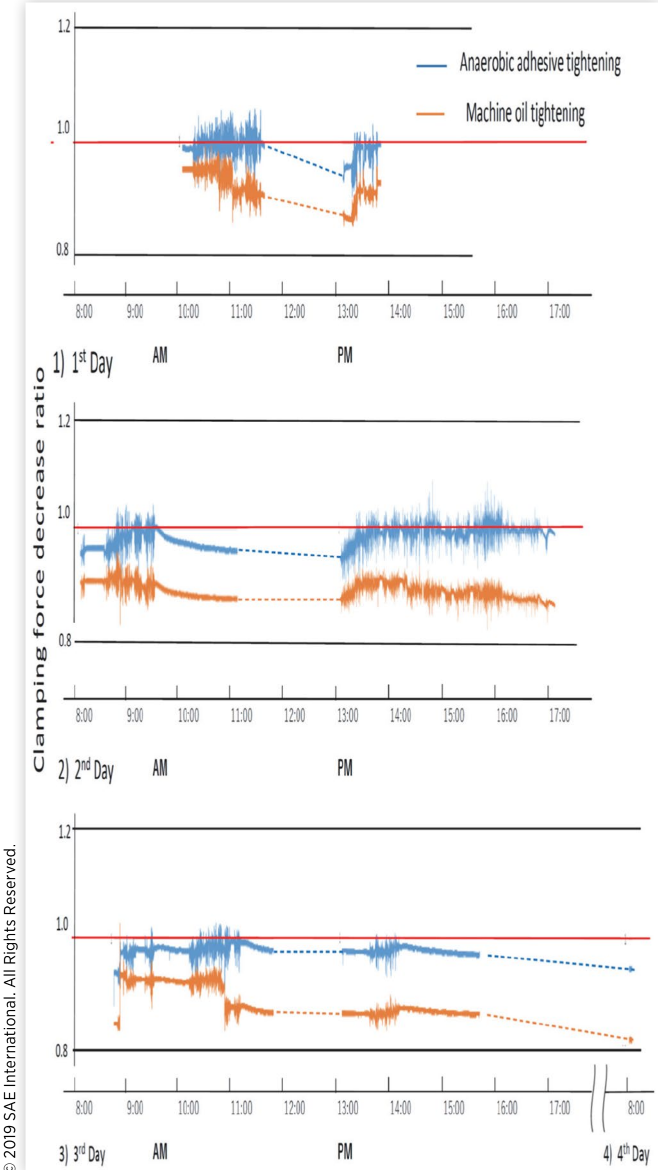





**FIGURE 16** Enlargement of impact waveform (Linear coordinates) [5]

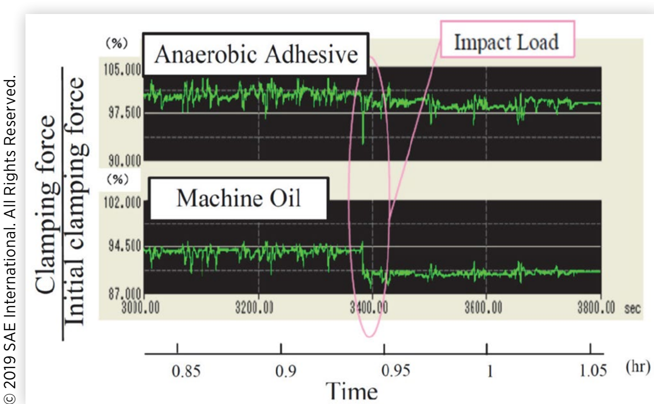
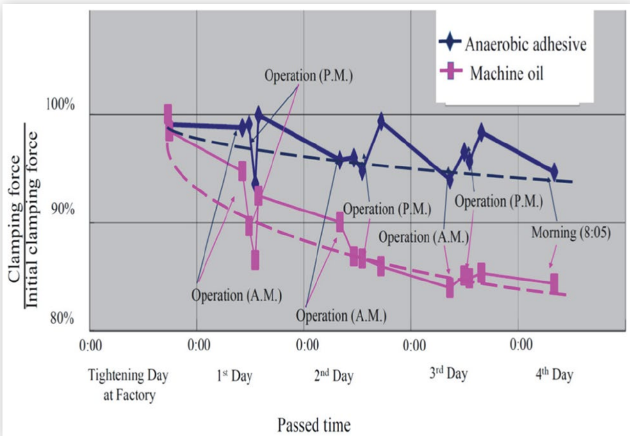


**FIGURE 17** Outline of whole waveform (Linear coordinates)






test forklift truck freely, the clamping force waveform appears to vary greatly. The first point plotted in Figure 17 is the clamping force ratio of the vehicle at rest the night before the start of a test. Other points show the clamping force ratio before the start of vehicle operation in the morning and afternoon. The final point shows the clamping force ratio of the vehicle at rest on a flat road at the end of its operation of the fourth morning time after the vehicle has cooled.

# Residual Clamping Force Estimation

Estimation of residual clamping force is analyzed as the depression-type loosening as static loosening and working-load-type loosening as dynamic loosening.

## Estimation of Residual Clamping Force for Depression Type Loosening(static)

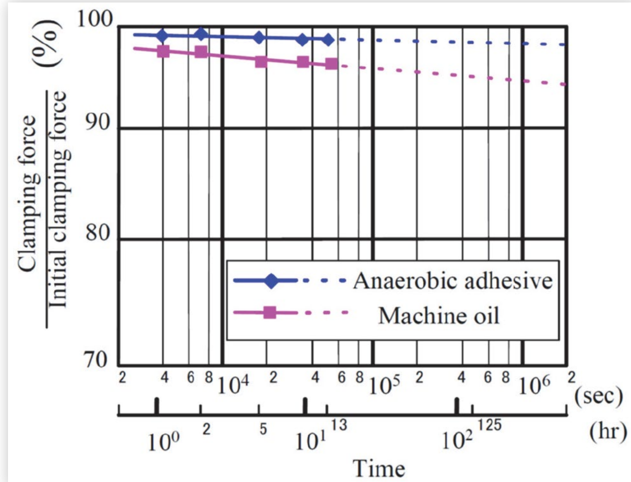
Figure 18 shows the depression type loosening waveforms (Figure 14) plotted for about 13 h on log-log axes and the extrapolation of the results. The center value of the oscillatory waveform during conveyance is plotted. These data do not include the actual work of the forklift, and it can be concluded that the data mainly capture the depression-type loosening. The observation result also shows a strong linear relation on logarithmic axes, which may be sufficient for lifetime prediction. The diagram in Figure 18 can be expressed by the following regression equation.

$$\log r = a + b \times \log h \tag{3}$$

If this equation is applied to the result in Figure 18, Equation (4) will be obtained for anaerobic adhesive tightening and Equation (5) will be obtained for machine oil lubrication tightening.

$$1000 \times \log r = 1996 - 0.571 \times \log h \tag{4}$$

**FIGURE 18** Prediction of depression type loosening (Logarithmic coordinates)





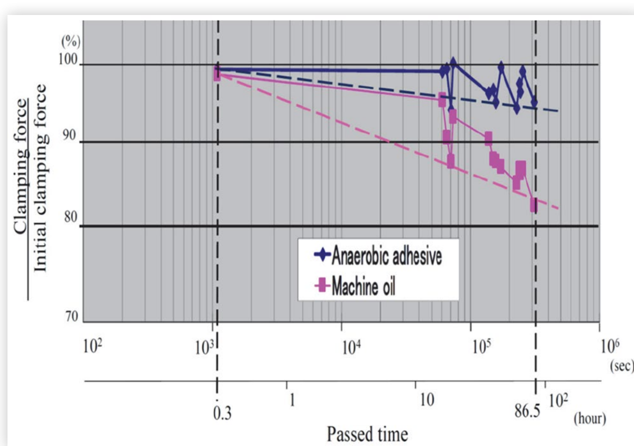

$$1000 \times \log r = 1989 - 9.137 \times \log h \tag{5}$$

These two regression equations can be used as formulas for depression-type loosening.

## Estimation of Residual Clamping Force for Working Load Type Loosening (Dynamic)

Figure 19 shows the waveform in Figure 17 plotted on log-log axes. Several points do not lie on the straight line because of the influence of the road surface, the stop posture, and so forth. However, these points almost lie on the regression line. We judge that the waveform is linear, that is, the relation when plotted on logarithmic axes becomes strongly linear in general, similarly to in our previous studies [5,6,7]. The following

**FIGURE 19** Outline of whole waveform (Logarithmic coordinates)



regression equation shows the relation for working-load-type loosening.

$$\log R = A + B \times \log H \tag{6}$$

Equation (6) is used when the number of operation hours is represented on the horizontal axis as in this example. When distance travelled is represented on the horizontal axis, such as for an automobile, Equation (7) can be used, and when the number of operations is represented on the horizontal axis, which is convenient for construction machines, Equation (8) can be used.

$$\log R = A + B \times \log L \tag{7}$$

$$\log R = A + B \times \log N \tag{8}$$

When the coefficients of the regression lines in Figure 19 are obtained from Equation (8), Equation (9) for anaerobic adhesive tightening and Equation (10) for lubrication tightening are as follows.

$$1000 \times \log R = 1992 - 8.135 \times \log H \tag{9}$$

$$1000 \times \log R = 1980 - 27.72 \times \log H \tag{10}$$

## Estimation of Residual Clamping Force

Such a regression formula is used to estimate the residual clamping force for locking devices (parts) and methods. Table 3 shows the calculation conditions used in the estimation. Since the test machine is a large forklift truck, the operation cycle time is set to a longer value than the standard value. As shown in Table 4, the calculations are performed to obtain the point estimates of the residual clamping force rate after one month, one year, five years, and ten years. The relationship between the number of operations N and the elapsed operation time H is H=N/30. By substituting this relationship in Equations (9) and (10), the residual clamping force is obtained as a function of the operation time.

Table 4 shows the residual clamping force calculated with Equations (9) and (10). The clamping force is maintained at about 78% of the initial clamping force after one year in the case of lubrication tightening. Even after ten years, it is estimated that the clamping force remains as high as 73% of the initial clamping force. On the other hand, the clamping force is maintained at about 92% of the initial clamping force after one year in the case anaerobic adhesive tightening and is about 91% after ten years. Table 4 also shows the estimated residual clamping force for depression-type loosening using Equations (4) and (5). Later in this study, we discuss the basis for evaluating the extent to which the residual clamping force should be allowed to decrease. Finally, the estimated residual clamping force is shown in Figure 20. The working load type loosening include depression type loosening.

Here w is the operation time ratio and is calculated as shown below

$$\begin{aligned} w &= (\text{operation time})/(\text{elapsed time}) \\ &= 1{,}800/(365 \times 24) = 0.205 \end{aligned} \tag{11}$$

**TABLE 3** Trial calculation conditions for the presumption [5]

| Prediction Condition Items | Prediction Condition (Time) | Prediction Condition (Number) |
|---|---|---|
| Cycle Time of 1 Operation | 120(Sec) | 1 (Cycle) |
| Operation Times / Day | 6 (Hour) | 180 (Cycle) |
| Operation Days / Month | 25 (Days) | 4, 500 (Cycle) |
| Operations / Month | 150 (Hour) | 4, 500 (Cycle) |
| Operations / 1 Year | 1, 800 (Hour) | 54, 000 (Cycle) |
| Operations / 5 Years | 9, 000 (Hour) | 270, 000 (Cycle) |
| Operations /10 Years | 18, 000 (Hour) | 540, 000 (Cycle) |



**FIGURE 20** Prediction of working load type loosening with depression type loosening (Logarithmic coordinates)

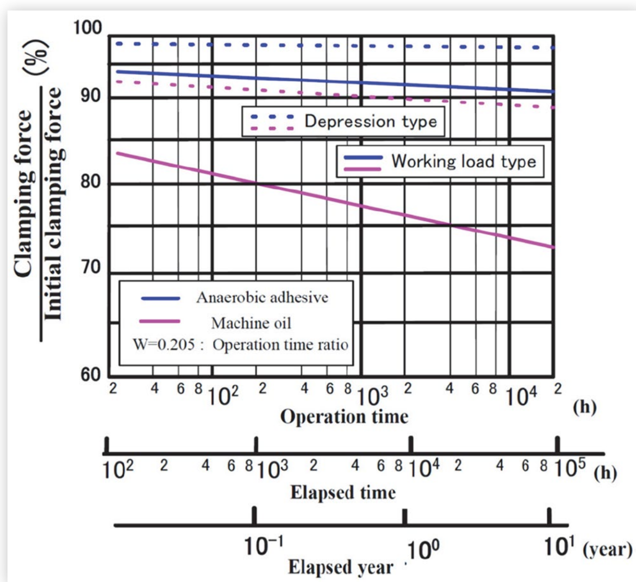





**TABLE 4** Estimation of residual clamping force [5]

| Estimation interval | Operations time (hour) | Working load type Residual clamping force R (%) Machine oil | Working load type Residual clamping force R (%) Anaerobic adhesive | Depression type Residual clamping force R (%) Machine oil | Depression type Residual clamping force R (%) Anaerobic adhesive |
|---|---|---|---|---|---|
| 1 Month | 150 | 83.1 | 94.2 | 93.1 | 98.7 |
| 1 Year | 1,800 | 77.6 | 92.4 | 91 | 98.6 |
| 5 Year | 9,000 | 74.2 | 91.2 | 89.7 | 98.5 |
| 10 Year | 18,000 | 72.8 | 90.7 | 89.1 | 98.4 |

And the actual operation time ratio w' is

$$w' = 0.179(15.5\,h/86.5\,h) \tag{12}$$

Equations (11) and (12) indicate the relationship between the test time (data measurement time) and the elapsed time, and are generally called the operation rate. Figure 20 and Figure 22 also show the elapsed time considering this operation rate.

## Lifetime Prediction to Loosening Failure

Start time of loosening observation (*T1*=0.3h) and finish time of loosening observation (*Tt* =86.5h) are shown in Figure 19. Then predicted lifetime to loosening failure is obtained by Equation (2) and data table in Table 5. Table 6 is the calculation results of predicted lifetime by Equation (2). Figure 21 illustrate the results of Table 6. Anaerobic adhesive has good performance to prevention of loosening than oil lubrication tightening.

**TABLE 5** Data table for lifetime prediction to loosening failure [5]

| Event | Time (hr) | Item | Anaerobic adhesive | Machine oil |
|---|---|---|---|---|
| Initial tightening time $T_0$ | 0 | Clamping force (kN) | 55.16 | 63.56 |
| | | Residual clamping force ratio (%) | 100 | 100 |
| | | Lost clamping force ratio (%) | 0 | 0 |
| Observation start time $T_1$ | 0.3 | Clamping force (kN) | 54.64 | 62.57 |
| | | Residual clamping force ratio $R_1$ (%) | 99.06 | 98.44 |
| | | Lost clamping force ratio (%) | 0.94 | 1.56 |
| Observation finish time $T_t$ | 86.5 | Clamping force (kN) | 52.22 | 53.63 |
| | | Residual clamping force ratio *Rt* (%) | 94.67 | 84.38 |
| | | Lost clamping force ratio (%) | 5.33 | 15.62 |



**FIGURE 21** Lifetime prediction graph to loosening failure (Logarithmic coordinates)

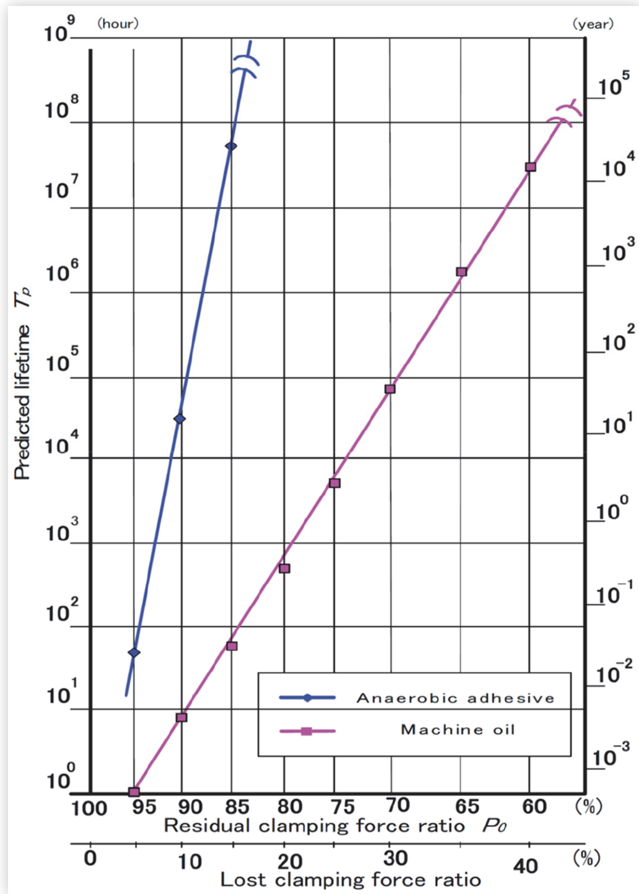





**TABLE 6** Results of lifetime prediction to loosening failure

| Tightening Method | | Anaerobic Adhesive | | | | | Machine Oil | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Residual Clamping Force Ratio *P0* (%) | Lost Clamping Force Ratio (%) | *log(P0)* | *log(T'p)* | *T'p* *(hr)* | Elapsed Time w=0.205 *(hr)* | Elapsed Year w=0.205 *(year)* | *log(P0)* | *log(T'p)* | *T'p* *(hr)* | Elapsed Time w=0.205 *(hr)* | Elapsed Year w=0.205 *(year)* |
| 95 | 5 | 1.978 | 1.748 | 56 | 273 | 0.0312 | 1.978 | 0.045 | 1 | 5.4 | 0.0006 |
| 90 | 10 | 1.954 | 4.682 | 48117 | 234719 | 26.79 | 1.954 | 0.908 | 8 | 39.5 | 0.0045 |
| 85 | 15 | 1.929 | 7.784 | 6.08E+07 | 2.97E+08 | 33878 | 1.929 | 1.820 | 66 | 322.4 | 0.0368 |
| 80 | 20 | 1.903 | 11.074 | 1.19E+11 | 5.79E+11 | 6.61E+07 | 1.903 | 2.788 | 613 | 2992.7 | 0.34 |
| 75 | 25 | 1.875 | 14.577 | 3.77E+14 | 1.84E+15 | 2.10E+11 | 1.875 | 3.818 | 6575 | 32075.3 | 3.66 |
| 70 | 30 | 1.845 | 18.321 | 2.09E+18 | 1.02E+19 | 1.17E+15 | 1.845 | 4.919 | 83011 | 404932.2 | 46.2 |
| 65 | 35 | 1.813 | 22.342 | 220E+22 | 1.07E+23 | 1.22E+19 | 1.813 | 6.102 | 1.26E+06 | 6.17E+06 | 704 |
| 60 | 40 | 1.778 | 26.686 | 4.85E+26 | 2.37E+27 | 2.70E+23 | 1.778 | 7.380 | 2.40E+07 | 1.17E+08 | 13345 |

## Design Basis of Evaluation Criterion of Clamping Force Level for Prevention to Loosening Failure

In this study, as a first proposal, it shows the estimation method of residual clamping force and also the lifetime prediction method for loosening failure of bolted joints during the actual machine operation. For the measurement of loosening tendency, there is a need for more accurate measurements in various machines. Besides that, for the present study there are still needs more precise investigations to be some resolution. One of them is the establishment of evaluation criterion of clamping force level for prevention to loosening failure (such as the criteria on the design basis). In addition, the fundamental study of loosening phenomenon is also important.

About the criterion of the clamping force level for prevention to loosening failure, there is a description in guidebook [20]. The guidebook shows the judgment criteria based on the stair-case method of the loosening test result in an axis-perpendicular angular vibration loosening tester as shown in Figure 1. It is judged that if the decrease in axial force at the time of 100 cycles elapses is 10% or less, it will not be loosened, if it is bigger than 10% to less than 30%, it will be intermediate (suspension) and if it is 30% or more, it will be loosened. It is unknown whether this criterion can be applicable to a criterion of the loosening of bolted joints in actual machine at present, but seems to be at least available for a benchmark.

In bolted joints used in actual machine, it is important to know the level of this transition point as shown in Figure 12. It seems that the criterion of the aforementioned guide book [20] can be regarded as this transition point. Figure 22 shows this in conformity with the results of Figure 20 or Figure 21. In addition, in Figure 22, the actual operation time and the elapsed time are shown on the horizontal axis considering that the actual operation rate was 0.205 in consideration of the end of work at night. It is a conclusion that the anaerobic adhesive is convincingly supporting that it is an effective loosening prevention. Machine oil lubrication tightening is in the zone where the estimated clamping force value after 10 years is intermediate (suspension). This type of product seems to corroborate that some effective loosening prevention is required. As mentioned above in Figure 12, how to know the transition point before catastrophic loosening is important.

Kasei [19] describes the evaluation of the loosening for external force. The lower clamping condition of the clamping force is to prevent the sliding of the bearing surface and it is necessary to satisfy the Equation (13).

$$Wl < \mu csFf \quad (13)$$

Here, Wl: Load in the direction perpendicular to the bolt axis,
μcs: Coefficient of friction of the bearing surface,
Ff: Axial force

As for the upper limit, the bearing surface pressure is assumed to be less than the critical surface pressure as shown in equation (14). Here, it is considered that the value of (0.8σyAs) takes an axial force value.

$$Pw = 0.8\sigma yAs / Ab <= PL \quad (14)$$

Here,
Pw: Bearing surface pressure,
σy: Lower yield point or yield strength,
As: Effective cross section area,
Ab: Bearing surface area,
PL: Limit Bearing surface pressure

Table 7 shows the results of evaluations the residual clamping force estimation results in Table 4. Regarding the upper limit surface pressure, it is in the safe region since it is lower than the marginal surface pressure (333.5 MPa) of mild steel [23] from the beginning of tightening. On the other hand, the lower limit frictional force was determined as μcs=0.13. As shown in Figure 13, the steering cylinder of the rear axle is responsible for the force in the direction perpendicular to



**FIGURE 22** Evaluation criterion of clamping force level for prevention to loosening failure at working load type loosening (Logarithmic coordinates)

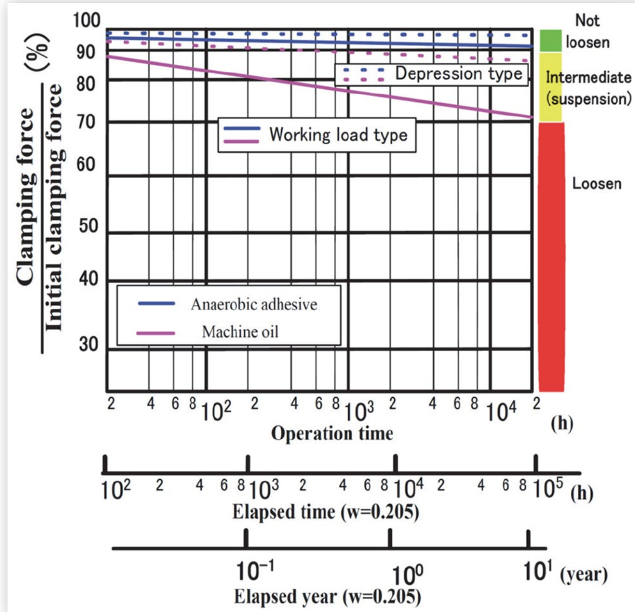





**TABLE 7** Evaluation results of residual clamping force at working load type

| Estimation interval | Anaerobic adhesive Ff (kN) | Pw (MPa) | μ cs Ff (kN) | Machine oil Ff (kN) | Pw (MPa) | μ cs Ff (kN) |
|---|---|---|---|---|---|---|
| Initial | 55.2 | 246 | 7.2 | 63.6 | 284 | 8.3 |
| 1 Month | 52.0 | 232 | 6.8 | 52.9 | 236 | 6.9 |
| 1 Year | 51.0 | 228 | 6.6 | 49.4 | 221 | 6.4 |
| 5 Year | 50.3 | 225 | 6.5 | 47.2 | 211 | 6.1 |
| 10 Year | 50.1 | 224 | 6.5 | 46.3 | 207 | 6.0 |
| Limit | | 333.5 | | | 333.5 | |

the axis by two knock pins, and the bolt is structured not to receive the force in the direction perpendicular to the axis at the time of changing. Therefore, basically, it is judged that the lower limit is also on the safe side in this case.

## Summary/Conclusions

In evaluation for the performance of locking devices (parts) and method, absolute evaluation is indispensable. In this paper, the research and examination are performed from this viewpoint. The knowledge acquired by this research is arranged below.

1. This paper presents a method for estimating the absolute lock effect in bolted joints during actual machine operation.
2. Loosening phenomenon of bolted joint is divided into a depression type (static) and working load type loosening (dynamic).
3. The loosening phenomenon of bolted joint is grasped with the decrease tendency of the initial clamping force or residual clamping force.
4. The loosening phenomenon is a strong linear relation on logarithmic coordinates (log-log paper) between residual clamping force (measured clamping force / initial clamping force) and number of operations (or working time or distance travelled) since last tightening.
5. Based on this relation, we show the method of lifetime prediction to loosening failure on bolted joints.
6. Also based on this relation and observation of loosening in the early stages of product development, we estimate the rate of residual clamping force (self-loosening level) accurately after prolonged operation by measuring the initial clamping force behavior by using the proposed regression equation.
7. The trial calculation of the residual clamping force after prolonged operation is made using the data of the industrial vehicle (stacking capacity 16 ton large-sized forklift-truck) at customer's site by loosening measurement.
8. Using only few days' data, it is presumed that the initial clamping force is maintained to 90% or more in case of anaerobic adhesive tightening and almost 73% in case of lubrication tightening after ten years.
9. We describe the evaluation criterion of clamping force level for prevention to loosening failure. The lower and upper clamping condition are assumed.

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