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A Proposal for the Absolute Estimation Method on Self-loosening of Bolted Joints during Off-road Vehicle Operation

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ABSTRACT: This paper presents a method for estimating the absolute lock effect in bolted joints during off-road vehicle operation. There is a good linear relation between axial tension decrease tendency (Loosening phenomenon) and the operation time (or mileage or number of operations) after the tightening on logarithmic coordinates. Based on this relation, this report leads to two estimating methods described below.

1) Decrease of axial tension (self-loosening) is estimated accurately after long hours since tightening by measuring the initial axial tension behavior using the bolt loosening evaluation diagram.

2) Method of Estimating the locking device availability (usefulness) on actual machine operation is obtained from laboratory loosening test results.

KEY WORDS: (Standardized) materials, test/evaluation, fatigue, design/prototyping (Free) joining, fixing element, bolted joint, self loosening, absolute loosening estimation, locking effect, locking method/device, bolt axial tension, off-road vehicle [D3]

1. Introduction

Bolted joint (screw thread) is used in many industrial commodities, such as cars, construction machinery, industrial trucks, general machinery, electrical machinery and electric devices, airplanes, and plant equipment, and has played an important role as the machine part. The spiral function was utilized in pumping technology and dyeing technology back in 6-4th century B.C.. And the pursuit of a screw principle had also started. In spite of its over 2000 years' long history as the machine element, troubles such as poor bolting, self-loosening, and insufficient strength occur even today.

Why does the bolted joints(screw) trouble still occur?

Why does it continue to be considered machine parts requiring special attention?

Because it has problems as shown below.

(1) It is always used at high stress. It is subjected to vibration and repeated external force.
(2) Although high initial axial tension is needed, there is no simple tool. Therefore, calibrated wrench method must be used in general.
(3) There are many kinds (coarse / fine screw thread, strength grade classification, etc.).
(4) Breakage of screw threads and damage through defomation (cross-sectional reduction) may be caused by tightening work.
(5) High stress concentration areas exist in the underhead fillet part and a threaded portion, etc.
(6) Fatigue breakage, hydrogen embrittlment, etc. occur during machine operation.
(7) Self-loosening easily occurs due to the spiral shape and is influenced by depression of bearing surface.
(8) Many bolted joints are used in one product.

This report particularly deals with the self-loosening of a bolted joint. The optimum tightening condition of bolted joint used in machines is defined as the state in which it is tightened with high axial tension sufficient to be free from breakage and loosening by any external force during machine operation[(1)].

The main troubles with bolts are fatigue fracture and self-loosening, and their cause is design error or insufficient tightening as shown in Junker's Road Map[(2)] (Failure mechanism of dynamically loaded bolted joints). There are various concrete case reports on the accident of bolted joints such as fatigue breakage of a hub bolt[(3)] , accident in an elevator[(4)] , and hydrogen embrittlement of a high strength bolt [(5)] .

The bolt troubles are classified by Ohashi and et al[(6)] in the guidebook on bolted joints. According to their investigation in Japan in 1977, 43% of troubles is caused by poor bolting, 20% by self-loosening, 12% by fatigue, and 4% by delay destruction due to hydrogen embrittlement, etc.. This report also shows that the review on fatigue strength and self-loosening is essential for reliability assessment of bolted joint in machine during operation.

In this report ,the absolute estimation method of self-loosening for the locking device of bolted joint is proposed. Our basic question is "Until how many tens of thousands of kilometers run does the locking device (method) keep from becoming loose?" for example. The availability (usefulness) of locking device (method) is positively verified through the examples of application to static and dynamic self-loosening in off-road vehicles that are construction machinery and industrial truck.

2. Self-loosening of Bolted Joints and its Absolute Estimation

2.1. Evaluation of self-loosening

There are many literatures or views and the elucidation of the self-loosening mechanism, etc. Especially, the research of Junker gives many suggestion on the mechanism and the laboratory loosening test method[7]. Many reports[7] ~ [13] describe the evaluation of a loosening test method and some locking devices, such as reports by Clark[9] and Hongo[10].

However, these estimation methods are just the evaluations on performance of locking devices in laboratory test. They enable qualitative evalution as well as relative comparion on loosening-preventive performance of locking parts(devices) quantitatively. Yet, they cannot perform absolute evaluation on whether the bolted joint makes specified performance and maintains its initial performance after lapse of certain period of time during actual machine operation. The absolute estimation method is indispensable for the evaluation of locking devices(parts) at actual machine running. Researches on this kind of absolute estimation method is not found other than the paper of authors[14] and the paper of Zhao and et al[15].

In this paper, loosening phenomenon in the actual machine is observed during long-term operation with the test equipment and test spot(customer's site). Aiming to establish the absolute evaluation standard, an evaluation diagram is proposed for absolute loosening estimation vs. relative loosening estimation.

This research does not deal with the principle of loosening of a screw (bolted joint) or the mechanism for cause of loosening. It deals with the evaluation of loosening when locking device (method) is used on the actual machine.

Until when does the locking effect continue?

Until when does it maintain the initial locking performance?

It aims at evaluation with the actual machine operation.

2.2. Grasp of Loosening Phenomenon

Figure 1 shows the result of measuring an axial tension decrease tendency of the hub bolt of the wheel loader under test operation. The loosening tendency of bolted joints happens significantly in early stages of operation, and the rate of decrease gradually becomes small. Figure 2 shows the plotting of these data on logarithmic coordinates(log-log paper), and data shows that it is in alignment with gradual decrease tendency and has a good linear relation[14]. These data are observed for about three days.

2.3. Observation of loosening phenomenon in bench test

Figure 3 shows fatigue testing equipment for the axle mount bolt of construction machinery (shovel loader). Figure 4 shows the specifications of a test bolt. Figure 5 shows the result of study using this testing equipment. The decrease of the bolt's initial axial tension is measured by the strain gauge attached to the shaft of test bolt.

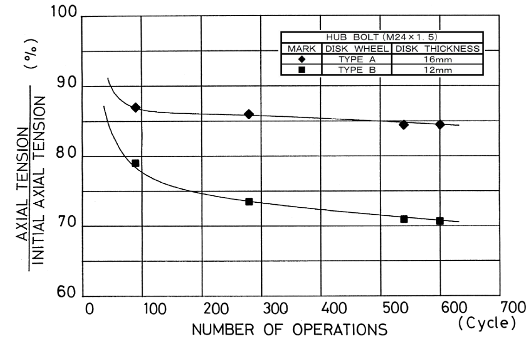


Fig. 1 Axial Tension Decrease Tendency of the Hub Bolt of the Wheel-loader(Linear Coordinates)

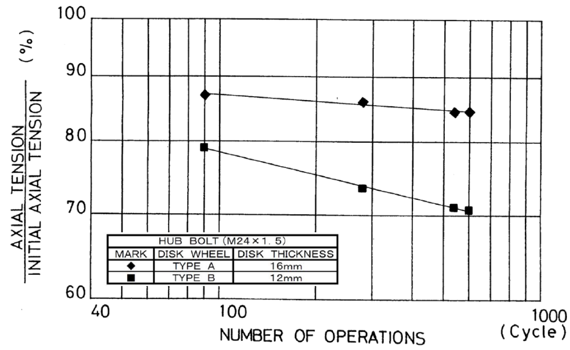


Fig. 2 Axial Tension Decrease Tendency about the Hub Bolt of the Wheel-loader(Logarithmic Coordinates)

Generation of inner power added to initial axial tension is observed through repeated load by the testing equipment. In particular, Figure 6 displays the measurement result of loosening of the depression type in early stages of bolting enlarged from Figure 5. The tendency for axial tension to decline significantly in early stages of bolting can be observed.

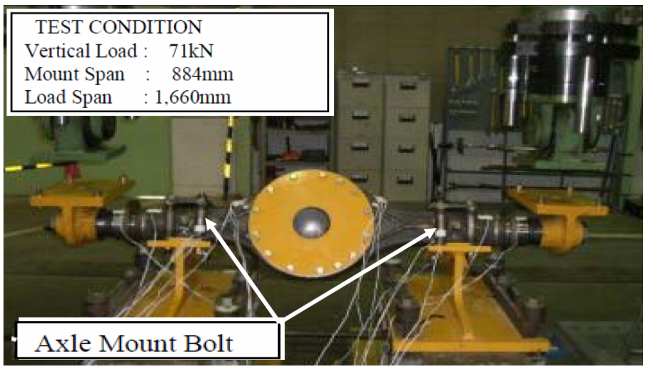


Fig.3 Fatigue test equipment of the axle mount bolt

Bolt : M20×1.5 Length : 230mm,
Grade 8.8
Strain Gauge : UFLA-2(Tokyo Sokki Kenkyujo CO.,LTD)

Fig.4 Specifications of a test bolt

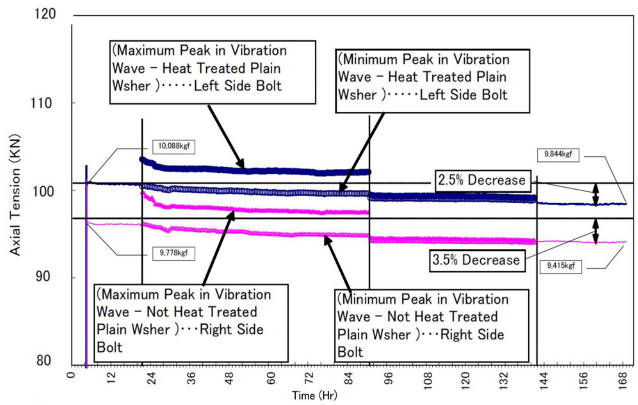


Fig.5 Decrease tendency of the initial axial tension of a bolt

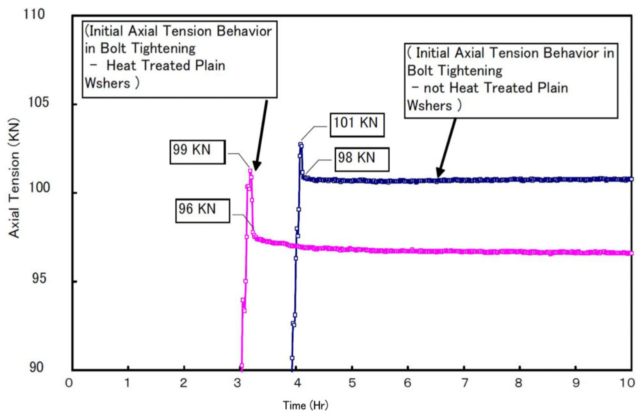


Fig.6 Result of loosening of the depression type in early stages of bolting

Among the waveforms in Figure 5, 20 - 90Hr is an axial tension change waveform under fatigue test operation, and it shows the maximum and the minimum peak values. Another waveform in Figure 5 is the gradually decreased type loosening when fatigue testing machine is stopped. Figure 7 is plotting of the whole waveform of Figure 5 on log-log paper, and it shows the good linear relation on the whole.

2.4. Observation of the loosening phenomenon in actual machine operation(customer's site)

The loosening tendency of the bolted joint used in machine is measured in the actual operation site. Figure 8 shows the industrial vehicle (stacking capacity 16 ton large-sized forklift-truck) used at customer's site loosening measurement. Figure 9 shows the setup state of a test bolt and its specifications.

There are cylinder mount bolts of the forklift-truck for steering , and receives the repeated external force in the direction of bolt axis at the time of operation. The test bolts are tightened with predetermined bolting torque. One is tightened with lubricant (machining oil, tightening torque 233N・m) and other one is tightened with the anaerobic adhesive (Loctite 262, tightening torque 268N・m).

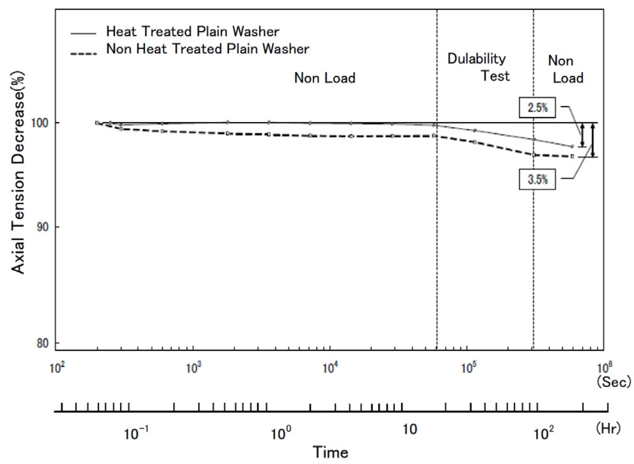


Fig.7 Loosening Behavior in Gradual Decrease (Logarithmic Coordinates)

Fig.8 Test Forklift-truck under Actual Operation in customer

Axial tension decrease tendency of test bolts is measured from the intial stage of bolting work in the factory to the transportation to a customer's site. The loosening phenomenon at the actual operation in the customer's site is continuously observed for about over one month, including the state such as self-running between customer's site and another site. The waveforms of Figure 10 show the continuous decrease tendency (loosening) of the bolt axial tension at the time of a series of above-mentioned operation. The figure is a part of result (for five days) measured with the linear scale for a long period of time at customer's site. The customer's operator use the test forklift-truck freely, and these waveforms are measured in free operation. Conditions are not demanded in particular to the operation. Therefore, when performing axial tension measurement, influences of many factors such as inclination of the road surface and the stop posture of the test machine are included.

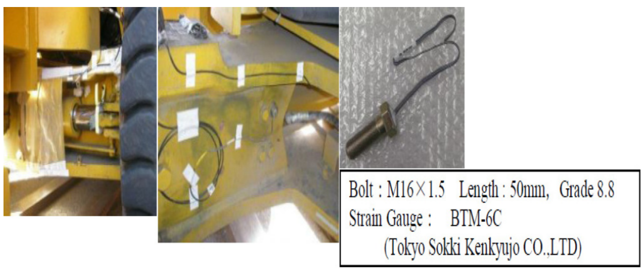


Fig.9 Test Fork-lift Axle and Test Bolt Specification

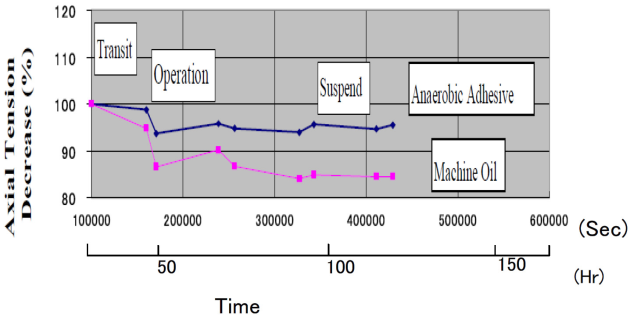


Fig.10 Loosening Behavior of Bolt Axial Tension

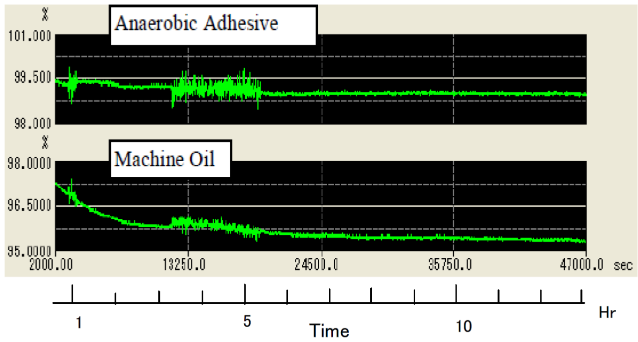


Fig.11 Axial Tension Behavior in Actual Machine Operation (Linear Coordinates)

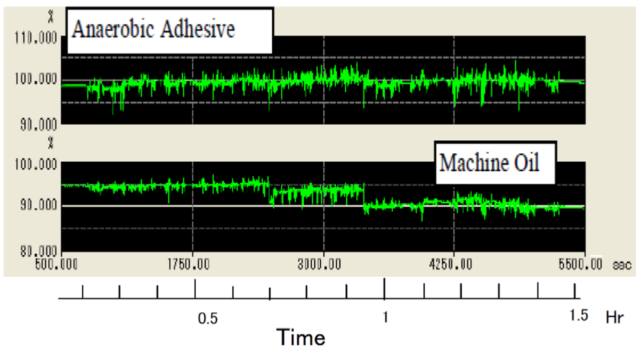


Fig. 12 Axial Tension Behavior in Actual Machine Operation (Linear Coordinates)

Figure 11 shows the observation result of the axial tension decrease tendency of the bolt in transit of the test forklift by a truck. As for bolt axial tension, a gradual decrease tendency is seen by the vibration from a road surface. Figure 12 shows the waveforms at the time of actual machine operation. Bolt axial tension makes repeated fluctuation to increase and decrease side by external force. Figure 13 captures the state in which bolt axial tension drastically fluctuates. In particular, impact load is received in a working waveform and axial tension is changing momentarily.

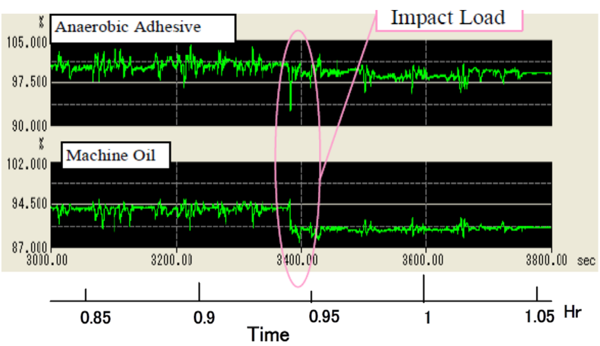


Fig.13 Axial Tension Behavior in Impact Load

2.5. Analysis and formulization of loosening phenomenon

The observation results are shown in Figures 11 - 13 for the loosening phenomenon of the bolt axial tension continuously from bolt tightening through the end of actual machine operation at customer's sites. Based on the result, the loosening of a bolted joint is classified as follows.

1) Static depression type loosening
2) Dynamic loosening by repeated load
3) Momentary loosening by impact load

In the loosening tendency of Figures 5, 6 and 10 - 13, these three kinds of loosening phenomena are observed. If the waveform of Figure 10 is expressed as a log-log scale, it becomes the graph as shown in Figure 14.

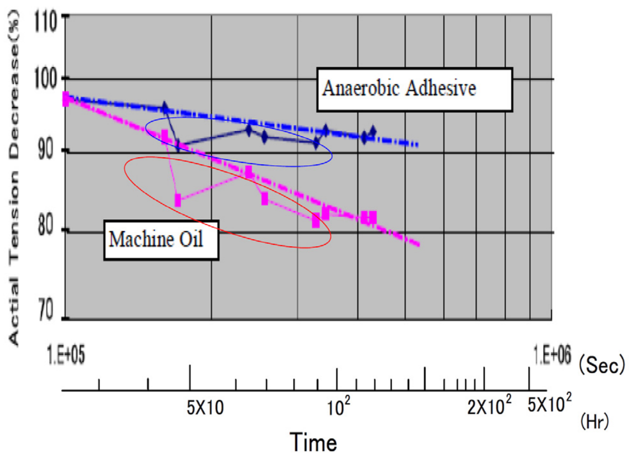


Fig.14 Loosening Behavior of Bolt Axtial Tension (Logarithmic Coordinates)

It looks that several points are not on linear line because of the road surface and the stop posture and so on. But these points are not over the line. So we judge the waveform is linear,that is the relation of this log-log scale turns into a good linear relation in general, which is same as the report of above-mentioned author.[14]

The linear relation figure shows a vertical axis with the decreasing rate of axial tension, and a horizontal axis with the mileage L in the case of automobiles, etc. In case of construction machinery or industrial vehicles, horizontal axis consists of the machine operation hours H, and in case of products (airplane and ship,etc.) evaluating by the number of times of use, the number of times N is available.

Each relation can be expressed in formula (1) - formula (3) respectively.

$\log R = A + B \times \log L$----- (1)

$\log R = A' + B' \times \log H$ ----- (2)

$\log R = A'' + B'' \times \log N$ ----- (3)

Here, L: Mileage(Km)
H: Operation Interval (hour)
N: Number of Operations (Cycle)
R: (Measured Axial Tension)/(Initial Axial Tension)
A, B, A', B',A",B": Constants

3. A Proposal for Absolute Estimation Method on bolted joints Loosening

From the result of the preceding chapter, the absolute estimation method of bolted joints loosening is proposed below.

3.1. Prediction for rate of axial tension decrease (loosening)

It can be concluded clearly from this report and author's previous one[14] that loosening phenomenon has a good linear relation in the logarithmic coordinates. From this relation and, the rate of the axial tension decrease (loosening) after prolonged operation can be predicted by observing the axial tension decrease tendency in early stages of the development phase. When the target durability life of the product(actual machine) is determined, the rate of the residual axial tension / initial axial tension is estimated by regression formula (1) - formula (3).

The trial calculation of the axial tension decrease tendency after prolonged operation is made using Figure 2 data.

Regression formula (4) is the prediction equation for TYPE A disk wheel by use of fomula (3). Formula (5) is for TYPE B disk wheel in the same way.

$$\log R = -0.0379 - 0.0127 \times \log N \cdots\cdots (4)$$

$$\log R = 0.0293 - 0.0652 \times \log N \cdots\cdots\cdots (5)$$

Table 1 shows the prediction condition. In consideration of work lost time etc., trial calculation could be cycle time 60 seconds. Table 2 shows the results of trial calculation. It is shown that the trial calculation value can predict the axial tension decrease tendency of ten years after(for example) by the data for only three days.

Table 1 Prediction Condition

Prediction Condition Items	Prediction Condition
Cycle Time of 1 Operation	60(Sec)
Operation Times / Day	5 (Hour)
Operation Days / Month	20 (Days)
Number of Operations N / Mounth	6, 000(Cycle)
Number of Operations N / 1 Year	72, 000(Cycle)
Number of Operations N / 2 Years	144, 000(Cycle)
Number of Operations N / 5 Years	360, 000(Cycle)
Number of Operations N / 10 Years	720, 000(Cycle)

Table 2 Results of Trial Calculation

Prediction Interbal	Number of Operations N(Cycle)	Prediction of Axial Tension Decrease R(%)	
		TYPE A	TYPE B
1 Mounth	6,000	82. 1	60. 7
1 Year	72,000	79. 2	51. 6
2 Year	144,000	78. 8	49. 3
5 Year	360,000	77. 6	46. 5
10 Year	720,000	76. 9	44. 4

Wheel loader works for 5 hours on a day, and works per month for 20 days. As shown in Table 2, the trial calculation of the point estimate of the axial tension decreasing rate one month after, one year after, two years after, five years after and ten years after is made. At TYPE A, axial tension keeps about 80% in one year. Even if ten year passes, it is presumed that initial axial tension is kept 75% or more. On the other hand, TYPE B will fall to about 50% to initial axial tension in one year and will fall to about 45% for ten years.

Here, evaluation of these prediction results is needed. The rate of the residual axial tension at the time of durability life serves as a judging standard of loosening of bolted joint.

An example of the judging standard diagram (Absolute Estimation Diagram) is shown in Figure 15. The judging standard should be uniquely determined according to the kind of product (automobile, construction machinery, hydrouric equipment and so on), the use purpose and location of a bolted joint, or the size of a product (machine), respectively.

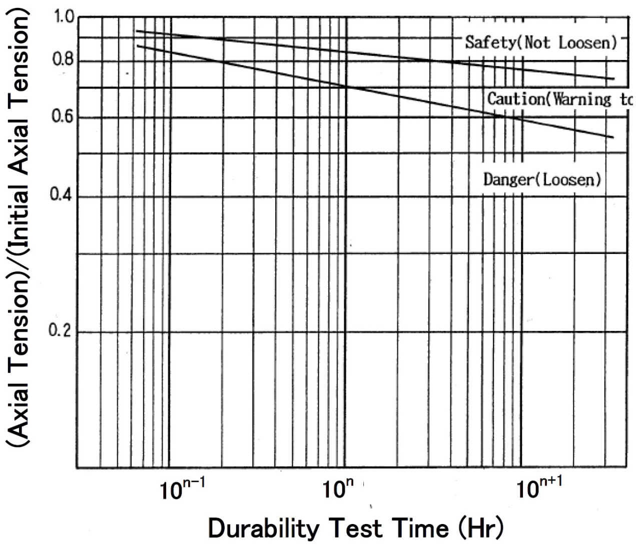
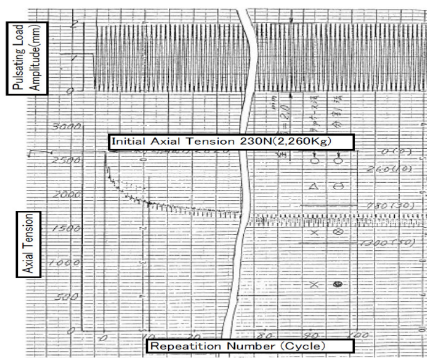


Fig. 15 Absolute Estimation Diagram for Self-Loosening

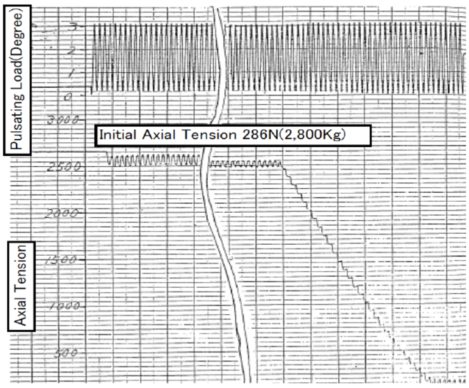
3.2. Consistency and relation of the loosening Phenomenon between loosening test machine (laboratory test) results and actual machine operation results

By the way, the loosening waveform as shown in Figure 16 is observed in the investigation of screw loosening using the loosening test machine; which it is conducted by the Japan Research Institute for Screw Threads and Fasteners(JFRI)[11]. Initial axial tension is considerably lost immediately after the test start as shown in the waveform of Figure 16(a) (Gradual Decrease Loosening), but loosening has stopped after that. On the other hand, Figure 16(b) (Catastrophic Loosening) shows that loosening has taken place catastrophically. It should never reach this catastrophic point (Transition Point) in self-loosening during actual machine operation. Then, the bolted joints loosening is classified into gradual decrease loosening region I and catastrophic loosening region II as shown in Figure 17. Because of this classification, locking device (method) in bolted joint should be allowed to use only in gradual decrease loosening region I. From these loosening test results, the next subject for loosening investigation is getting to know the characteristic of a transition point in the diagram shown in the figure 17, such as a decreasing rate for the mileage (or time, the number of times of operation, etc.) from initial axial tension.

Furthermore, it is important to get to know the relation of loosening with laboratory loosening test result and result of the actual machine operation. In other words, it is to clarify the relation between the load level in a bench test or a loosening testing machine, and the load level in the actual machine operation.



(a) Gradual Decrease Loosening



(b) Catastrophic Loosening

Fig. 16 Loosening Process from Loosening Testing Machine

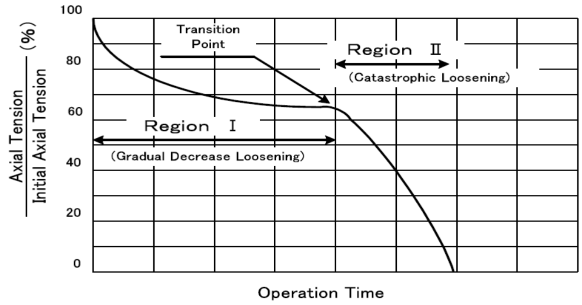


Fig.17 Example of Loosening Behavior at Laboratory Test

4. Discussion

This paper investigates the absolute evaluation method in bolted joint self-loosening and the locking device (method) availability to prevent loosening during the actual machine operation. The following descriptions are considerations for the action of the external force and the inner force, and screw(bolt) flanks action by the force in change.

4.1. Action of the inner force generated in a bolted joint by the external force(working load)

As shown in Figure 18, at the time of actual machine operation, a bolted joint is subjected to repeated tensile and compressive load from external force(working load). Thereby, also bolt axial tension is subjected to tensile and compressive load from additional intenal force to initial axial tension. On the other hand, in this time, also a clamping force in clamping member(material) is subjected to compressive and tensile load respectively to the initial axial tension. It is thought that self-loosening causes gradually by such internal force.

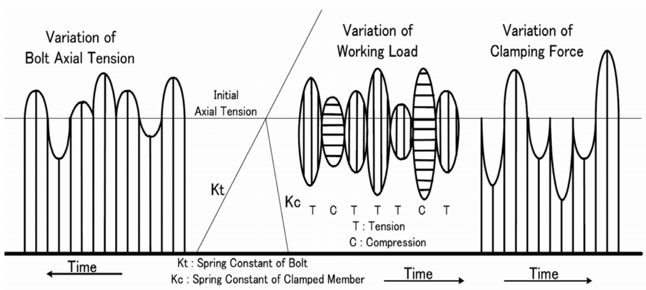


Fig.18 Typical Behavior of Working Load, Bolt Axial Tension and Clamping Force

4.2. Action of screw(bolt) flanks in impact load

When a working load variation is shocking, loss of bolt axial tension or loss of the residual compressive force of a clamping member(material) takes place momentarily.

What is happening at the screw flanks at this time? The typical case of lubrication by machine oil is shown in Figure 19. By external force, the screw thread flank is separated momentarily and the decrease in axial tension has taken place. Or, the vertical force or horizontal force which is added to a screw flank surface decreases, and then bolt and nut rotates relatively in a general understanding.

Also decrease in bolt axial tension takes place momentarily, when the screw thread flank is adhered with the anaerobic adhesive, etc. However, axial tension returns after that, and it is thought that relative rotation of a bolt and a nut does not take place by the effect of adhesive. Figure 20 shows this phenomenon typically.

As for the adhesive waveform result of Figure 13, no axial tension decrease is observed, even after receiving impact load. A certain amount of loss of axial tension is observed momentarily, but it returns to original level.

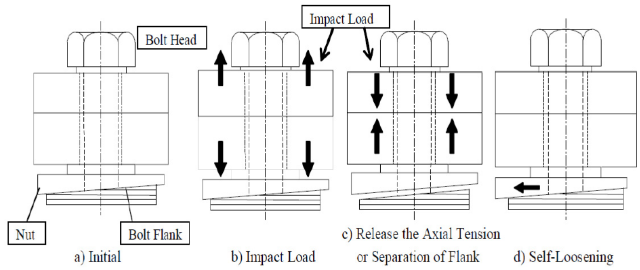


Fig.19 Schematic Illustration of Loosening Process On Screw Thread Flank

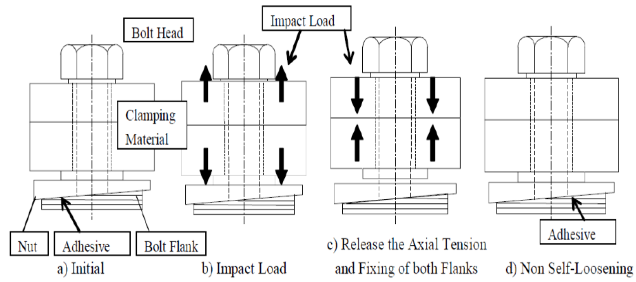


Fig. 20 Schematic Illustration of Anti-Loosening Process on Anaerbic Adhesive

5. Conclusion

In this report, the absolute estimation method of bolted joint self-loosening is proposed and the evaluation process is clarified. The essential points are summarized as follows.

1) Absolute estimation method

・Absolute estimation method for various kinds of locking devices (method) is proposed; "For how many tens of thousands of hours (mileages) can it really maintain the preventive performance ?" This absolute evaluation of the self-loosening with the actual machine is indispensable.

・There is a good linear relation between axial tension decrease tendency(Loosening phenomenon) and the operation time (or mileage or number of operations) after the tightening on logarithmic coordinates.

・Based on this relation in the development test in early stages of the actual machine, the method of presuming the rate of axial tension decrease (self-loosening) after prolonged use is shown by using the proposed regression formula.
・By trial calculation we show that the absolute estimation will be possible. Described in detail, we predict the rate of axial tension decrease after ten years (for example) from initial tightening using only three days data.
・The evaluation diagram shown in Figure 15 is proposed not for laboratory's relative evaluation test but as an absolute estimation method of an locking effect for bolted joints' self-loosening.

2) Possibility (locking device availability) to use the actual machine

・In some locking devices, the evaluation method which judges the possibility of application to the actual machine is shown.
・The application possibility (locking device availability) to the actual machine is judged from a laboratory loosening test result, it will be classified the two regions.

Region Ⅰ : Gradual Decreasing Loosening
Region Ⅱ : Catastrophic Loosening

It should be allowed to use only in Region Ⅰ at actual machine.

・While arranging the transition point of the loosening observed at the laboratory loosening test and the allowable limit of loosening of the actual machine, it shows that evaluation standard can be established. The prevention effect for loosening is judged by this evaluation standard.

We would like to research for the elucidation of the mechanism of bolted joint loosening, especially the relation of the analysis of loosening by impact load, and also to clarify the load waveform in the actual machine, and the relation in the bench test (loosening testing machine). Moreover, we would like to work on the quantitative evaluation of the absolute estimation method of the bolted joint loosening and establish the evaluation standard, etc. for prediction and judgment of self-loosening.

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