Journal of Template

Absolute Estimation on Self-Loosening of Bolted Joints during Actual Machine Operation

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Abstract

Many papers have been published on the self loosening of bolted joints, making estimations of the locking effect from laboratory tests using a loosening test machine. However this kind of test method is only effective for the comparison of locking devices. In this paper we propose a method for estimating the absolute lock effect during actual machine operation ,that is construction machinery and material handling equipment. The authors found that there is a linear relation between axial tension and the time after the tightening on a log-log scale, in both static and dynamic loosening. Based on this relation , the authors propose a method for estimating the decrease of axial tension accurately after long hours of tightening by measuring the initial behavior as the bolt loosening evaluation chart.

Key words: Fixing Element, Bolted Joint, Self Loosening, Static Loosening, Dynamic Loosening, Locking Device, Locking Effect, Absolute Estimation, Bolt Axial Tension, Machine Operation, Construction Machinery, Material Handling Equipment

1. Introduction

The optimum tightening condition of bolted joint used in machines is defined as that in which they undergo neither breakage nor loosening during machine operation while at the same time being fastened with higher enough axial tension(sufficient initial clamping load) so that no separation can be caused by any external forces[(1)(2)]. The authors have previously devised a method to show mathematical and statistical axial tension distribution of bolt fastening measured by the calibrated wrench method, and also have showed that it is possible to decide on reasonable tightening torque using a confidence limit ellipse. Further, we showed that a higher initial bolt axial tension could be applied by this method than ever before[(1)].

The main troubles with bolts are fatigue fracture and

*Received XX Xxx, 200X (No. XX-XXXX)
[DOI: 00.0000/ABCDE.2006.000000]

self-loosening, and the causes for these are design-based faults or insuffiecient tightening as shown in Junker's Road Map (Failure mechanism of dynamically loaded bolted joints)[2]. In the classification of bolt troubles done by Ariyoshi et al[3], loosening accounted for 60%, breakage 28% and others 12% of all troubles, so the investigation of fatigue strength and self-loosening is essential for reliability assessment of a bolted joint in a machine during operation. Therefore, in this report, firstly the self-loosening of bolts is considered. Specifically, a reliable estimation method of self-loosening of bolted joints is proposed and its effectiveness is estimated by applying it to examples of static loosening and dynamic loosening in Construction Machinery and Material Handling Equipment.

2. Self-loosening of bolts and its absolute estimation

There are many explanations and reviews of self-loosening of bolted joints and many explications of the loosening mechanism have been attempted[2]-[7]. Hongo[8] classified them into two main mechanisms: a) generated by relative rotation between the bolt and the nut, and b) generated without any relative rotation between the bolt and the nut.

As for detection of self-loosening, detection results of various kinds of locking devices using a loosening testing machine have been reported[2][9]-[14]. Those methods, however, estimate only experimentally the performance of the locking devices, and although they have made possible not only qualitative but also quantitative relative comparison of the anti-loosening function (locking effect), they still cannot make such absolute determinations as whether bolted joints in an actual machine can continue to perform their function without loosening, or to what extent the initial functioning state be maintained after a certain period. This absolute estimation is indispensable for the estimation of bolt-loosening under actual machine operation.

Figure 1 shows the measured reduction of bolt fastening axial tension as measured by strain gages attached to the shanks of hub bolts which mount disk wheels to a construction machinery (Wheel Loader), subjected to the pattern of work load used to test durability by the maker, the main part of which is travel motion. The figure shows the axial tension changes in the cases of two kinds of disk wheels. The horizontal axis gives the number of operation cycles. As shown in the figure, the change in bolt-loosening delineates a curve, loosening rapidly in initial operation soon after fastening the bolts, but then with the loosening becoming more gradual.

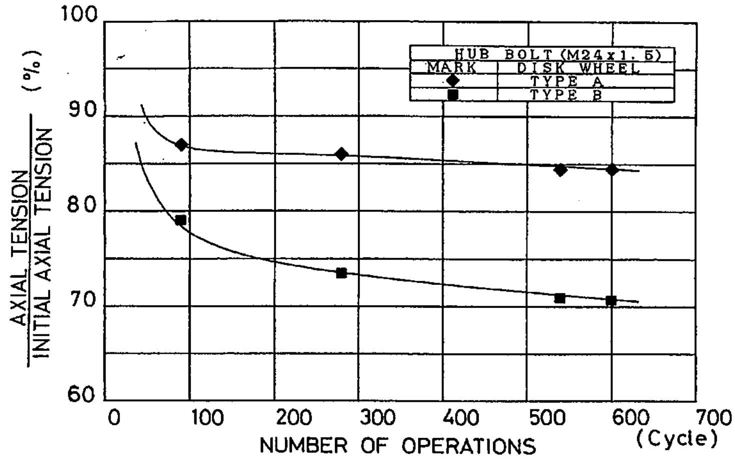

Fig.1 Axial tension change in an actual machine (linear coordinates)

Figure 2 shows the same data plotted on a logarithmic scale (log-log) chart, the linear gradient here making clear the change in the rate of decrease. Fig.3 shows the results of a bolt-loosening test under lateral vibration carried out by The Japan Research Institute for Screw Threads and Fasteners (JFRI) [9] plotted on the same logarithmic scale chart, the linear gradient here also making clear the change in the rate of decrease. Judging from these figures, the measured changes in bolt axial tension seem to approximate Eq.(1) or Eq.(2).

$$\log R = A' + B' \log N \quad \text{-----} \quad (1)$$

$$\log R = A + B \log H \quad \text{-----} \quad (2)$$

Here, N: Number of Operation Cycles (cycle)

R: (Measured Axial Tension)/(Initial Axial Tension)

A, B, A', B': Constants

H: Operation Interval (hour)

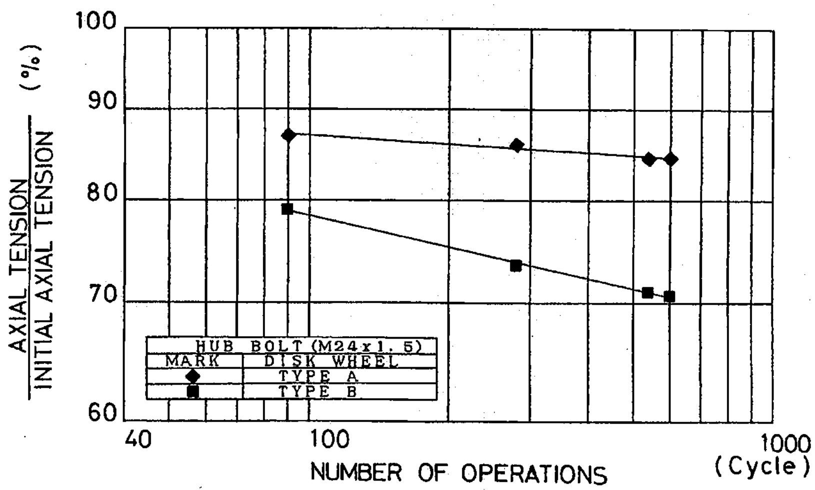

Fig.2 Axial tension change in an actual machine (logarithmic coordinates)

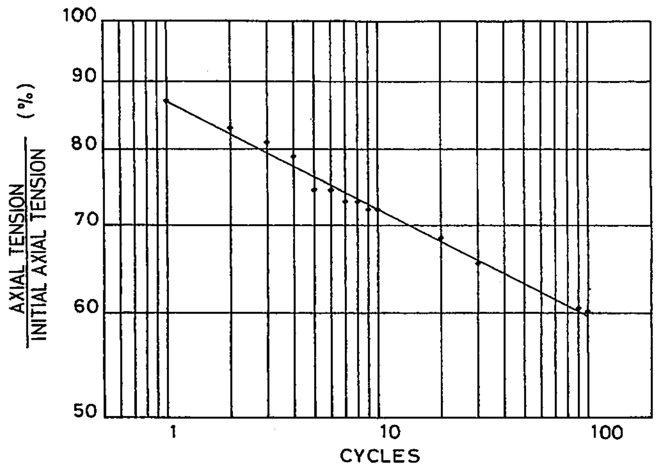

Fig.3 Bolt-loosening test result under lateral vibration (logarithmic coordinates)

In this report, an absolute estimation method of bolt-loosening is proposed utilizing the linear relation of Eq. (1) for bolt axial tension change after initial tightening and start of operation. That is to say, we tried to estimate the amount of loosening after a long operation period from the results of axial tension change during a comparatively short interval measured at the beginning of machine deployment. An estimation standard of bolt-loosening needs proper criteria corresponding to the function of bolts, i.e., the necessary amount of axial tension after a period of stress is determined mainly by considering the load amount during operation and fatigue strength of bolts which are themselves used as strength members, and by considering minimum contact pressure between members fastened by the bolts needed to keep tightness.

The above-mentioned method is only an empirical one, and uses no essential insight into the mechanism of bolt-loosening, but it is a very practical method for use in manufacturing at the present stage where no absolute estimation method for bolt-loosening has been available. The usability and characteristics of this method are investigated for both initial static loosening and dynamic loosening during machine operation.

3. The estimation of static loosening

In this chapter, the effectiveness of the conception of measuring static bolt-loosening proposed in this report is investigated, taking as an example the measurement of loosening caused by static permanent strain or a depression of fastened portions occurring immediately after bolt-fastening, carried out to estimate loosening of hub bolts used to fix disk wheels of an Material Handling Equipment(Forklift Truck).

3.1 Test samples

The bolts used as test samples were fitting hub bolts for a two-piece rim type disk wheel of an Forklift Truck (here called just "hub bolts"); their fitting configuration is shown in fig.4.

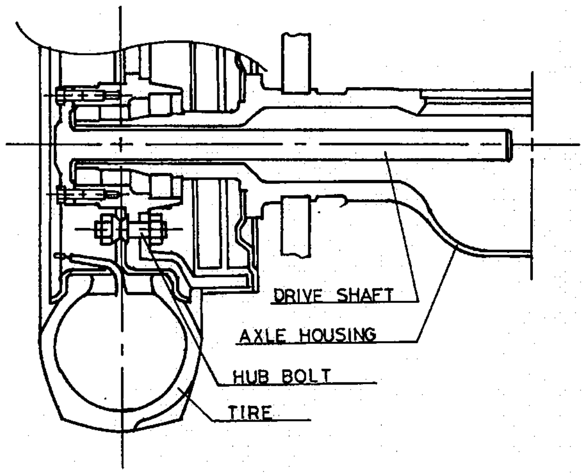

Fig.4 Structure of a disk wheel

3.2 Experimental procedure

Axial tension of hub bolts was measured by strain gages attached to the shank of the bolts as shown in fig.5. A disk wheel was fastened with 8 hub bolts to a hub fixed to a test stand. Axial tension was measured in two of these eight. Strain was measured statically by a two gage method using a universal digital instrument (UCAM-8BLr, Kyowa Electric Instrument Co., Ltd.). The relation of axial tension and strain of each hub bolt was calibrated by a tension test before the experiment. The bolt-loosening was measured as axial tension change, measuring time from immediately after fastening with a specified torque (dry,715N·m).

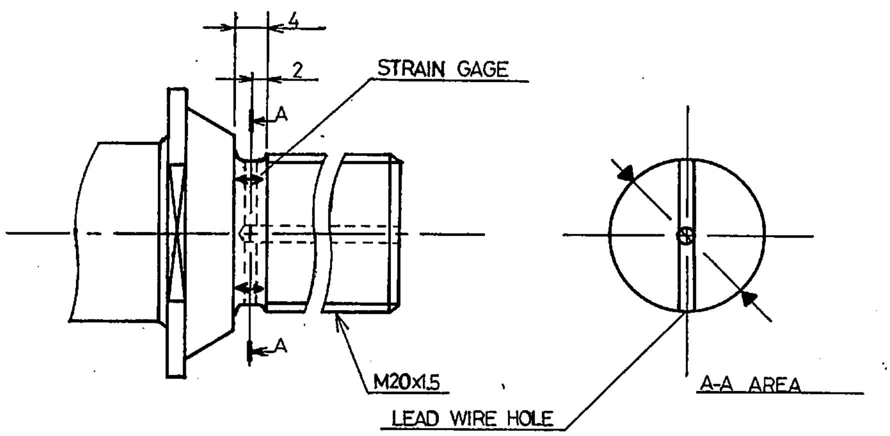

Fig.5 Position of strain gages attachment to a hub bolt

3.3 Experimental results and investigation

Figure 6 shows the axial tension change over time, measured from immediately after initial fastening. The same decreasing tendency of axial tension change is observed as in the example data in Fig.1.

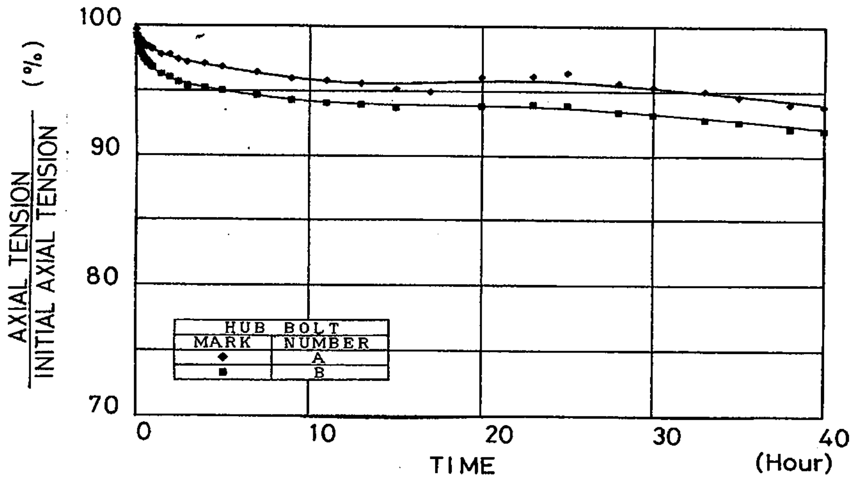

Fig.6 Axial tension change over time (linear coordinates)

Figure 7 plots the partial data up to 180 minutes on a logarithmic scale chart, and shows the same linear relation as in Figs.2 and 3.

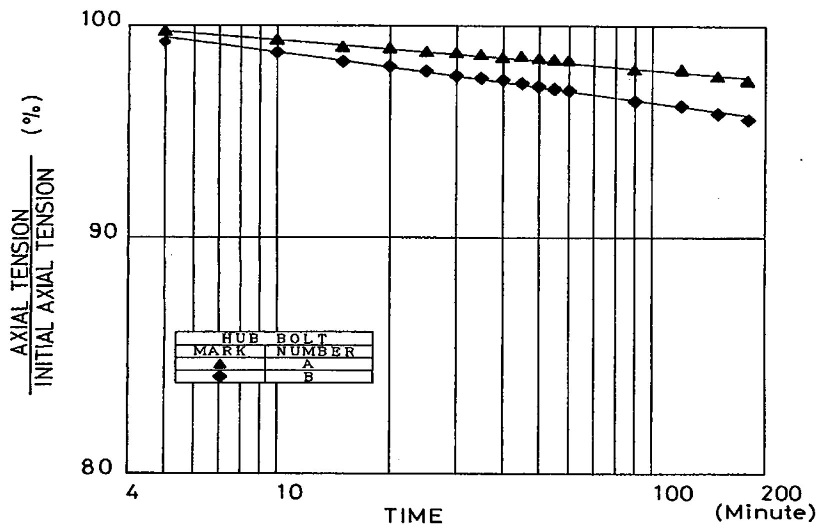

Fig.7 Axial tension change over time (logarithmic coordinates)

Table 1 Estimation of axial tension after a long period of operation

		BOLT A				BOLT B			
		Measurement	Estimate			Measurement	Estimate		
			a	b	c		a	b	c
			5～30min evry 5min	5～60min evry 5min	30～180min evry 5min		5～30min evry 5min	5～60min evry 5min	30～180min evry 5min
r		——	−0.996	−0.997	−0.979	——	−0.997	−0.998	−0.996
A		——	2.0023	2.0024	2.0054	——	2.0035	2.0040	2.0072
B		——	−0.00575	−0.00577	−0.00758	——	−0.00950	−0.00998	−0.01200
R	11 hour	95.81%	96.86%	96.86%	96.38%	94.10%	94.77%	94.59%	94.05%
	20	96.07	96.53	96.52	95.94	93.89	94.23	94.03	93.37
	30	95.35	96.30	96.30	95.65	93.22	93.88	93.65	92.92
	40	93.88	96.14	96.14	95.44	92.06	93.62	93.38	92.60
ERROR	11 hour	——	1.10%	1.10%	0.60%	——	0.71%	0.52%	−0.05%
	20	——	0.48	0.47	−0.14	——	0.36	0.15	−0.55
	30	——	1.00	1.00	0.32	——	0.71	0.46	−0.32
	40	——	2.41	2.41	1.66	——	1.70	1.43	0.59

r: Correlation Coefficient

R: (Axial Tension) / (Initial Axial Tension)

Table 1 shows axial tension after a long period of operation estimated from the data in Fig.7 using regression lines. Rows a in the table show estimated axial tension every 10 hours from 10 to 40 hours, and this is compared to the actually measured data in Fig.6. These estimates were acquired by calculating a regression line of Eq.(2) using data taken every 5 minutes from 5 to 30 minutes after fastening. Rows b and c show the estimates of tension after the same periods as rows a, based on the data taken every 5 minutes from 5 to 60 minutes, and every 5 minutes from 30 to 180 minutes respectively. Every result shows that a highly accurate estimation is possible. Especially, it is remarkable to be able to estimate tension 40 hours later from the data up to 30 minutes after fastening shown in rows a, that is, to estimate the tension after a period 80 times longer than the measurement, with the accuracy of 3%. This estimation method of axial tension degradation, estimating the amount of bolt-loosening after a long time period using the regression lines of Eq.(1) or Eq.(2) in a logarithmic scale chart, is seen to be highly useful.

4. The estimation of dynamic loosening

In this chapter, the effectiveness of the absolute estimation method of bolt-loosening proposed in this report for the dynamic conditions of actual machine operation is investigated, applying the method to fitting bolts of axle members of a construction machinery(Wheel Loader).

4.1 Test samples

Figure 8 shows the structure of the axle part of Wheel Loader, comprising a final reduction gear, a braking device, etc. In this report, experiments were carried out for hub bolts, axle flange bolts and differential gear ("dif.") carrier bolts in the figure.

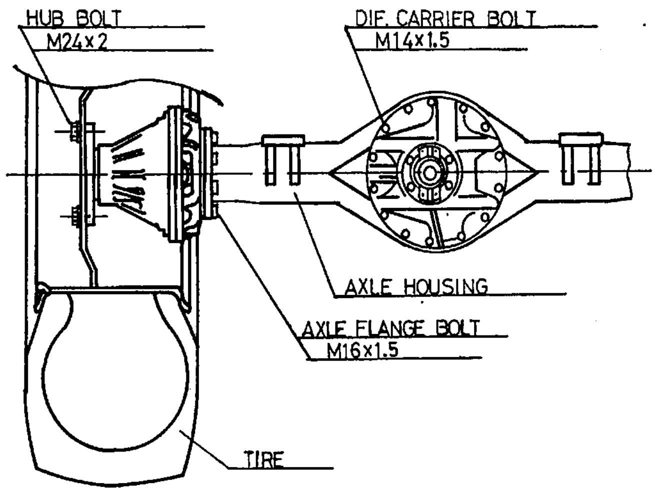

Fig.8 The axle part of Construction machinery(Wheel Loader)

4.2 Experimental procedure

Bolt-loosening was estimated by measuring axial tension with a magnetic axial tension meter (MTM-2A, Shibaura Ltd.). Proto-type machines in the development stage were used. The tendency of axial tension to decrease was confirmed by measuring periodically at a certain interval during a durability test of the machines. Axial tension was measured when enough time passed after the machine stopped for the temperature of the measured parts to become equal to ambient temperature.

4.3 Experimental results and investigation

The experiments were carried out for a shoveling and dumping operation which is a typical working pattern for a wheel loader. Fig.9 shows the measured load applied to tires etc. in one operation cycle. The durability tests of the machines were carried out by repeating this operation cycle. Fig.10 shows the bolt-loosening measured in machines type A and B, plotted in a logarithmic scale chart, exhibiting a linear decrease in axial tension as in Fig.2 showing static bolt-loosening. As the experiments were carried out on actual machines, it was impossible to perform precise experiments or make the same investigation as in static loosening. The point is that axial tension after a long interval can be estimated from the measured initial axial tension change only if the change in the rate of decrease of axial tension proves to be linear on a logarithmic scale chart, regardless of the load applied to the bolts or whether the loosening factor is static or dynamic.

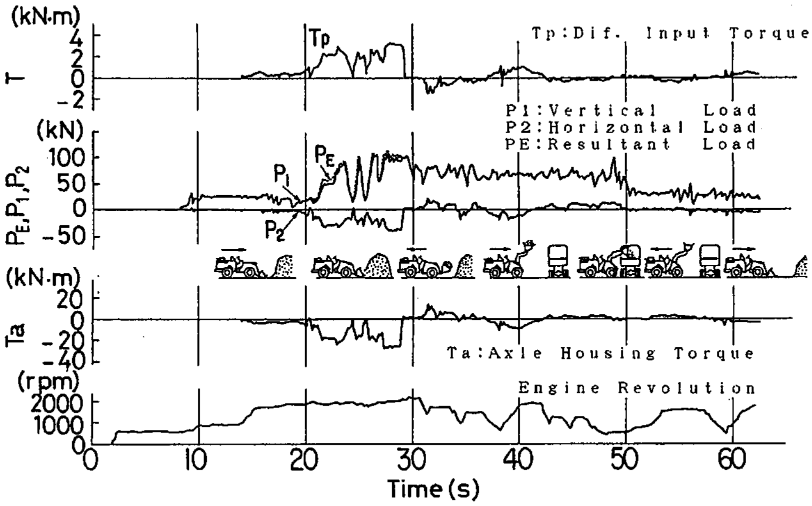

Fig.9 Load pattern of the axle part during shoveling and dumping operation

Table 2 Estimation standard for Bolt-Loosening

Bolt axial tension decrease rate (r)	Estimation standard
r ≦ 10%	O (Not Loosen)
10% < r < 30%	Δ (Pending Case)
30% ≦ r	× (Loosen)

note : Over 100 cycle test using loosening test machine

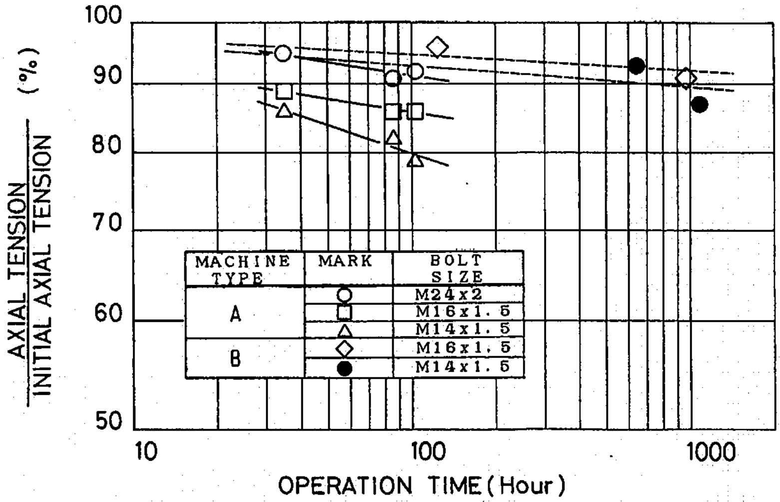

Fig.10 Bolt-loosening measurement during machine operation (logarithmic coordinates)

From the results of these experiments, we must describe about the evaluation criteria for bolt-loosening. Fig.11 shows the image of the evaluation chart for bolt-loosening. JFRI arranged the estimation standard as shown in table 2 of bolt-loosening , classifying axial tension changes into three zone[15]. This evaluation and the above methods provide good hints for establishing evaluation criteria for bolt-loosening.

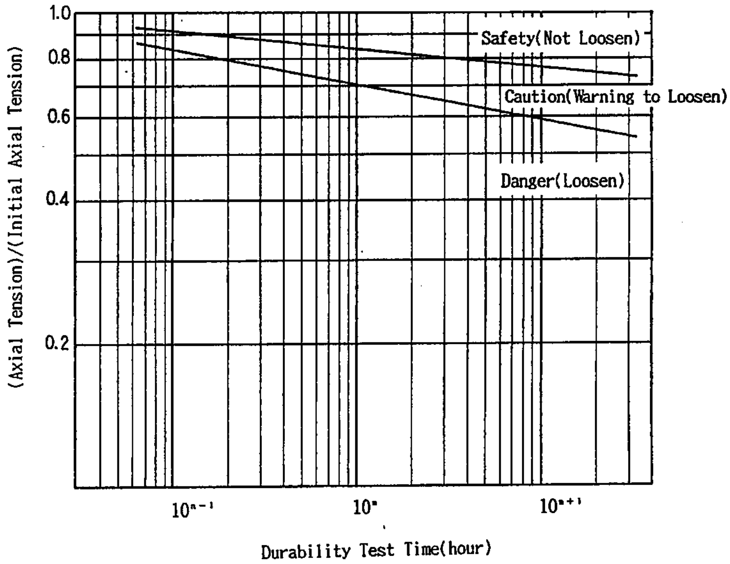

Fig.11 Absolute Bolt-Loosening Evaluation Chart

5. Conclusions

In this report, an absolute estimation method for bolt-loosening under actual machine operation was investigated, as part of our research on the estimation of loosening and strength of bolts under machine operation. It was found that the rate of decrease in bolt axial tension over elapsed time plotted on a logarithmic scale chart exhibits a clear linear relation both for static and dynamic loosening. It was also demonstrated that the decrease of axial tension after a long period can be estimated accurately using this linear relation in the case of static bolt-loosening.

From the results of these experiments , the authors proposed the evaluation criteria for bolt-loosening as the evaluation chart. We have already established these empirically and utilized the above method as evaluation criteria for bolt-loosening, to be used in the development stage of new machines.

Finally, the authors would like to express their appreciation for the instruction and advice of the deceased Professor Shotaro Kodama, Tokyo Metropolitan University.

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