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Self-Locking of Bolt-Nut Joints under Repeated Impacts*

(Theory and Experiments)

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In a bolted joint receiving repeated impacts, the slip between external and internal threads is the cause of loosening of the employed fastener and subsequent failure of the joint. Selection of right locking method is important to minimize the detrimental effects of the slip in a joint.

In this paper, firstly, a theoretical formula for self-locking of threaded fastener has been deduced from the theory of self-loosening process. Secondly, an equation for critical preload to cope with a certain repeated impact has been derived from the experimental results. Thirdly, by comparing the equation with the formula, the significance of parameters in equation has been clarified and the expressions of the parameters have been found out. Lastly, on the basis of experimental results, the performances of different locking methods have been evaluated, the causes of difference of each performance have been clarified, and the coefficients of impulsive friction for the threads have been calculated.

1. Introduction

The theory of self-locking of threaded fasteners which are statically loaded has long been known⁽¹⁾⁽²⁾. However, it seems that the reports of study on self-locking of threaded fasteners which receive repeated impacts have not been published to date.

The process of rotational loosening of a nut (or bolt) owing to the axial impacts was previously clarified by K. Koga⁽³⁾⁽⁴⁾. In consideration of the propagation of stress waves in the threaded fastener, the theory of the above-mentioned process was accomplished. The theory can be summarized as follows:

(1) It is the prime condition of self-loosening that the tensile internal force F_{RO} which reduces the preload F by impact is bigger than the F . The friction between the clamped parts and the friction between the clamped part and the nut are negligible when $F_{RO} > F$.

(2) A compressive impact on the thread surfaces is caused by cut-off effect of the thread groove against the propagation of stress waves. When a compressible impulsive force F_{PR} is caused axially on the thread surfaces, a repulsion is produced at once. Therefore, the axial load on the thread surfaces decrease by F_{PR} .

(3) Most of the stress waves which propagate from the pressure flank inside the bolt arrive at the pressure flank of the opposite side as tensile stress waves, and decrease the compressive stress there. At this moment, an impulsive shear is induced on the thread surface along the helix so that the fastener tends to loosen. We call the above-mentioned waves "return

waves". When the fastener does not loosen by impact, one half of the shearing stress caused on the thread surface of the bolt remains there and the other half moves to the thread surface of the nut.

In this way, some of the impulsive energy is accumulated as the torsion of fastener, and the conditions of self-loosening are produced by the repeated impacts.

The bigger the employed preload is, the harder the fastener becomes to loosen. Accordingly, it is likely that a thread fastener has a critical preload to cope with repeated impacts at a certain degree.

In this paper, we will derive a theoretical formula of self-locking from the theory of self-loosening, and will also propose an experimental equation of the relation between the impulsive force and the critical preload. And also, we will clarify the significance of parameters in the experimental equation and will find out the expressions of the parameters by comparison with the theoretical formula. Furthermore, on the basis of experimental results, we will evaluate and analyze the self-locking performance of different threaded fasteners, and will calculate the coefficients of impul-

Three figures from the left show the elevation of engaged bolt and nut, the cross section of thread, the axial section of thread.

Fig.1 How to obtain the lead directional and the normal components of F_b

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sive friction for threads.

2. The theory of self-locking

The coordinates x , y and z are determined as in Fig.1. The z -axis stands for the screw axis and its positive direction points by the screw end. In Fig.1, the axial load F_b is shown as a force which acts from nut on bolt. It is obvious that the tangential component of F_b along the thread surface is $F_b \sin \beta$, and the component of F_b normal to the thread surface is $F_b \cos \beta / \cos \alpha'$ (2).

In deriving the theory of self-locking, the friction on the bearing surface of the nut is negligible as mentioned in the reference (1) of the introduction. Therefore, the equation of self-locking at the moment when the thread fastener is subjected to an impact is written as follows:

$$F_b \sin \beta = \mu_s F_b \frac{\cos \beta}{\cos \alpha'} \quad (1)$$

where $\tan \alpha' = \tan \alpha \cos \beta$

β is lead angle, α a half angle of thread on the cross section along the axis of screw, α' a half angle of thread on the cross section of thread perpendicular to the helix and μ_s coefficient of friction on the thread flank.

Subsequently, F_b in Eq.(1) is changed as follows under the condition described in the reference (2) of the introduction:

$$F_b = F_t - F_{PR} + F_w \quad (2)$$

where F_t is critical preload, and F_w is spring force of washer under the nut.

Figure 2 shows how to find both the tangential and the normal components of an impulsive force which is caused by the return waves mentioned in the reference (3) of the introduction. F_{rx} , F_{ry} and F_{rz} are the components of the impulsive force, in x , y and z directions respectively, which is induced by the total return waves reflected at the clearance flank and the top face of bolt. Figure (a) shows that $F_{rx} \sin \beta$ is induced in the tangential direction when $F_{rx} > 0$. Figure (b) shows that $F_{ry} \cos \beta$ is induced in the tangential direction and $F_{ry} \sin \beta / \cos \alpha'$ is induced in normal direction, and that $F_{ry} \times (\sin \beta / \cos \alpha') \tan \beta$ which acts from the nut to the bolt is induced in the tangential

Fig.2 How to obtain the lead directional and the normal components of impulsive force caused by "return waves"

direction owing to the unbalance of force by $F_{ry} \sin \beta / \cos \alpha'$ when $F_{ry} < 0$. Figure (c) shows that $F_{rz} \sin \beta$ is induced in the lead direction and $F_{rz} \cos \beta / \cos \alpha'$ is induced in normal direction, and that $F_{rz} (\cos \beta / \cos \alpha') \times \tan \beta$ is induced in the tangential direction as mentioned in Fig.(b) when $F_{rz} < 0$.

When $F_t < F_t$, and while the threaded fastener is subjected to repeated $N-1$ times impacts, the twist of the bolt is accumulated and increased as mentioned in the reference (3) of the introduction. Also, when $F_t < F_t$, and at the moment when N times impact is applied, impulsive components as seen in Fig.2 are induced. The loosening slip occurs between the thread surfaces. When the following expression (3)

$$\begin{aligned} & (F_t - F_{PR} + F_w) \sin \beta + \left\{ 1 + \frac{1}{2} (N-1) \right\} \{ F_{rx} \sin \beta + F_{ry} (\cos \beta - \sin \beta \sec \alpha' \tan \beta) \\ & + F_{rz} (\sin \beta + \cos \beta \sec \alpha' \tan \beta) \} > \mu_s \{ (F_t - F_{PR} + F_w) \cos \beta \sec \alpha' \\ & - F_{rx} \sin \beta \sec \alpha' + F_{ry} \cos \beta \sec \alpha' \} \quad (3) \end{aligned}$$

holds where, F_t is an employed axial load. Also when $F_t = F_t$, the twist of the bolt is accumulated. But, the loosening does not occur (See Fig.15). The reasons are considered as follows:

(1) At the N times impulse, the twist of the bolt is momentarily accumulated as is done within $N-1$ times impulses.

(2) But, right after the accumulation of twist, F_{ry} and F_{rz} in the right side of expression (3) disappear.

(3) Thus, the slip is continuously caused by the reaction of the twisting of bolt, and the earlier mating condition of the bolt-nut joints is restored. This is the self-locking.

Therefore, the formula of self-locking is presented as follows:

$$\begin{aligned} & (F_t - F_{PR} + F_w) \sin \beta + \frac{N}{2} \{ F_{rx} \sin \beta + F_{ry} (\cos \beta - \sin \beta \sec \alpha' \tan \beta) \\ & + F_{rz} (\sin \beta + \cos \beta \sec \alpha' \tan \beta) \} = \mu_s (F_t - F_{PR} + F_w) \cos \beta \sec \alpha' \quad (4) \end{aligned}$$

Let us denote the ratio of forces as follows:

$$\xi_x = \frac{F_{rx}}{F_{PR}}, \quad \xi_y = \frac{F_{ry}}{F_{PR}}, \quad \xi_z = \frac{F_{rz}}{F_{PR}} \quad (5)$$

So, Eqs.(6) and (7) are obtained.

$$F_{PR} = k_3(F_i + F_w), \quad \frac{1}{k_3} = 1 + \frac{N}{2} \frac{\xi_x + \xi_y(\cot \beta - \sec \alpha' \tan \beta) + \xi_z(1 + \sec \alpha')}{\mu_t \sec \alpha' \cot \beta - 1} \quad (6)$$

$$\mu_t = \cos \alpha' \tan \beta \left\{ 1 + \frac{N}{2} \frac{\xi_x + \xi_y(\cot \beta - \sec \alpha' \tan \beta) + \xi_z(1 + \sec \alpha')}{1/k_3 - 1} \right\} \quad (7)$$

Where we call k_3 "screw thread constant".

Next, when 2α is 60° and the screw point is a flat point, the propagation of the stress waves in the external thread can be analyzed approximately by the two-dimensional analysis⁽⁵⁾. As the result of analysis, the return waves reflected at the clearance flank come to the pressure flank as tensile waves of x -direction, and the return waves reflected at the screw point come to the pressure flank normally as tensile waves. Now, let the impulsive forces by the former be $\xi_1 F_{PR}$ ($\xi_1 < 0$), and the latter $\xi_2 F_{PR}$ ($\xi_2 < 0$). Then, the following equations are derived from Eqs.(6) and (7).

$$F_{PR} = k_3(F_i + F_w), \quad \frac{1}{k_3} = 1 + \frac{N}{2} \frac{-\xi_1 - \xi_2(\sin \alpha + \cos \alpha + \sec \alpha' \cos \alpha)}{\mu_t \sec \alpha' \cot \beta - 1} \quad (8)$$

$$\mu_t = \cos \alpha' \tan \beta \left\{ 1 + \frac{N}{2} \frac{-\xi_1 - \xi_2(\sin \alpha + \cos \alpha + \sec \alpha' \cos \alpha)}{1/k_3 - 1} \right\} \quad (9)$$

where it is considered that the impulsive force owing to the return waves acts from nut to bolt, and its direction is contrary to the arrow in Fig.2 because the return waves are all tensile waves.

3. Experimental procedure

3.1 Apparatus

Figure 3 shows a sectional view of the essential parts of the experimental apparatus. A pair of bolt and nut clamps the upper and the lower cylinders, and forms a threaded fastener. The fastener is pushed up by the notched cam with 60 mm lift through the following rod and is fallen down, whereby the upper cylinder collides against the base. Six steps of the collision velocity is produced by changing the length of the following rod and the stiffness of the coil spring.

The above mentioned collision causes F_{RO} on the top face of the lower cylinder and F_{PR} on the thread surfaces of the bolt-nut joints as mentioned in the introduction. And F_{RO} and F_{PR} are expressed as follows⁽³⁾⁽⁴⁾⁽⁷⁾⁽⁸⁾.

$$F_{RO} = \left[E \frac{\gamma}{g} \right]^{1/2} \frac{A_5 + A_6}{A_3 + A_4 + A_5 + A_6} A_4 v_0 \quad (10)$$

$$F_{PR} = \left[(\lambda + 2G) \frac{\gamma}{g} \right]^{1/2} \frac{A_5 + A_6}{A_3 + A_4 + A_5 + A_6} \frac{b}{2} A_4 v_0 f$$

$$b = \begin{cases} \frac{2A_3}{A_2 + A_3} & : \text{without washer} \\ \frac{2A_3}{A_3 + A_w} \frac{2A_w}{A_2 + A_w} \left(1 - \frac{A_2 - A_w}{A_2 + A_w} \frac{A_3 - A_w}{A_3 + A_w} \right) & : \text{with washer} \end{cases} \quad (11)$$

where E is Young's modulus, G shearing modulus, γ specific weight, g acceleration due to gravity, each A sectional area of each part shown in Fig.3, A_5 contact area of thread surfaces, A_w area of cross section of washer, v_0 collision velocity, b transmission factor of stress waves from the upper cylinder to the nut and f ratio of real value to calculated value of F_{PR} . When a washer exists, the factor b should be calculated considering the sum of the primary and the secondary waves, where the secondary waves are reflected once at the upper and once at the lower face of the washer.

In using a coil spring, the thread fastener should be placed on the base and the spring holder should be set so as to keep a distance between the upper cylinder and the spring holder equal to the free length of the coil spring. The velocity v_0 of each collision step at each experimental condition in Table 2 is calculated by using the actual weight and falling distance of fastener, and spring constant of the coil spring. F_{RO} and F_{PR} are calculated by using

the following figure: $E = 20\,900 \text{ kgf/mm}^2$, $G = \lambda = 8\,360 \text{ kgf/mm}^2$, $\gamma = 7.84 \times 10^{-6} \text{ kgf/mm}^3$, $f = 1$. The results are shown in Fig.8~14.

Fig.3 Experimental apparatus

The slip between the upper and the lower cylinders is restricted within the loosening gap of the pins shown in Fig.3. It is expected that the frictional resistance of the following rod in the up-stroke is small, and its falling speed is faster than that of the fastener, and the clearance between the cam and the rod is ensured at the bottom dead center. The cam is driven by a 100 watt universal motor with a 1/10 reduction gear, and the speed of revolution fluctuates 173~436 rpm by v_0 .

The lower cylinder acts as a load cell which has a four-strain gauge bridge for the measurement of axial force. In the experiment to find F_L , the foil gauges are used as strain gauge and a pair of strain meter and electromagnetic oscilloscope as measuring instrument. In the experiment to detect F_{PR} , the semiconductor gauges are used as strain gauge and a storage-type electromagnetic oscilloscope as measuring instrument. And the number of impacts is counted by a revolution counter which is directly coupled to the cam shaft.

3.2 Experimental conditions and procedure

Figure 4 should the shape and dimensions of the standard bolt and nut for experiments which are marked with an asterisk in Table 2. The measured values of the screw thread are

Table 1 The measured values of the standard screw threads

Screw thread	Hardness Hv	Major diameter mm	Pitch diameter mm	Roughness of thread surface $\mu m R_{max}$
External	271	9.91	8.96	1.9
Internal	259	8.50	9.10	16

Fig.4 The standard bolt and nut for experiments

Fig.5 Examples of the experimental result to find F_L (which is indicated as $\odot$ in Fig.8)

given in Table 1 where the roughness of thread surface radially measured is also given. The bolt is a JIS-Regular hexagon head bolt-M10-8.8, and the nut is a JIS-Regular hexagon nut type 1-M10-6. The screw point is flatwise lathed.

The bolt and nut are cleaned by ultrasonic waves, the thread surfaces and the bearing surface of nut are applied with a new spindle oil, and the bolt-nut joints are assembled. Then, the upper cylinder is locked in the groove of the guide cylinder with a key, and the head of bolt is tightened by a spanner to keep it from rotation, and the nut is screwed up. In this way, the initial torsion of bolt is limited. Besides, the protruded length u from screw point to the top of nut is 1.7 mm.

It is considered that the above mentioned conditions are the standard for experiment.

Figure 5 is an example of the results of the experiment carried out in order to find F_L , critical preload. As the employed preload gradually increases at a certain collision step, the fastener becomes harder to loosen. After n (100~5 000) times impacts, its self-loosening tends to disappear. The same preload is applied in every experiment. This experiment is repeated three times, until the self-loosening can no longer be observed. The residual preload in this

(a) is the whole wave at the collision step No.2. (b), (c) and (d) are the primary wave at the collision steps No.1, 2 and 6 respectively.

Fig.6 Impulsive stress waves

Fig.7 How to obtain the transmission of F_{PR} and b_{S1} from the internal thread to the body of bolt

experiment is determined as F_L . It has been verified by our experiment that the threaded fastener preloaded by the F_L does not loosen after as many as 70 000 impacts.

4. Experimental results and discussions

4.1 Impulsive force F_{PR} on the

Figure 6 shows several examples of stress waves. The fastener which holds a rubber plate between the upper and the lower cylinders, is screwed by a standard bolt and nut, is lifted up by hand, and then is dropped. It is lifted up by hand, and then is dropped. Figure (a) shows all the propagating process of stress waves from generation to vanishing. It is considered that the first wave crest is caused by the primary waves of F_{PR} , and the later wave crests by the resultant of high order waves which reflects or transmits both on the contact surfaces and the free surfaces of the parts of the fastener. Figures (b), (c) and (d) show each first wave crest in the experiment at the collision steps No.1, 2 and 6 respectively.

F_{PR} in the above mentioned experiments can also be obtained by calculation, putting $A_4 = 0$ and $f = 1$ in Eq.(11). On the supposition that the thread surfaces are a plane as shown in Fig.7, the transmittivity of stress waves caused on the thread surfaces which propagate to the body of bolt is derived as b_{S1} in Fig.7 by using Mr. Matsumoto's Eq.(5) in his work⁽⁸⁾. And the transmittivity from the body of bolt to the lower cylinder can be derived also by using his Eqs.(3) and (4)⁽⁸⁾. The theoretically calculated values of the force of first wave crest at the same collision steps as (b), (c) and (d) in Fig.6 respectively are 235 kgf, 334 kgf and 822 kgf in the form of compressive force. Theoretically, the rise time of the first wave crest is the sum of times which the stress waves take to pass the nut and the head of bolt back and forth. Putting the propagation velocity of waves equal to 5 190 m/s, the calculated result at each collision step is

approximately 6 μ s. All the calculated results agree with the experimental results.

Thus, it is well proved that F_{PR} generates as explained in Koga's theory⁽³⁾⁽⁴⁾. The relationships between F_{RO} and F_{PR} on each experimental condition are as shown in Figs.8 to 14.

4.2 Experimental equation of F_L

The experimental value of F_L at each collision step in each experimental condition is marked with a point of F_{RO} and F_L co-ordinates as in Figs.8 ~ 14. From these points, the following experimental equation which is common to each experimental condition can be assumed:

$$F_{RO} = K(F_L + F_w) \exp c F_L \dots \dots \dots (12)$$

where both K and c are the experimental constants, and their values are shown in Table 2.

From Eq.(12), the experimental curves in Figs.8 ~ 14, and K and c in Table 2, it is clear that (1) K means the inclination of a tangent which touches the experimental curve at $F_{RO} = 0$, (2) c means the rate of inward separation of the curve from the tangent as F_{RO} gets bigger, (3) the bigger the values of K and c are, the harder the fastener becomes to loosen, and the effect of K is big when F_{RO} is small, and that of c is big when F_{RO} is big. Therefore we call K and c "evaluating constants".

Both Eqs.(6) and (8) are rewritten by using Eqs.(10) and (11) as follows:

$$F_{RO} = k_1 k_2 k_3 (F_L + F_w) \frac{1}{f} \dots \dots \dots (13)$$

where $k_1 = \left[\frac{E}{\lambda + 2G} \right]^{1/2} \dots \dots \dots (13)'$

$$k_2 = \frac{2A_4}{bA_1} \dots \dots \dots (13)''$$

we call k_1 "material constant" and k_2 "dimensional constant".

Furthermore, the following equations are obtained from Eqs.(12) and (13)

Table 2 The experimental conditions, the self-locking performances and the factors which have effects upon the performances

Experimental condition		Fig. No.	Experimental constant		Dimensional constant		Screw thread constant						
No.	Distinction		K	c	A_s mm	k_2	k_3	u mm	ξ_1	ξ_2	$\tan \beta$	N	μ_s
①	* M10-Standard	8	1.51	0.20	114	5.16	0.032	1.7	-0.059	-0.095	0.052	2-4	0.06-0.07
②	M 8		4.56	0.29	66	8.87	0.563	1.4	-0.047	-0.037	0.054	3-4	0.07
③	M12		1.15	0.10	147	3.78	0.334	3.0	-0.055	-0.091	0.050	2-4	0.06
④	** M10 $\times$ 1.25	9	3.53	0.31	74	7.50	0.516	2.4	-0.050	-0.091	0.043	2-3	0.06-0.07
⑤	MoS ₂		0.75	0.23	114	5.16	0.159	1.7	-0.059	-0.095	0.052	2-4	0.053
⑥	* Plain sheared point	10	1.62	0.20	114	5.16	0.344	2.2	-0.059	-0.049	0.052	3-5	0.06
⑦	* Flat point accompanied with an orifice		1.74	0.19	114	5.16	0.369	1.7	$\xi_1 = +0.012$ $\xi_2 = -0.019$		0.052	3-5	0.06-0.08
⑧	* Small diameter body		2.03	0.20	114	5.16	0.431	2.0	-0.059	-0.053	0.052	2-4	0.06-0.07
⑨	*** M10-6H/6g	11	1.26	0.39	113	5.24	0.263	2.2	-0.057	-0.101	0.052	3-4	0.06
⑩	M10-5H/8g		1.27	0.45	104	5.69	0.245	1.6	-0.050	-0.074	0.053	5-7	0.06
⑪	* Spring washer	12	1.32	0.22	114	5.18	0.279	0.2	-0.059	0	0.052	2-4	0.05
⑫	* Conical spring washer		1.45	0.21	114	5.18	0.307	1.5	-0.059	-0.052	0.052	3-5	0.06
⑬	* External toothed lock washer		0.88	0.23	114	5.33	0.181	2.5	-0.059	-0.164	0.052	2-3	0.06
⑭	** Spring washer	13	2.24	0.31	73	8.08	0.304	0.7	-0.050	-0.011	0.043	3-4	0.04
⑮	** Conical spring washer		3.73	0.31	74	8.37	0.489	2.0	-0.050	-0.082	0.043	2-4	0.06-0.07
⑯	*** Double nut (1)		1.98	-0.02	113	5.16	0.420	2.1	-0.057	-0.056	0.052	2-4	0.06-0.07
⑰	*** Double nut (2)		1.81	0.24	113	5.24	0.378	2.1	-0.057	-0.056	0.052	3-5	0.06-0.07
⑱	* Anaerobic locking compound		3.72	0.20	114	5.16	0.789	1.7	-0.059	-0.095	0.052	15	0.65

Notes: (1) Experiments indicated by the same number of * use the same screw threads. (2) When $E = 20\ 900\ \text{kgf/mm}^2$ and $\lambda = G = 8\ 360\ \text{kgf/mm}^2$, all k_1 is 0.913. Because $A_4 = 487\text{--}549\ \text{mm}^2$ and $b = 1.69\text{--}1.86$, A_4 and b in each experiment are similar. (3) $\cos \alpha' = 0.8663$. β of $\tan \beta$ is the lead angle on the average of external and internal diameters of screw threads.

$$K = k_1 k_2 k_3 \dots (14)$$

$$\exp cF_t = \frac{1}{f} \dots (15)$$

4.3 Evaluation of the self-locking performance and the locking methods

In Figs.8 to 15, number ①, ② ⑮ correspond to the threaded fastenings shown in Table 2, respectively. Table 2 shows the calculated results of both the parameters and their main factors in experimental conditions for the evaluation. From the $F_L - F_{RO}$ curves in the Figures and the constants in the Table 2, we can say the following.

In Fig.8, F_L for the threaded fastenings ①, ② and ③ are shown. The smaller the nominal size of coarse screw thread is, the bigger K and c are and the harder the fastener becomes to loosen. K gets bigger mainly when the contact area of thread surfaces A_S is smaller. "Yield" on the curve at the collision step No.6 is a phenomenon that F_L cannot be found. The reason for such a phenomenon is that the sum of the fastening static stress and the impulsive stress at the bolt becomes bigger than the yield point.

In Fig.9, F_L for the threaded fastenings ①, ④ and ⑤ are shown. ④ has bigger K and c , and is harder to loosen than ①. K in ④ gets bigger than in ① because A_S and β in ④ are smaller than in ①. A_S in ④ gets smaller than in ① because the effective contact surfaces of thread are de-

creased as much as the chamfered surfaces of the bearing surface of nut by the effect of the propagation of stress waves.

⑤ has a smaller K , and is easier to loosen than ①. K in ⑤ gets smaller than in ① because μ_S in ⑤ is smaller than in ①. "Yield" on the curve ⑤ at the collision step No.5 can be explained as was done about the curve ③.

In Fig.10, F_L for the threaded fastenings ①, ⑥, ⑦ and ⑧ are shown. Comparing ①, ⑥ and ⑦, it is seen that K is bigger and they are harder to loosen in this order. K gets bigger because the return tension waves are poorer in the same order.

⑧ has a bigger K and is considerably harder to loosen than ①. K in ⑧ gets bigger than in ① because it is considered that the possibility of $N = 2$ is higher in ⑧ than in ① though N in both ⑧ and ① are equally 2~4; in other words, N is smaller in ⑧ than in ①.

In Fig.11, F_L for the threaded fastenings ①, ⑨ and ⑩ are shown. ⑨ and ⑩ have a slightly smaller K , and are slightly easier to loosen than ① at a smaller F_{RO} . K in ⑨ and ⑩ get smaller than in ① because N in ⑨ and ⑩ is bigger than in ①. On the contrary, c gets bigger and the fastener gets harder to loosen at a bigger F_{RO} when the clearance of the engaged threads is larger. However, ① does not "Yield", and ⑨ "Yields" when the collision step is No.6, and ⑩ tends to "Yield" at the steps No.5 and 6. Therefore, if the clearance is much larger, the fastener may "Yield" more easily.

In Fig.12, F_L for the threaded fasten-

Fig.8 Effects of application of coarse screw threads in different sizes

Fig.10 Effects of application of different screw points and body diameters for bolt

Fig.9 Effects of application of different pitches and lubricants

Fig.11 Effects of application of different accuracies for engaged screw threads

4.4 The coefficient of impulsive friction on the thread surfaces

Figure 15 shows the examples of the recordings of oscillograph in several experimental conditions when $F = F_t$. Each F - n curve in the figure proves that the twisting of bolt increases while getting N times impulses and disappears at the final impulse, and that the loosening of fastener does not advance. The theoretical explanation has been made at the derivation of Eq.(4).

The storage of the twisting appears as an increase of preload in Fig.(a) (the experimental condition is ① and the collision step is No.1), and as a decrease of preload in Fig.(b) (the condition is ⑦ and the step is No.2). A difference of change in preload comes from the tensility of the return waves in ① and on the contrary from its compressibility in ⑦. The theoretical explanation has been made at the derivation of Eqs.(6) and (8). The appearance in other conditions, for example Figs.(c) and (d), is similar to that in ①.

The constant k_3 in Table 2 is obtained from Eq.(14) substituting K obtained by experiment and k_1 and k_2 calculated from Eqs. (13)' and (13)". The ratios ξ_1 and ξ_2 are obtained by a two-dimensional analysis of the propagation of stress waves⁽⁵⁾. The ratios ξ_x , ξ_y and ξ_z are derived from the direction cosines of the return waves obtained by the three-dimensional analysis⁽⁵⁾. N in each experimental condition is obtained from the F - n curve as seen in Fig.15.

The coefficient μ_s is calculated by using Eqs.(7) and (9), and accordingly is much smaller as shown in Table 2 than the generally known coefficient of friction. Paland⁽⁹⁾ reported about a coefficient by far smaller. It seems that he did not realize the effect of the return waves.

5. Conclusions

The theoretical formula and the experimental equation of the self-locking of the threaded fastener, on which the compressive

Number in circle under each figure indicates experimental number.
No.1 and 2 are collision steps.

Fig.15 Variation of preload by repeated impacts

impulses are axially repeated, are shown as Eqs.(4) and (12) respectively. The significances of the parameters in Eq.(12) and their factors are clear from Eqs.(14) and (15).

The results of evaluation on the self-locking performance about various threaded fasteners can be summarized as follows:

(1) The smaller the size of the screw thread is, the harder the threaded fastener becomes to loosen. And a threaded fastener with a fine thread is harder to loosen than one with a coarse thread, and the same thing can be said about one with a small hexagon nut type 2 as compared with one with a regular hexagon nut type 1; a plain sheared point with a flat point; and a reduced shank bolt with a regular shank bolt.

(2) In regard to the JIS accuracy, a threaded fastener with class 2 screw thread is harder to loosen than one with class 1 screw thread. However, the bolt tends to "Yield" when the screw threads are inaccurate.

(3) Anaerobic locking compound is very efficient, but it is easy to "Yield" when the impulses are big.

(4) Spring washer or other kinds of washers, and double nut are less effective as locking devices than they are expected. There is a case that a fastener with them is easier to loosen than one without them. Therefore, they are not recommendable.

(5) Coefficient of impulsive friction for a thread is very small, its value being is 0.06~0.08 when the thread surfaces are lubricated with spindle oil.

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