Investigations of Bolt Loosening Mechanisms*
(3rd Report, On the Bolts Tightened over Their Yield Point)

By Tomotsugu SAKAI**

With regard to the bolts tightened over their yield point and subjected to the tensile load, the relation between the load and the residual bolt clamping force after unloading was theoretically analyzed, and a static bolt loosening test was carried out. It was verified that the theoretical results coincide very well with the results of experiments.

And under the same condition a fatigue test was carried out with the measurement of the bolt clamping force, and the following results were obtained: ① Except the loss in the initial stage, there is no loss of the clamping force. ② With an increase of the initial clamping force, the residual clamping force and also the bolt fatigue life increase.

So, judging from the above results, the tightening of bolts over their yield point has an advantage over the tightening of bolts below their yield point.

1. Introduction

The fundamental principle in bolt tightening has been to tighten them below their yield point. Recently, however, some new methods of tightening bolts over their yield point, which are contrary to the above mentioned principle, called yield-tightening, have been introduced in some papers.4(−8) Yield-tightening has two advantages: one is a larger bolt clamping force and the other is a smaller deviation of the clamping force. On the other hand, decrease in both the bolt fatigue strength and the clamping force is feared when the joints fastened by yield-tightening are subjected to dynamic load. 6(9)

As Kwami and Kanosen have reported that yield-tightening brings about an increase in loading capacity of bolts, it seems that there is no bad effect of yield-tightening on the bolt fatigue strength. But the problem of the decrease in the clamping force (bolt loosening) has not yet been solved completely, though Kwami made some studies on it. 9(9)

In the present paper, a theoretical analysis of bolt loosening is made on the bolts tightened over their yield point and subjected to the tensile load, and some bolt loosening tests are carried out under static and dynamic loadings. Then the experimental results are compared with the theoretical analyses.

2. Theoretical analysis of bolt loosening

2.1 Conditions for bolts not to yield under loading

(1) The case when the clamped parts do not separate (Q≥(1−Φ)F).

When a separating load F acts on a joint, the force in the bolt increases by the amount of ΦF (Φ= Ks/(Ks+K0)), where Ks: spring constant of the bolt, K0: spring constant of the clamped parts). So, the stresses of the bolt shank are represented by the equation (1), where µ* is the friction coefficient of the screw thread surface, p is the pitch of the screw, α is the half angle of the screw, Q is the clamping force, Ts is the torque acting on the bolt shank, assuming that the diameter of the bolt shank is equal to the effective diameter of the screw ds (the cross-section area of the bolt shank A=πds²/4).

\[ \sigma = \left( Q + \Phi F \right) / A \]

\[ \tau = 16T_s \div \pi d_s^2 = \frac{16}{\pi d_s^2} Q + \frac{\mu}{G} \frac{p}{\pi d_s^2} = \frac{2\mu^* Q}{A} \]  

(1)

where, \( \mu^* = \frac{\mu}{G \pi d_s^2} + \frac{p}{\pi d_s^2} \)  

(2)

From distortion energy theory it is concluded that if the effective stress of the bolt shank \( \sigma_{eff} = \sqrt{T_s^2 + 5r^2} \) is smaller than the uniaxial yield stress \( \sigma_y \), the bolt does not yield. So the condition for the bolt not to yield is as follows.

\[ \sigma_{eff} = \sqrt{T_s^2 + 5r^2} = \sqrt{\left( Q + \Phi F \right)^2 + \frac{12\mu^2 Q^2}{A^2}} < \sigma_y \]

\[ \left( 1 + 12\mu^2 \right) Q^2 + 24QF \Phi + \Phi^2 1 < Q_y \]

(3)

The bolt clamping force Q_f that makes the bolt yield by only tightening is derived as follows, putting F=0 in Eq. (3).

\[ Q_f = \frac{Q}{\sqrt{1 + 12\mu^2}} \]

(4)

The tensile load F_t that makes the clamped parts separate from each other and makes the bolt yield simultaneously is derived as follows, putting Q=(1−Φ)F in the equation that contains = instead of < in Eq. (3).
\[ F_A = \frac{Q_1}{\sqrt{1 + 12\mu^2(1 - \Phi)^2}} \]  
(6)

(2) The case when the clamped parts separate 
\[ Q < (1 - \Phi)F \]

When the tensile load \( F \) acts on the joint, both \( F \) and the shank torque \( T_s \), which has been generated by tightening, act on the bolt. So, the condition for the bolt not to yield is given by Eq. (6), instead of Eq. (3).

\[ \sigma_f = \frac{Q^2}{A^2} + \frac{12\mu^2Q^2}{A^2} < \sigma_y \]

\[ \therefore 12\mu^2 Q^2 + F^2 < \sigma_y^2 \]  
(6)

When \( Q = 0 \), Eq. (6) becomes \( F < \sigma_y \), that is the same condition as under uniaxial loading.

From the above, the region on the \( Q-F \) coordinates for the bolt to yield is shown in Fig. 1.

2.2 Relation between tensile force and residual clamping force after unloading

(1) The case when the bolt does not yield, \( (Q_1 < Q_1 - \sqrt{1 + 12\mu^2} \) and \( 12\mu^2Q_1^2 + F^2 < Q_y^2 \) and \( 12\mu^2Q_1^2 + F^2 < Q_y^2 \).

If the bolt does not yield when the tensile load \( F \) acts on, there is no decrease of the clamping force due to the bolt yielding. So, the residual clamping force \( Q \) after unloading equals to the initial one \( Q_0 \).

\[ Q = Q_0 \]  
(7)

(2) The case when the bolt is tightened over the yield point and the clamped parts do not separate. \( (Q_0 > Q_1 - \sqrt{1 + 12\mu^2} \) and \( Q_0 > (1 - \Phi)F \)

In Fig. 2 it is assumed that when \( F \) acts on the joint whose bolt is tightened to \( Q_0 \), the bolt is elongated by \( \lambda_F \) and the force acting on it becomes \( Q' \) and after unloading \( F \) the clamping force becomes \( Q \). \( Q \) is given by Eq. (8), where \( K_B \) is the gradient of the tensile load-elongation curve of the bolt in the range of work-hardening.

\[ Q = Q_0 - F \cdot \frac{K_B}{K_C} + \Phi F \]  
(8)

Here

\[ \lambda_F = \frac{F}{K_C} \]  
(9)

Then

\[ Q = Q_0 - \frac{K_B}{(K_B + K_C)(K_B + K_C)} F \]  
(9)

The amount of the decrease in the clamping force \( \Delta Q \) is calculated with \( K_B, K_C, K_B \), and \( F \) by using Eq. (10).

In a special case where the bolt can be regarded as an ideal elastic-plastic material (that means \( K_B = 0 \)), \( Q \) is represented by Eq. (11).

\[ Q = Q_0 - \Phi F \]  
(10)

And the loading factor of the bolt that has been tightened over \( Q_1 \) and is loaded for the first time, \( \Phi_1 \), is given by Eq. (12), and after the second loading \( \Phi = K_B/(K_B + K_C) \).

\[ \Phi_1 = \frac{K_B}{K_B + K_C} \]  
(12)

(3) The case when the bolt yields under loading and the clamped parts do not separate \( (Q_0 > Q_1 - \sqrt{1 + 12\mu^2} \) and after \( (1 + 12\mu^2)Q_1^2 + 2\Phi Q_1 F + \Phi^2 F^2 = Q_y^2 \), \( Q \geq (1 - \Phi)F \).

After the bolt yields with an increase of \( F \), the condition is the same as the previous case. So, the loosening characteristic lines on \( F-Q \) coordinates are parallel with ones represented by Eq. (10).

(4) The case when the bolt has yielded and the clamped parts separate under loading \( (Q_0 > Q_1 - \sqrt{1 + 12\mu^2} \) and \( Q < (1 - \Phi)F \).

The tensile load \( F_\text{cr} \) under which the clamped parts begin to separate from each other is derived as follows from Fig. 2.

\[ F_\text{cr} = \frac{(K_B + K_C)Q_0}{K_C} \]  
(13)

The following equations are derived from Fig. 3.

\[ K_B\lambda + F_\text{cr} = F \]  
(14)

\[ K_C\lambda = Q \]  
(15)

\[ Q + (\lambda + \lambda)K_B = F \]  
(16)
Then, \( Q \) is derived as follows using Eqs. (13) - (16).

\[
Q = F_{h} (K_{B} + K_{C}) Q_{a} / K_{C} \]  
\[
Q = F_{h} (K_{B} + K_{C}) Q_{a} / K_{C} \]  
\[
Q = F_{h} (K_{B} + K_{C}) Q_{a} / K_{C} \]  
\[
Q = F_{h} (K_{B} + K_{C}) Q_{a} / K_{C} \]

The clamping force when the clamped parts begin to separate from each other, \( Q_{a} \), is derived as follows from Eqs. (13) and

\[
Q_{a} = F_{h} (1-\Phi) F \]  
\[
Q_{a} = F_{h} (1-\Phi) F \]  
\[
Q_{a} = F_{h} (1-\Phi) F \]  
\[
Q_{a} = F_{h} (1-\Phi) F \]

(5) The case when the clamped parts separate from each other after the bolt yields under loading

\[
(1-\Phi) Q_{a} / \sqrt{1+12\mu^2} (1-\Phi) < Q_{a} < \sqrt{1+12\mu^2} \]  
\[
(1-\Phi) Q_{a} / \sqrt{1+12\mu^2} (1-\Phi) < Q_{a} < \sqrt{1+12\mu^2} \]  
\[
(1-\Phi) Q_{a} / \sqrt{1+12\mu^2} (1-\Phi) < Q_{a} < \sqrt{1+12\mu^2} \]  
\[
(1-\Phi) Q_{a} / \sqrt{1+12\mu^2} (1-\Phi) < Q_{a} < \sqrt{1+12\mu^2} \]

After the increasing load separates the clamped parts whose bolt has yielded, the condition is the same as the previous case. So, the loosening characteristic lines on F-Q coordinates are parallel with the ones represented by Eq. (17).

(6) The case when the bolt yields after the clamped parts separate from each other under loading

\[
Q_{a} < F_{h} (1-\Phi) F < \sqrt{1+12\mu^2} (1-\Phi) \]  
\[
Q_{a} < F_{h} (1-\Phi) F < \sqrt{1+12\mu^2} (1-\Phi) \]  
\[
Q_{a} < F_{h} (1-\Phi) F < \sqrt{1+12\mu^2} (1-\Phi) \]  
\[
Q_{a} < F_{h} (1-\Phi) F < \sqrt{1+12\mu^2} (1-\Phi) \]

The condition is the same as represented by Fig. 3, the loosening characteristic lines are also parallel with the ones represented by Eq. (17).

From the above relation between the tensile load F and the residual clamping force Q of the bolt, whose initial clamping force is \( Q_{a} \), after unloading is represented as Fig. 4.

When the bolt is tightened over its yield point \( (Q > F_{h} (1-\Phi) F) \), the relations among \( Q_{a} \), F and Q are represented by the following equations.

\[
Q > F_{h} (1-\Phi) F \quad Q_{a} = F_{h} (K_{B} + K_{C}) Q_{a} / (K_{B} + K_{C}) \]  
\[
Q > F_{h} (1-\Phi) F \quad Q_{a} = F_{h} (K_{B} + K_{C}) Q_{a} / (K_{B} + K_{C}) \]  
\[
Q > F_{h} (1-\Phi) F \quad Q_{a} = F_{h} (K_{B} + K_{C}) Q_{a} / (K_{B} + K_{C}) \]  
\[
Q > F_{h} (1-\Phi) F \quad Q_{a} = F_{h} (K_{B} + K_{C}) Q_{a} / (K_{B} + K_{C}) \]

From Fig. 4 it is seen that the point at which the clamping force of the yielding bolt begins to drop abruptly (that is called the critical point of loosening) lies on \( Q_{a} = F_{h} (1-\Phi) F \). That means the critical point of loosening corresponds to the point for the clamped parts to separate from each other. This critical point \( (F_{h}, Q_{a}) \) is represented by the following equations.

\[
F_{h} = (K_{B} + K_{C}) Q_{a} / K_{C} \]  
\[
F_{h} = (K_{B} + K_{C}) Q_{a} / K_{C} \]  
\[
F_{h} = (K_{B} + K_{C}) Q_{a} / K_{C} \]  
\[
F_{h} = (K_{B} + K_{C}) Q_{a} / K_{C} \]

2.3 Critical load of the joint whose bolt is tightened over its yield point, \( F_{h} \).

Since \( F_{h} \) is given by Eq. (20), it is larger than \( Q_{a} \) as far as the bolt workhardens \( (K_{B} > 0) \). So, it is concluded that even the yield-tightened bolt does not lose its clamping force so much under loading, if the load is smaller than the initial clamping force.

2.4 Relation between the initial and the residual clamping forces

When the tensile load acts on the joint under condition that the clamped parts do not separate from each other, the residual clamping force after unloading \( Q_{a} \) is larger with a larger initial clamping force \( Q_{a} \), except in the case when \( Q_{a} \) is represented by Eq. (21) (in this case, the loosening characteristic lines in Fig. 4 cross each other and the previous relation does not hold).

\[
(Q_{a} = F_{h} (K_{B} + K_{C}) Q_{a} / (K_{B} + K_{C}) \]  
\[
(Q_{a} = F_{h} (K_{B} + K_{C}) Q_{a} / (K_{B} + K_{C}) \]  
\[
(Q_{a} = F_{h} (K_{B} + K_{C}) Q_{a} / (K_{B} + K_{C}) \]  
\[
(Q_{a} = F_{h} (K_{B} + K_{C}) Q_{a} / (K_{B} + K_{C}) \]

So, it is concluded that tightening bolts up to just below their ultimate strength is very desirable in order to get a larger residual clamping force.

3. Loosening test

3.1 Static loosening test

Test pieces are given in Table 1. First, the relation between the clamping force \( Q \) and the elongation of the bolt \( \lambda \) is recorded by tightening bolts until they break down in a bolt testing machine. The bolts are tested with engine oil (SAE 30). The test results are summarized in Figs. 5 and 6. Here, \( \lambda \) is calculated by the rotating angle of nut and the pitch of the screw.

Secondly, the uniaxial tension test of bolts is carried out with the results given in Figs. 7 and 8, where the abscissa represents not the elongation of the bolt, but the displacement of the crosshead of the testing machine.

From the results above, the yielding load and the ultimate load of the bolts under tightening and uniaxial tension, \( Q_{1} \), \( Q_{2} \), \( Q_{3} \), \( Q_{4} \), are obtained, and they are given in Table 2.

The testing apparatus for static loosening test is shown in Fig. 9. In Fig. 9, a strain-gauged thick tube that serves as the load cell for measuring the clamping force is set between the jig and the jig 1, and these three parts are tightened by bolt and nut lubricated with engine oil. The calibration curve of the load cell is given in Fig. 10. After the bolt is tightened to a certain clamping force, the bolted joint

\[
F_{h} = (K_{B} + K_{C}) Q_{a} / K_{C} \]  
\[
F_{h} = (K_{B} + K_{C}) Q_{a} / K_{C} \]  
\[
F_{h} = (K_{B} + K_{C}) Q_{a} / K_{C} \]  
\[
F_{h} = (K_{B} + K_{C}) Q_{a} / K_{C} \]

### Table 1. Test pieces (ML2, p=1.25, zinc plated)

<table>
<thead>
<tr>
<th>Material (Hardness)</th>
<th>Overall length</th>
<th>Shank diameter</th>
<th>Head width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt (421)</td>
<td>820 C</td>
<td>81</td>
<td>120</td>
</tr>
<tr>
<td>Bolt (421)</td>
<td>845 C</td>
<td>82</td>
<td>120</td>
</tr>
<tr>
<td>Nut (774)</td>
<td>845 C</td>
<td>82</td>
<td>10</td>
</tr>
<tr>
<td>Nut (774)</td>
<td>845 C</td>
<td>82</td>
<td>10</td>
</tr>
</tbody>
</table>
is stretched by the load \( F \) which is applied by compressing the jig \( J_1 \) with a compression tester.

At that time, the force \( Q_e \) acting on the load cell is measured. Then, the force \( Q \) acting on the load cell after unloading, that is equal to the residual clamping force, is measured. With \( F \) increased gradually until the bolt breaks down, this measurement is repeated.

By setting \( Q_e \) at several levels from the elastic range to just below the tensile breakage, several results of the above-mentioned test are obtained, as given in Figs. 11~17, where \( Q_e, Q_c \) and \( F' = Q_e + F \) in oridine, \( F \) in abscissa. Only the relations between \( Q \) and \( F \) in these figures are summarized in Figs. 18 and 19.

### Table 2. Yield load and ultimate load of test bolts (t)

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Bolt grade</th>
<th>4T</th>
<th>5T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tightening</td>
<td>Yield load</td>
<td>3b, 3a, 37, 38, 39</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Ultimate load</td>
<td>42, 43, 44, 45, 46</td>
<td>44</td>
</tr>
<tr>
<td>Uniaxial tension</td>
<td>Yield load</td>
<td>4a, 4b, 4c, 4d</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>Ultimate load</td>
<td>52, 53, 54, 55</td>
<td>53</td>
</tr>
</tbody>
</table>

*Bolts were tightened under the lubrication with engine oil SAE 30 (\( \nu = 0.12 \)).
**Yield load of 4T bolts is not well known.
Fig. 10 Calibration curve of load cell for measuring clamping force.

Fig. 11 Result of static loosening test (5T bolt-1).

Fig. 12 Result of static loosening test (5T bolt-2).

Fig. 13 Result of static loosening test (5T bolt-3).

Fig. 14 Result of static loosening test (5T bolt-4).

Fig. 15 Result of static loosening test (4T bolt-1).

Fig. 16 Result of static loosening test (4T bolt-2).

Fig. 17 Result of static loosening test (4T bolt-3).
The force acting on the bolt under loading, $Q'$, is calculated by the equation $Q' = Q_0 + P$. That equation was verified by a test in which both $Q'$ and $Q_0$ were measured simultaneously with the strain-gauge cemented on the bolt shank and the load cell respectively. The result is shown in Fig. 20.

No relative rotation between the bolt and the nut could be detected with the naked eye during the test.

3.2 Dynamic loosening test

Test pieces are the same as those used in the static test and ones produced in the same lot.

The testing apparatus for the dynamic loosening test is shown in Fig. 21. The specifications of the bolted joint are the same as that for the static loosening test, shown in Fig. 9. The jig I is fixed and the jig II, to which the jig I is bolted, is jointed to the electro-hydraulic vibration machine (capacity: ±4 tons) and the jig III is subjected to the repeated tension load (0~3.5 tons) with about 30 Hz. Bolts and nuts are tightened after lubrication with engine oil. The residual bolt clamping force is measured several times during the test, with the vibration machine stopped and the load released.

The test results are summarized in Figs. 22 and 23. The relative rotation between the bolt and the nut could not be detected at all in any case with the naked eye.

4. Consideration

4.1 Static loosening test

4.1.1 Residual bolt clamping force

By comparing Fig. 4 with Figs. 18 and 19, it is concluded that the theoretical and the experimental relations between the load and the residual bolt clamping force coincide with each other very well.

But, the loosening characteristic lines in Figs. 18 and 19 have smaller gradient in the region where the bolt is tightened over its yield point and the load is small, and have larger gradient in the region where the load is larger. The assumed reason for this phenomenon is that $K_b = \frac{dQ}{d\lambda}$ decreases with $\sigma_t = \sqrt{Q^2 + P^2}$, as shown in Fig. 24, which means that the gradient of the loosening characteristic lines $K_c(K_b + K_{cb})/(K_{bc} + K_c)$ increases with $\sigma_t$.

The experimental $Q-\lambda$ curves, given in Figs. 5~8, show that $dQ/d\lambda$ decreases with $Q$ or $P$ which is related to $\sigma_t$. 
time tightening is stopped, and the residual shank torque $T_{S*}$, which is recorded after the torque wrench is released, are measured by using the strain-gauged bolt, and the results are $T_{S MAX}=380Kg-cm$, $T_{S*}=240Kg-cm$. The reason for this is that $\mu_B$ is larger than the friction coefficient on the bearing surface $\mu_w$. The experimental mean values of $\mu_B$ and $\mu_w$ are 0.12 and 0.08 respectively. Then, $T_{S}=0.97Q$, $T_{S*}=0.62Q$ ($T_w$ is the friction torque on the bearing surface), and $T_{S*}/T_S=0.64$ are obtained. Since $T_{S*}/T_{MAX}=0.63$, it is found that $T_{S*}$ is approximately equal to $T_w$. This means that though $T_S$ acts on the bolt shank at the end of tightening, $T_w$ can not sustain $T_S$ and the bolt head rotates loose for the shank torque to balance with $T_w$. So, as the bolt comes back to the elastic state at the time of releasing the torque wrench after the bolt work-hardens at first under yield-tightening (shown in Fig. 25), the bolt yielding does not progress any farther with a small load. Then, as far as the load F does not promote the bolt yielding, the loosening characteristic lines in Fig. 4 become horizontal ones. From the above, it can be presumed that when $T_w$ is smaller than $T_S$, the loosening characteristic lines in Fig. 4 become horizontal ones in the region where $F$ is small.

Also, the loading method to increase $F$ gradually by repeating loading and unloading every other time (Figs. 11~17 are obtained by this method) brings about a little smaller decrease in the bolt clamping force than the one-time loading method (Fig. 4 is calculated by this method). The assumed reason for this is that $F$ is applied when $T_S$ has decreased in proportion to the decrease in $Q$ that occurs under every unloading.

The loosening characteristic lines in Fig. 18 or 19 cross each other because of the variation of the static strength of bolts given in Table 2.

4.1.2 Critical load

The initial clamping force $Q_0$, the load that begins to separate the clamped parts $F_{Pw}$ and the critical load of loosening $F_{cr}$ are taken from Figs. 11~17 and other figures, and $Q_0$, $F_{max}$, $F_{cr}$, $F_{cr}/Q_0$, $F_{cr}/F_{Pw}$ are given in Table 3. $F_{cr}/F_{Pw}$ is always equal to 1 when the bolt is tightened over its yield point, and by this fact Eq. (20) is verified.

The values of $K_{HH}$ are calculated from Eq. (20) by using the values of $F_{cr}/Q_0$ shown in Table 3 and the results are given in Table 3. As it is evident from Figs. 7 and 8 that the bolts of grade 4T work-harden more per unit elongation than grade 5T, the values of $K_{HH}$ in Table 3 for these two grades also show this tendency. Next, the values of $K_{HH}$ of 5T bolts in Table 3 show the tendency that $K_{HH}$ is small near the yield point $Q_{Y}$, becomes large over $Q_{Y}$, and turns negative over the ultimate strength $Q_{U}$.

It is concluded that $F_{cr}/Q_0$ is always larger than 1 as far as $Q_0$ is smaller than $Q_{Y}$. In other words, the joint can sustain the load that is equal to $Q_0$ without any abrupt decrease in its clamping force.
Table 3. Initial clamping force $Q_a$. Load under which clamped parts begin separating from each other $F_m$, critical load of loosening $F_m$ and ratios of them.

<table>
<thead>
<tr>
<th>Bolt grade</th>
<th>$Q_a$</th>
<th>$F_m$</th>
<th>$F_t$</th>
<th>$F_r$</th>
<th>$F_{y,p}$</th>
<th>$F_{y,p}$</th>
<th>Note</th>
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<tbody>
<tr>
<td>4T</td>
<td>2.15</td>
<td>3.20</td>
<td>(40)</td>
<td>(51)</td>
<td>(128)</td>
<td>(153)</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>3.85</td>
<td>5.0</td>
<td>5.1</td>
<td>5.3</td>
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<td></td>
<td>5.65</td>
<td>5.2</td>
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<td>5.2</td>
<td>1.05</td>
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</table>

(Notes) When $F_t$ does not appear clearly under tightening below yield point, values are parenthesized.

4.2 Dynamic loosening test
4.2.1 Amount of decrease in clamping force

It is found from Figs. 22 and 23 that the decrease in the clamping force does not progress at all except in the case when the clamped parts separate from each other ($Q \leq 3t$). Though yield-tightened bolts lose a portion of their clamping force in the initial stage of the test, the larger the initial clamping force, the larger the residual clamping force is. Then, it is concluded that tightening bolts over their yield point has no disadvantage from the point of view of loosening.

4.2.2 Fatigue strength of bolt

It is found from Figs. 22 and 23 that the fatigue life of bolts tightened over their yield point is longer than that of ones tightened in elastic range. The assumed reason for this is that, in general, the larger the clamping force, the smaller the force (applied to the bolt by the load) becomes, which means a longer fatigue life.

5. Conclusions

(1) The relations between the load and the residual clamping force after unloading were analyzed theoretically on the bolts tightened over their yield point and the result shown in Fig. 4 was obtained.
(2) A static loosening test was carried out on the abovementioned bolts and it was verified that the theoretical and the experimental results coincide with each other very well.
(3) The bolt clamping force was measured several times per one specimen throughout the fatigue test of bolts tightened over their yield point, and the results shown in Figs. 22 and 23 were obtained. From these results it is concluded that tightening bolts over their yield point brings about no disadvantage of loosening and any smaller loading capacity, at least with the ductile bolts as used in the present test.
(4) The critical load for loosening increases in proportion to the bolt clamping force, as shown in Eq. (20). So, the loading capacity of a joint is increased by yield-tightening that brings about a larger initial clamping force.

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