Loosening of Bolts and Its Countermeasures, 9th Report

Failure of Fastening Screws and Their Preventive Methods

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1. Introduction

The failure due to loosening of bolts and thereafter fatigue will be introduced as follows: April 11th, 11:08 a.m. in 2008, a tire separated from a large truck, which was running on the Tomei up-expressway, got over the central reservation and badly hit the sightseeing bus directly which was running on the Tomei down-expressway. The tire had unfortunately crashed through the front glass of the bus and shot at the bus driver and 7 passengers. The 8 bolts fastening the tire were all broken and the fracture surface of the 2 bolts among them were covered with rust. There were 41 members including the driver and the tour conductor for one day trip in the bus. It is considered that the above rusted bolt fractured from loosening and thereafter "fatigued" earlier than the above accident.

In addition, there was another failure accident where 11 commuters were injured due to failure of bolts, which were used in the escalator. May 9th, in 2008, the up-escalator suddenly stopped and ran down in Hisaya-odori station of Nagoya city municipal subway. The 11 commuters were badly injured due to the failure of 3 bolts. The 3 bolts, which were used for the stand of motor etc. were broken in that escalator system. In addition, the stand was moved by several centimeters from the normal position. The failure of the step caused such a sudden accident due to slackness of the driving chain. (Similar accident happened in the other escalator and 2 bolts were broken in that case). The above fracture of the bolts is also considered due to "fatigue" after loosening.

As considered above, loosening of bolts is closely related to failure accidents and induces "fatigue fracture of bolts. Therefore, loosening of bolts and its countermeasures will be referred in this report in viewpoint of security.

2. The Importance of Anti-loosening of Bolts

Figure 9.1 shows the balancing relation between the external force and the internal one applied to the screw fastened member.

where Wa: external force, ft, fc: internal forces, respectively

Kt: spring constant of the bolt,

Kc: spring constant of the fastened member,

Ff: tightening force to the bolt,

Ft: internal force due to external varying force Wa

In this case, F_t and F_c are expressed as shown below:

$$F_t = K_t \cdot \lambda \quad \cdots(1)$$

$$F_c = K_c \cdot \lambda \quad \cdots(2)$$

From the balance of forces,

$$W_a = (F_f + F_t) - (F_f - F_c) = F_t + F_c \quad \cdots(3)$$

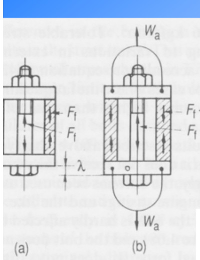
Substituting eqs. (1) and (2) into Eq.(3)

$$W_a = (K_t + K_c) \cdot \lambda$$

$$\lambda = \frac{1}{K_t + K_c} W_a \quad \cdots(4)$$

Substituting eq. (4) into eqs. (1) and (2)

$$F_t = \frac{K_t}{K_t + K_c} W_a \qquad F_c = \frac{K_c}{K_t + K_c} W_a \quad \cdots(5)$$



The ratio of the tensile force K_t added to the bolt by the external force W_a to the external force W_a applied to the fastening screw is expressed in terms of the internal force coefficient φ of the bolt as shown below:

$$\phi = \frac{K_t}{W_a} = \frac{K_t}{K_t + K_c} \quad \cdots(6)$$

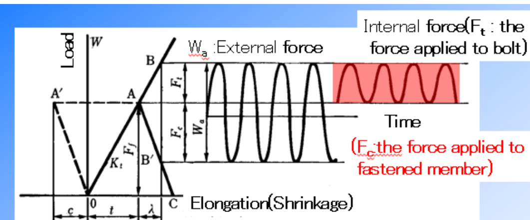
F_t and F_c in eq. (5) can be expressed as shown below by using φ

$$F_t = \phi W_a$$

$$F_c = (1 - \phi) W_a \quad \cdots(7)$$

Fig. 9.1 Balancing relation between the external force and the internal one applied to the screw fastened member

Figure 9.2 shows the relation between the force and shrinkage in the bolt and the fastened member, respectively. In addition, Table 9.1 lists the non-loosening condition of the bolt. That is, the non-loosening condition is expressed by the eq. (10) or (11).



K_t: Spring constant of bolt, K_c :Spring constant of fastened member,
W_a: External force less than tightening force, F_f :Tightening force to bolt,
F_t: Internal force due to external varying force W_a, F_c: ref. to the above

Internal force due to external force W_a :
one fifth of external force in the case of Φ=0.2

$$F_t = \frac{K_t}{K_t + K_c} W_a \quad \cdots\cdots\cdots(8)$$

Maximum force applied to bolt

$$F_{max} = F_f + \frac{K_t}{K_t + K_c} W_a \quad \cdots\cdots\cdots(9)$$

Fig. 9.2 Relation between the force and shrinkage in the bolt and the fastened member

Table 9.1 Non-loosening Condition of the Bolt

Referring to the above Figs. 9.1 and 9.2,

$$F_f \geq K_c \cdot W_a / (K_t + K_c) \quad \cdots\cdots\cdots\cdots(10)$$

or

$$W_a \geq (1 + K_t / K_c) \cdot F_f \quad \cdots\cdots\cdots\cdots(11)$$

W_a: External force、K_t: Spring constant of the bolt、
K_c: Spring constant of the fastened member、
F_f: Tightening force to the bolt
F_t: Internal force due to external varying force W_a

The external force is divided into the internal force to the bolt and that of the fastened member.

For example, let's consider the following case: the internal force factor is φ=0.2 (ref. Fig. 9.3) under the non-loosening condition. In eq.(7), when the fatigue limit of a conventional bolt (Kt=Kc) is Ft=6 kgf/mm^2, this bolt can endure the varying external force until Wa=6/0.2=30kgf/mm^2, because 80% of the external force is applied to the fastened member. In other words, the fastened bolt can endure the varying stress of 30kgf/mm^2, if the fastened bolt does not loosen. That is, the fatigue limit of the bolt with the fastened member becomes practically 30kgf/mm^2 under the non-loosening condition. On the other hand, if loosening occurs in the fastened bolt, all of the external stress will be applied to the bolt. Therefore, the bolt will be immediately broken.

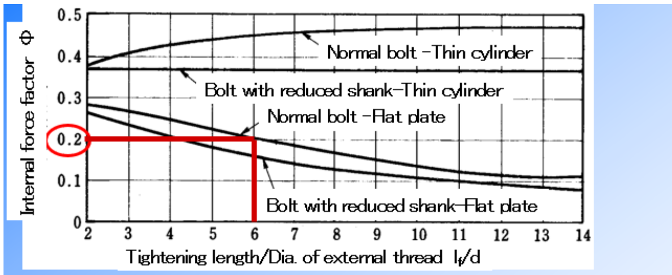


Fig. 9.3 Quick calculation diagram of internal force factor

Therefore, anti-loosening countermeasure will be essentially required for the fastened screw.

3. Introduction of Anti-loosening Countermeasures

Several kinds of anti-loosening tools have been already sold in the market. These are almost expensive, not repeatedly used, not applied for an embedded bolt and required for longer setting time before operation etc.

Here is the anti-loosening bolt, in other words, "Super Lock Bolt" as the brand name. Two kinds of nuts with different thread pitches are fastened to one bolt and this system can even endure violent vibration. Figure 9.4 shows composition of the double thread bolt compared with JIS standard double nuts. In the case of JIS double nuts, the power nut and the lock one are the same with coarse pitch. On the other hand, the power nut is coarse thread and the lock nut is fine pitch thread in the case of "Super Lock Bolt". Even if the power nut is loosened by the vibration etc., the interference will occur between the power nut and the lock nut due to the pitch difference between them (ref. Fig.9.5)[4),5)].

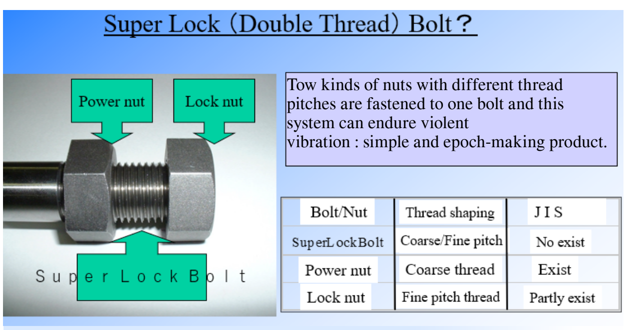


Fig. 9.4 Composition of the "Double Thread Bolt" (compared with JIS standard double nuts)

Fig. 9.5

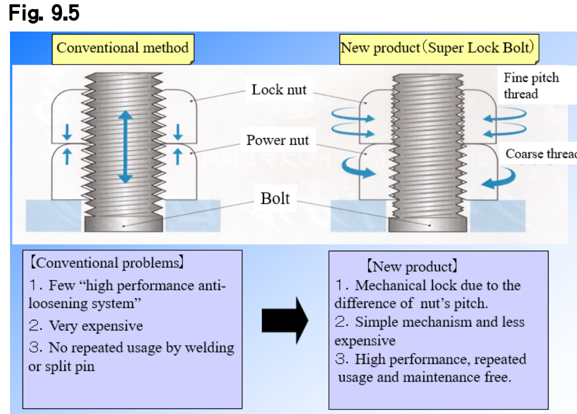


Figure 9.6 shows an outer appearance of "the double thread bolt, M8", which is produced by actual mass production equipment. Though this double thread bolt shows excellent performance for anti-loosening, there are some defects in this one. That is, the above system is not applicable for an embedded bolt, the double nut system is heavier than the single nut, required for longer time for working, etc.

Fig. 9.6 An outer appearance of the double thread bolt

4. New Anti-loosening Countermeasures

In the case of anti-loosening method, the most popular one is the double nuts system. This method is pretty heavy, needs longer thread and requires longer time to tighten the bolt, not reusable, etc. Now, the need appears if there are some superior countermeasures for anti-loosening by a single nut. The new anti-loosening countermeasures with a single nut based on a very simple mechanism are as follows;

4.1 Anti-loosening by Pitch Difference Between the Bolt and the Nut

Figure 9.6 shows the typical combination of a bolt and a nut. In addition, Fig. 9.7 shows the enlargement of A part in Fig. 9.6. Generally, the pitch of the bolt coincides with that of the nut. Therefore, the axial stress does not occur between the thread of the bolt and the nut. On the other hand, the axial stress will occur between them, when the pitch of the nut is processed to be a little larger than that of the bolt. That is, the thread of the nut will expand the thread of the bolt after fastened between the two parts. Especially, the compressive residual stress will occur in the most dangerous section of the bolt; that is in the B point in Fig. 9.8. This compressive residual stress can serve to improve the fatigue strength of fastened portion. In addition, the above axial stress induced by the difference of the pitch between the two should operate for anti-loosening between the bolt and the nut.

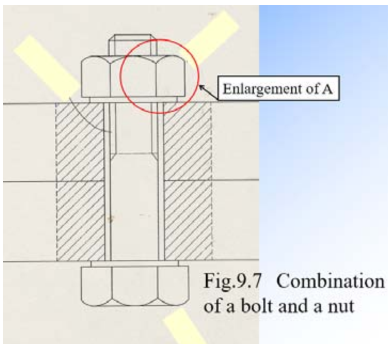


Fig.9.7 Combination of a bolt and a nut

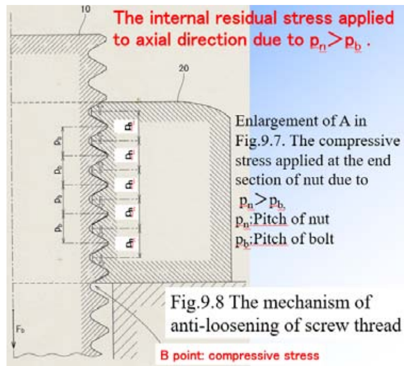


Fig.9.8 The mechanism of anti-loosening of screw thread

Figure 9.9 shows the outer appearance of an anti-loosening screw with a single nut due to the pitch difference between the bolt and the nut. This anti-loosening screw consists of a very simple mechanism and this mechanism can also be applied to an embedded bolt. In the case of fastening, only several pitches can be set by a human hand and easily fasten the nut by a screw fastener thereafter.

Fig. 9.9 The anti-loosening bolt with a single nut (This mechanism can be applied to an embedded bolt)

Figure 9.10 shows the loosening test result. The loosening test was performed according to NAS3354 specification. That is, cyclic frequency: 1,780cpm, stroke of the vibration base: 11mm, impact stroke: 19mm, the direction of vibration: right angle to the axis of the bolt, judgement for loosening: the gap of the marking line on the bolt and the nut after 30,000 cycles (about 17 minutes). As clearly found, though the nut annealed by 650℃×60min, loosened after 3 minutes, the nut annealed by 900℃×60min, endured 17min in the test . The soft nut is also effective for its anti-loosening in this system.

Fig.9.10 Loosening test by NAS3354 specification

4.2 Shot Peening Treatment to Threads of Bolts or Nuts

One more anti-loosening countermeasure is introduced below.

Figure 9.11 shows an outer appearance of shot peening treatment at the end of the nut in this case. As is known, the shot peening method has been used for removing the surface rust on thick plates. In addition, this method is also applied for giving the residual compressive stress at the dangerous section of the part and for improving the performance of the part, that is, especially fatigue properties by giving surface plastic deformation slightly. The surface by shot peening treatment was locally deformed toward shot-peened direction. As the inner layer is not deformed, the surface is compressed and the inner layer suffers the tensile stress due to the difference of deformation between the surface and the inner layer. In the case of the nut, the thread of the nut is plastically deformed due to the shot peening treatment. That is, the thread of the nut is a little bit declined to the shot-peened direction. This treatment could be applied not only to the thread of the nut, but also to that of the bolt. This anti-loosening screw also consists of a very simple mechanism and can be applied to an embedded bolt. In the case of fastening, only several pitches can be set by a human hand and easily fasten the nut by a screw fastener as similar to the above anti-loosening by pitch difference.

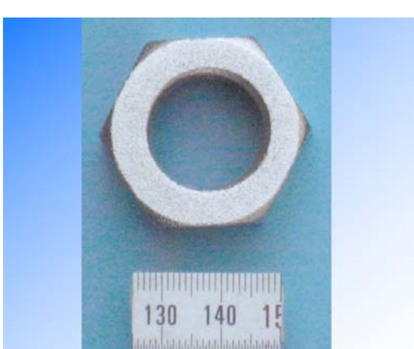


Fig. 9.11 Shot peening treatment at the end of nut

Table 9.2 lists the new anti-loosening countermeasures. Both methods can also be used together if necessary.

Table 9.2 Anti-loosening Countermeasures:

(1)Anti-loosening by pitch difference:
Small pitch difference between the bolt and/or the nut →Axial force will be applied in the fastened thread members→Anti-loosening properties.

(2)Shot peening to the thread:
Shot peening to threads of the bolt, nut or both →Anti-loosening propertie

(3) (1)+(2) in the above

5. Conclusions

The main results described above in this report are summarized below;

(1) In order to avoid fatigue fracture, anti-loosening properties are very important for the safety of the fastened portion.

(2) Although there are several kinds of anti-loosening fasteners, they are almost expensive, heavy, unreusable use and badly workable etc.

(3) Although the Super Lock Bolt, which features dual threads, shows high anti-loosening properties, it also features some disadvantages described in (2).

(4) The anti-loosening countermeasures by pitch difference or shot peening are both developed by a very simple mechanism and show superior performance.

References

(1) e.g. April 12th(Saturday) and 13th, in 2008, Mainichi morning news paper.

(2) May 3rd (Saturday), in 2008, Mainichi morning news paper.

(3) S. Nishida, Failure Analysis in Engineering Applications, (1993), pp.68, Butterworth Heineman Co. Ltd., UK.

(4) Shin-ichi Nishida et.al., Development of the double thread bolt, which is superior to anti-loosening performance, (2004)

(5) Shin-ichi Nishida et.al., Mass Production of the double thread bolt by form rolling with plane dies, (2007).