Failure of Fastening Screws and Their Preventive Methods

-A new method for improvement of the fatigue strength of bolt (the last half), 7^{th} report-

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Introduction

In the 6th report (the first half) and the 7^{th} one (the last half), the author has referred to a new method for improvement of the fatigue strength of bolt. First of all, the factors related to the fatigue strength of bolt have been quantitatively evaluated by performing fatigue tests accounting on thread profile, root radius, mechanical properties of bolt and of nut, and pre-stressing. In addition, the author will introduce a new method for improvement of the fatigue strength of bolts in this report. The main results described above are summarized in **Table 7.1**[(1)-(4)].

Items for study	*Type of bolt*	*Materials used*		*Size of bolt* (mm)			*Pretreatment*	*Test conditions*		*Fatigue strength at* 2×10^6 *cycles* (kgf/mm^2)	*Increasing ratio of fatigue strength* (%)	*Remarks*
		Bolt	*Nut*	*Minor diameter-*	*Root radius, r*	*Pitch*		*Mean stress* (kgf/mm^2)	*Frequency* (*cycles/min*)			
Fatigue strength of bolts with various threads	Triangular thread	SCM440	SCM440	25.0	0.30	3.0	No pretreatment	18.0	500	±6.0	100	Normal shape (standard bolt)
	Trapezoidal thread	SCM440	SCM440	25.0	0.25	3.0	ibid	18.0	500	±7.0	117	
	Positive buttress thread	SCM440	SCM440	25.0	0.35	4.0	ibid	18.0	500	±6.0	100	No effect
	Negative buttress thread	SCM440	SCM440	25.0	0.30	4.0	ibid	18.0	500	±7.0/±8.0	117/133	
Size effect	Triangular thread	SCM440	SCM440	32.0	0.80	3.6	ibid	18.0	350	(±6.0)	100	
	ibid	SCM440	SCM440	40.0	1.00	5.5	ibid	18.0	350	(±6.0)	100	
Effect of root radius *r*	ibid	SCM440	SCM440	25.0	0.50	3.25	ibid	18.0	500	±6.0	100	No effect
	ibid	SCM440	SCM440	25.0	0.70	3.5	ibid	18.0	500	±6.0	100	No effect
Effect of mechanical properties of bolt	ibid	SNCM630	SNCM630	25.0	0.40	3.25	ibid	18.0	500	±6.0	100	No effect† Slightly negative effect
Material of nut	ibid	SNCM630	S20C	25.0	0.40	3.25	ibid	18.0	500	±7.0	117	
Effect of prestressing (new method)	ibid	SNCM630	SNCM630	25.0	0.40	3.25	Prestress 43 kgf/mm^2	18.0	500	±9.0	150	
	ibid ibid	SNCM630	S20C	25.0	0.40	3.25	Prestress 37 kgf/mm^2	18.0	500	±7.5	125	
	Gradual cut-off of bolt's thread	SNCM630	SNCM630	25.0	0.40	3.25	Prestress 33 kgf/mm^2	18.0	500	±12.0	200	CD bolt
Effect of gradual cut-off method of bolt's thread (new method)	ibid* Gradual cut-off of bolt's thread	SNCM630	SNCM630	25.0	0.40	3.25	Gradual cut-off from 1st thread to 8th one	18.0	500	±11.0	183	Engaged nut at 4th thread

* Gradual cut-off of bolt's thread means CD bolt.
† Fatigue life becomes about 1/10th.

Table 7.1. Summarized Fatigue Test Results for Bolts

A New Method for Improvement of the Fatigue Strength of Bolts

2.1 Remarkably High Fatigue Strength of the CD Bolt

As introduced in the 5^{th} report, the fatigue limit of conventional bolt is rather low at 5~6 kgf/mm^2 (about 50~60MPa) for its representative value. Now, the author would like to present the remarkably high fatigue strength of the CD bolt. The CD bolt is the trade name of a bolt manufactured by the Nippon Steel Bolten Co. Ltd. The name of CD stands for Critical Design for "Fracture" including "Fatigue", which means the ultimate profile of a thread at the present time. This design is most effective not only for fatigue properties but also for delayed fracture (HE, hydrogen embrittlement) and stress corrosion crack (SCC) because of the stress relaxation effect by "CD shaping". The delayed fracture and the stress corrosion crack are in other words called "environmental brittle fracture". The shaping method based on the CD bolt is called CD shaping. As know-how is involved in the use of the method, the manufacturer should be consulted by the engineer related. As described before, the fatigue strength of normal bolts is far lower than that of a specimen with a single notch which is made of the same material. This is because the load is transmitted in the bolt through the contact between external threads and internal ones. The low fatigue strength is attributable to the following four factors, which have been clarified for the first time by the author:

(1) Uneven load sharing among the threads

(2) Tensile stress concentration at the thread root

(3) Bending stress concentration at the thread root, and

(4) Localized loading.

The factors, except for factor (2), are not encountered with conventional notched specimens. Accordingly, the other three factors are the dynamic phenomena which are characteristic of fastening screws. So far, only two methods have been proposed for the four factors as described in 5th report.

One is the method for ensuring equal load sharing among the threads. The other is the method in which the internal force coefficient is decreased depending on the part to be fastened as the bolts are normally used in a tightened condition (see **Fig. 5.10**, in 5th report). However, the former method is effective for only one of the four factors, while the latter method is only effective when the bolt is used by applying a tightening force. Moreover, the above methods become ineffective if the bolt becomes loose or if an external force which is large enough to cause plastic deformation of the bolt is applied.

2.2 Shape of the CD Bolt

The method introduced below is newly developed for improving the fatigue strength of bolts itself. The typical shape of the bolt (hereinafter referred to as the CD bolt) is shown in **Fig.7.1.** Shown here is the CD bolt with a nominal diameter body. Needless to say, the idea of the CD bolt is not only applicable to the bolt with a pitch diameter body but also to the bolt with a reduced shank.

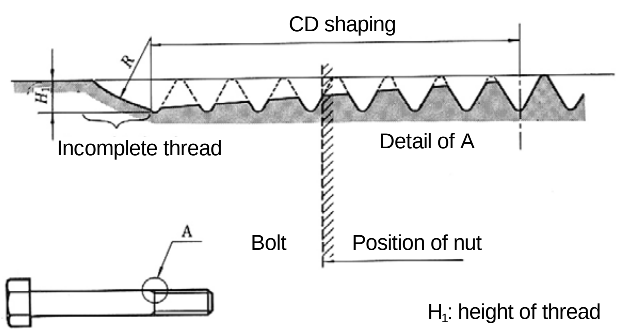


Fig.7.1 Typical shape of CD bolt

A typical example of CD shaping is described below. In the case of coarse threads of normal size, the CD shaped portion has an adequate gradient (e.g. 6/100) and becomes a complete thread. In addition, the incomplete thread is almost completely removed by CD shaping and this portion is connected to the body by a gentle arc (R≧10mm). The optimum end section of the nut is such that about 70～80% of the CD-shaped part of the bolt goes into the nut. If the distance between the end section of the nut and the incomplete thread is too long because of a long thread, the length of the part from which the thread is removed should be increased. The fatigue strength at the end section of the nut and the incomplete thread can be considerably improved by this method. Moreover, the fatigue strength of the under-head fillet should be improved. For this improvement, the radius R under the head should be increased (R≧5mm), or work hardening will be adoptable for the above purpose. That is, compressive residual stress could be applied to the rounded part under the head by cold working (shot peening or punching).

2.3 General Features of the CD Bolt and Precautions in Its Use

The CD bolt has been developed from the dynamic standpoint to improve the fatigue characteristic of bolts. The CD bolt incorporates all the measures necessary for the improvement of the fatigue strength of bolts. Accordingly, there is remarkable difference in effect of the fatigue properties between the CD bolt and the conventional ones. The fatigue characteristic of the CD bolt is excellent, as described below:

(1) The load is shared uniformly.

(2) As the height of the threads of bolt in engagement with the nut is reduced, the tensile stress concentration is relaxed at the thread root.

(3) As the height of the bolt thread is reduced, the distance between the loaded portion of the thread and its root is decreased if the thread is assumed to be a cantilever. Accordingly, the bending stress concentration at the thread root is remarkably relaxed.

(4) As the contact surface pressure is increased, the contact area between the bolt and the nut is easily deformed and contact is made between the bolt thread and the tip of the thread on the nut side which is more likely to be deflected.

Accordingly, localized loading due to low shaping accuracy or other factors is reduced. In other words, the CD bolt is the only one for which all measures being necessary for the improvement of fatigue strength have been taken.

Precautions in the use of the CD bolt are described below. The optimum position of engagement between the CD bolt and the nut is determined depending on the characteristic thread profile of bolt. On site, however, the nut and the CD bolt are not necessarily engaged at the optimum position. In such cases, adjustment should be made by changing the thickness of the washer. However, there may be the cases in which adjustment with a washer is difficult. As a rough guide, the tolerance is about ±1 thread. In other words, all allowance of about 5 mm can be made for tightening in the case of bolts with M20 coarse thread as a typical example. This allowance is considered to be practically sufficient.

2.4 Fatigue Strength of the CD Bolt[(1)-(4)]

The fatigue characteristic curves in the cases where CD shaping is applied are shown in **Figs.7.2-7.4**. The bolts shown in **Fig.7.2** is usually used for mechanical parts. On the other hand, the bolt, which is called high tension bolt, shown in Fig.7.3 is applied for the parts of civil engineering and constructions. As shown in these figures, the CD bolt shows about twice fatigue limit than a conventional JIS bolt. The reason why the fatigue strength in Fig.7.3 becomes lower than that in **Fig.7.2** is due to the clearance between the bolt and the nut. In other words, this is because the fatigue strength of a bolt is dependent upon the combination with a nut. In the case of machine bolts, both the bolt and the nut are threaded by a lathe, and therefore this combination is nearly free from looseness (looseness means clearance between threads of a bolt and a nut). In the case of the high-tensile bolt and the anchor bolt, however, looseness is increased because of their uses (as the nut threads are over-tapped). **Figure 7.4** shows the calculation result of the stress concentration at thread root by three-dimensional analysis. As shown in this figure, the stress concentration of the CD bolt becomes half of that of the JIS bolt. In addition, though the un-uniform loading becomes fairly relaxed by CD shaping, this profile does not necessarily access the ideal uniform loading. If time allows, it is desirable to conduct a fatigue test of bolts and nuts made of various materials in various shapes by various methods and to design the bolt on the basis of the results of the tests.

For CD shaping, a gradient of a about 6/100 is desirable from the standpoint of the fatigue characteristic. In the case of large-diameter bolts with fine or coarse threads larger than M40 in which the thread height is relatively lower for their diameter, it is necessary to change this gradient from 6/100. Ideally, it is necessary to eliminate or relax all the factors governing the fatigue strength of bolts as described previously. CD shaping is designed so that all of the four factors are eliminated only by taking a suitable measure for ensuring uniform load sharing (see **Tables 7.1**[(1)-(4)] **and 7.2**, **Figs.7.4, 7.5**[(1)-(3)] and **7.6**). Accordingly, CD shaping should be done in line with this idea. In other words, the gradient of the part to be subjected to CD shaping can be so determined that the shaped part accounts for 70-80% of the whole thread and the thread engagement at the end section of the nut becomes 20-30% of the conventional engagement. These values are determined by the empirical methods.

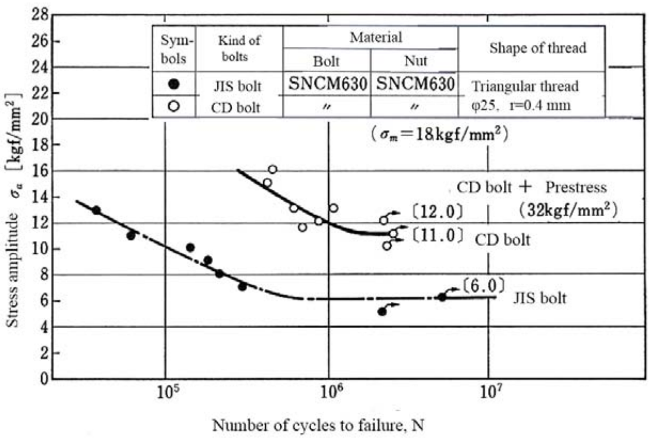


Fig.7.2 S-N curve of C D bolt

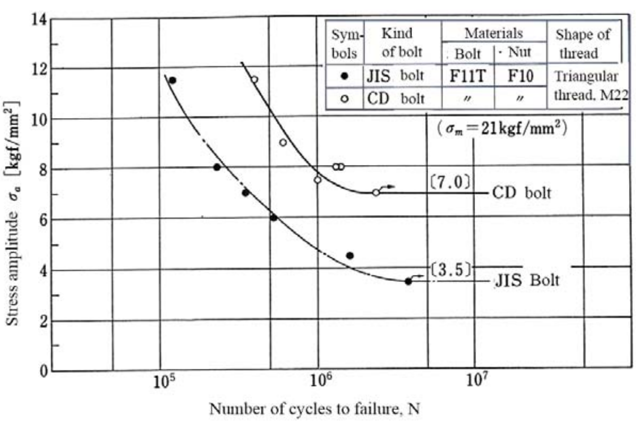
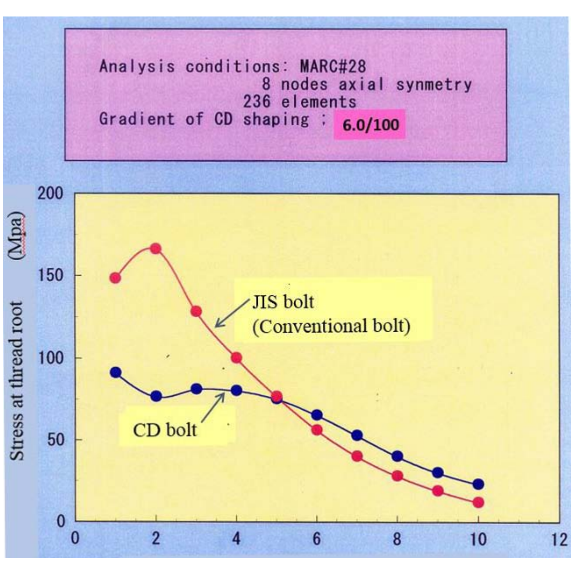


Fig.7.3 S-N curve for C D bolt for high-tension bolts



Number of thread in engagement with the nut

Fig.7.4 Calculation result of the stress concentration at thread root by three-dimensional analysis

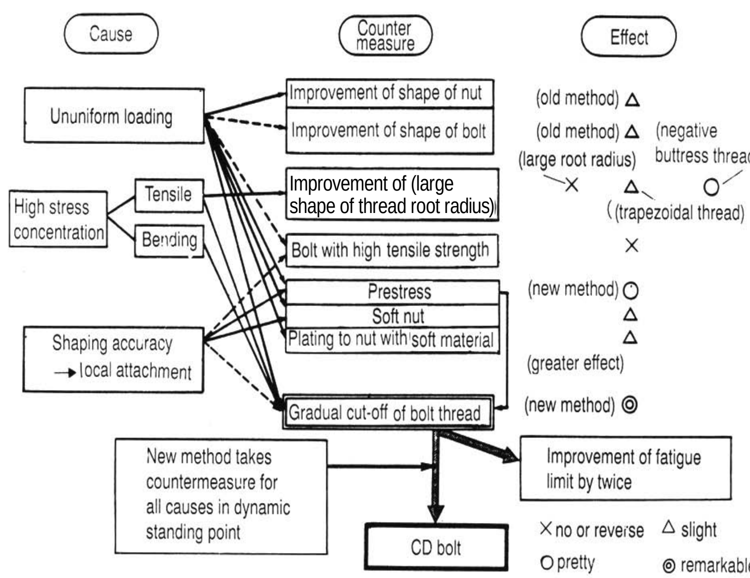


Fig.7.5 General factors governing the fatigue strength of bolts, countermeasures and their effects

Table 7.2 Comparison between conventional bolt and CD one

	JIS bolt	CD bolt
Uniform loading	Loading to the first thread by about 1/3 of the total load (see Table 2.2)	Decrease to half of JIS bolt (see Fig.6.11)
High tensile stress con-centration	High stress concentration	Relaxation of stress concentration
High bending stress con-centration	High stress concentration	Relaxation of stress concentration
Local attach-ment	Remarkable increase in high tensile material and large diameter bolt	Relaxation in local attachment

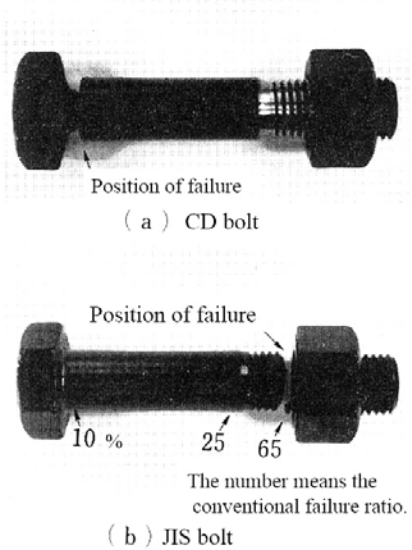


Fig.7.6 Difference in position of failure between (a) CD bolt and (b) JIS bolt

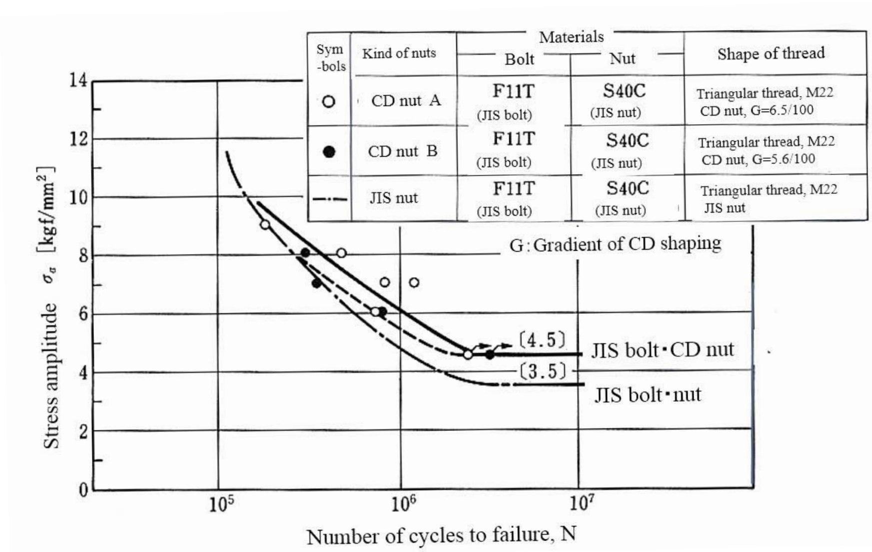


Fig. 7.7 S－N curves for CD nuts

2.5 The CD Nut Based on CD Shaping

In case where the bolts in stock are used in an emergency, the threads cannot always be engaged in the optimum way. The CD bolt is inconvenient in this point. In such cases, the use of the CD nut for which there is no limitation on the position of engagement is recommended, although the fatigue strength may be considerably decreased (see **Fig.7.7**) comparing with that of the CD bolt. When the CD nut is used, the fatigue limit is improved by about only 1 kgf/mm^2, which is about one-third or one-quarter of the improvement made by the use of the CD bolt. This may be because the one measure are taken among the four measures for governing the fatigue strength of the bolt, i.e. uniform load sharing.

Static Characteristic of the CD Bolt

The static characteristics of the CD bolts, the proof loads of nut and the torque coefficients of high-tensile bolts are shown in **Tables 7.3, 7.4 and 7.5**, respectively. As is apparent from these tables, there is little difference in the static tensile characteristic between the CD bolt and the conventional one. Looking at the shape of the CD bolt shown in **Fig.7.1**, it may be intuitively apprehended that the threads may be fractured by shear or plastically deformed and the bolt may easily come out of the nut if the bolt is pulled. However, it will be understood from Tables 7.3 and 7.4 that such fears are groundless.

Table 7.5 lists the testing results of the torque coefficient. The torque coefficient is given by the following equation:

$$k = \frac{T}{d \cdot N} \times 1000 \qquad \cdots\cdots\cdots\cdots (7.1)$$

Table 7.3 Static tensile properties

Nominal dia. × total length	Type of bolt	Proof stress $\sigma_{0.2}$ [kgf/mm²]	Tensile strength σ_B [kgf/mm²]	El. [%]	φ [%]	σ_B' [kgf]
M16×55	CD bolt	110	116	18	68	18000
	JIS bolt					18500
M22×140	CD bolt	112	118	17	63	35100
	JIS bolt					35800

El., elongation; φ, reduction in area, σ_B', tensile strength of bolt with nut

Table 7.4 Guarantee test result of nut

Nominal diameter × total length	Type of bolt	Maximum load [kgf]
M16×55	CD bolt	18 200
	JIS bolt	18 300
M22×65	CD bolt	36 400
	JIS bolt	36 200

Table 7.5 Torque coefficient of high-tension bolt

Nominal dia. × total length	Type of bolt	Torque coefficient $\bar{K}$	Standard deviation σ	Specification
M16×55	CD bolt	0. 163	0. 0046	B type $\bar{K}$=0. 150～0. 190 ≦0. 013
	JIS bolt	0. 166	0. 0012	
M22×65	CD bolt	0. 122	0. 0088	A type $\bar{K}$=0. 110～0. 150 ≦0. 010
	JIS bolt	0. 123	0. 0045	

where k is the torque coefficient, T is the torque (nut tightening moment, kgf-m), d is the basic size of thread diameter of the bolt (mm) and N is the axial tension of the bolt (tensile force produced in the axial direction of the bolt, kgf).

The deformability of the bolt is shown in **Fig.7.8.** There is little difference in the deformability between the CD bolt and the conventional one.

The test results for loosening of axial load by vibration are shown in **Fig.7.9**, although the loosening does not belong to the static characteristic in the strict sense. There is little difference between the CD bolt and the conventional one.

As the CD bolt, particularly the threaded part, has a higher fatigue strength, the fracture of the CD bolt occurs under the head. On the other hand, the fracture of the conventional bolt initiates at the end section of the nut. An example of such kind of fracture is shown in **Fig.7.6**.

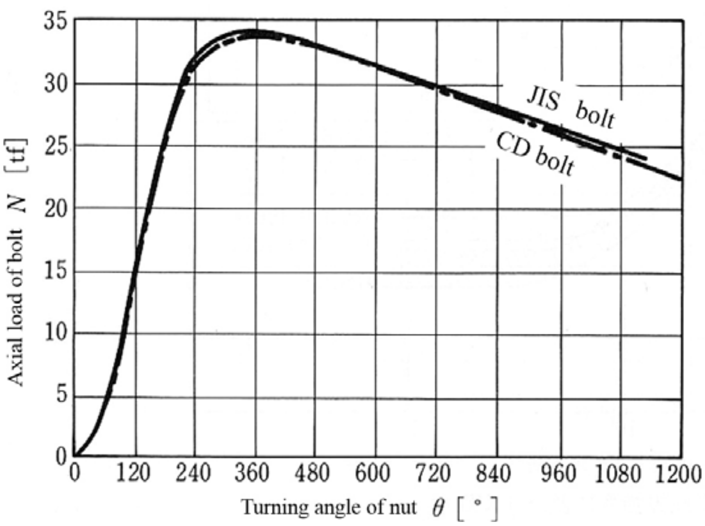


Fig.7.8 Deformability of bolts

Table 7.6
A new method for improvement of the fatigue strength of bolts (summary) :

(1) Countermeasure to the four factors governing the fatigue strength of bolts:

1. Uneven load sharing among the threads→Uniform loading

2. High tensile stress concentration→Relaxation of stress concentration

3. High bending stress concentration→Relaxation of stress concentration

4. Local attachment→Relaxation in local attachment.

∵ As the contact surface pressure is increased, the contact area between the bolt and the nut is easily enlarged due to the contact between the bolt thread and the tip of the nut thread which is more likely to be deflected.

(2) Improvement of fatigue limit by twice→

Several times improvement for the external load →

∴ Remarkable improvement of fatigue strength such a notched parts and a loaded mechanism by the contact with bolt and nut.

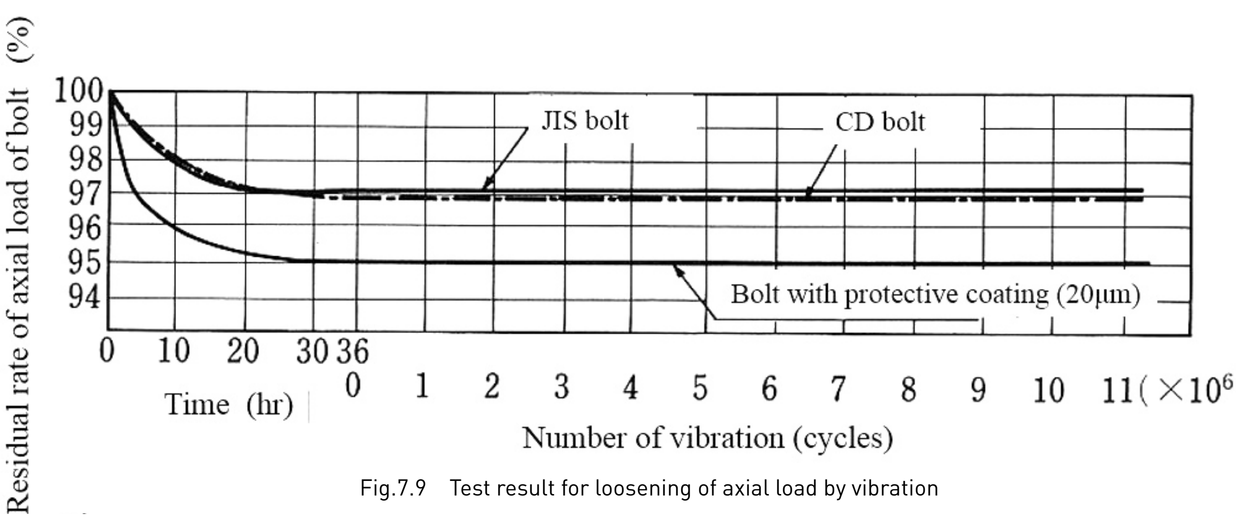


Fig.7.9 Test result for loosening of axial load by vibration

Summary of the Fatigue Strength of CD Shaping

The summarized fatigue test results about the bolts are listed in **Table 7.1**, again. As shown in this table, the fatigue strength of the other kinds of bolts is nearly equal to that of the bolt with a triangular thread. Conversely, the fatigue strength of the bolt with triangular thread is not so low. It may be said that the triangular thread is nearly the ideal shape if its workability is taken into account. For this reason, we may be given the impression that the triangular thread is nearly the perfect thread, leaving little room for further improvement.

When comparing among these results, the CD bolt shows the predominant high fatigue strength. **Figure 7.5** shows general factors governing the fatigue strength of bolts, countermeasures and their effects. These are un-uniform loading, high stress concentration (tensile and bending), and local attachment. Only the CD bolt copes with all of the factors which governing the fatigue strength of bolts and becomes more excellent than the JIS bolts.

Table 7.2 lists the comparison between the conventional (JIS) bolt and the CD one. In addition, as the threaded portion of the CD bolt becomes improved for fatigue strength, the fracture occurs under the head because the fatigue strength is considered to be higher, while fracture of the conventional bolt initiates at the end section of the nut (see **Fig.7.6**). As this table lists the four factors controlling the fatigue strength of a bolt, it is clear about the reason of the excellent improvement of fatigue strength of the CD bolt as the summary (see **Table 7.6**).

Conclusions

The main results described above in this report are concluded below:

Shape of the CD bolt: In the case of coarse threads of normal size, the CD shaped portion has an adequate gradient (e.g. 6/100) and becomes a complete thread. In addition, the incomplete thread is almost completely removed by CD shaping and this portion is connected to the body by a gentle arc (R≧10mm).

Fatigue strength of the CD bolt (at 2×10^6 cycles): the fatigue limit of the CD bolt is nearly two times of that of the conventional bolt. This improvement is remarkable because a bolt is a kind of notched specimen and the load is transmitted by the contact between the threads of a bolt and a nut.

The above result shown in (2) would be considered to be first achievement in the world for the outstanding improvement of fatigue strength. The reason why the above results are induced is to eliminate or relax all the factors governing the fatigue strength of bolts. CD shaping is designed so that all these factors are eliminated only by taking a suitable measure for ensuring uniform load sharing.

The CD nut: though there is no limitation on the position of engagement between a bolt and a nut, the fatigue strength is improved only by about 30%, which is about one-third or one-quarter of the improvement made by the use of the CD bolt.

Static characteristic of the CD bolt: there is little difference in the static tensile characteristic including the loosening of axial load by vibration between the CD bolt and the conventional bolt.

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Don't ask How Much Security Isn't Penny

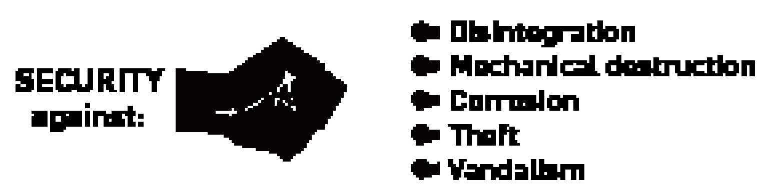
by Josef Dominik

The slogan in the title is intended to emphasize the importance of security in general and, as will be shown in the following text, particular in the screw connections and that it is not a cheap matter. Dramatic accidents on railways, on the road, in various constructions, means of transport and others are a sufficient reason to be serious about this issue.

Introduction

As shown in the table below, there are five reasons why screw connections must be secured. They are disintegration due to the vibration and dynamic stress, mechanical overload, theft and vandalism.

With the exception of vandalism in all other cases, the designer is competent to take appropriate measures.



Measures

Against disintegration

In principle, a properly dimensioned and well-tightened screw connection does not need external protection due to vibration and/or dynamic stressing. In practice, however, there are cases of extreme stress where necessary. The process of spontaneous loosening of bolted joints is sufficiently explored and therefore there is no need to talk about it in this post. Unfortunately, the current theory of screw joint self loosening is based only on one type of dynamic stress, that is in the axial direction. In the previous publications, the author has often emphasized that dynamic axial stress is equally dangerous (Fig. 1). Typical examples are in Fig. 2 and 3. Since there is no universal way of securing the screw connections, the constructor must make the professional decision and not succumb to overblown advertising.