Failures of Fastening Screws and Their Preventive Methods

Fatigue failures of bolts, 2nd report

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Fastening screws are so widely used in daily life that their usefulness is not fully recognized. We are apt to attach less importance to screws by saying "only one bolt", or "only one screw" in spite of their important functions. In practice, machine design begins with major parts and ends with small parts, such as bolts. In many cases, therefore, the manufacture of bolts and other small parts is started without fully examining their safety, including fatigue. In short, bolts and the like are machine parts for which serious consideration is apt to be neglected.

The examples described below indicate the importance of fastening screws. On 4 February 1966, All Nippon Airways' regular flight from Chitose Airport in Hokkaido, in the northern part of Japan, crashed into the sea just before landing at Haneda Airport in Tokyo. In this accident, all 133 people aboard the plane (both passengers and crews) were killed. Immediately after the accident, an Accident Investigation Committee was set up by the Ministry of Transportation. The committee submitted reports, including the results of a simulation which was voluntarily undertaken by one of the committee members[1]. For us, there is no way of knowing the exact cause of the accident. However, the official reports suggest that the most probable cause of the accident was complete failure of the engine due to fatigue failure of the engine set bolts (called "cone bolts"). The failure must have caused the plane to lose its balance and crash into the sea.

In July 1975, the hook of a crane in use at a certain steelworks broke, resulting in the death of employees. The accident is attributable to the fatigue failure of the screws. In any case, the screws are the most critical parts in the crane hook. For this type of failure, the report prepared by Y. Kitsunai will be of good reference.[2-4]

Apart from such serious accidents, failures of bolts occur frequently[5-7]. Figure 1.4 (1st report), bolt failures stand third in importance but the number of bolt failures that actually occurred is estimated to be the largest. Bolts can be more easily manufactured and purchased than other parts. If they are broken, therefore, they are simply replaced by new bolts. For this reason, the number of failures reported is far smaller than the number of failures which have actually occurred.

In modern plants, the operations are performed online to increase production efficiency. It may not be too much to say that the smooth operation of machines at these plants is dependent largely upon only a single bolt. Since failure of a bolt is attributable mostly to fatigue, designing against fatigue is very important for bolts.

In this paper, several examples of bolt failures are described by fatigue and their macroscopic fracture surfaces are analyzed with simple calculation methods.

Failure of fastening screws[5-7]

2.1 Failure of the tie rod of a rolling mill

The front view of a rolling mill and the position of failure in the mill are shown in **Fig.2.1.** The mill is designed so that the rolling reaction force is received by four giant bolts (called the tie rod: outside diameter of thread=φ475mm, body diameter φ450×total length 13,975mm). Failure was detected in two out of four tie rods. One of the two tie rods was completely broken and cracks were detected in the other rod. This failure is shown schematically in **Fig.2.2.** In the two tie rods, failure occurred in the end section of the nut or its vicinity on the side where the material to be rolled is bitten. The material of the tie rod is SCM440. The chemical composition of SCM440 is listed in **Table 2.1.**

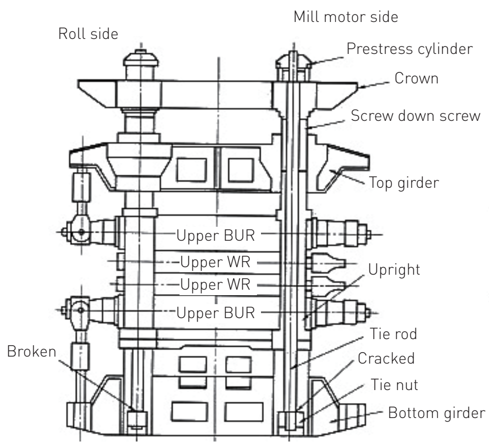


Fig.2.1 Schematic illustration of rolling mill and position of failure

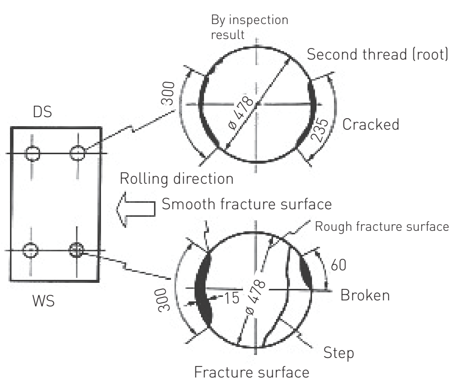


Fig.2.2 Schematic illustration of failure

The fracture surface is shown in **Fig.2.3.** For the most part of the fracture surface is brittle, while a smooth surface with a step is observed near the thread root. This surface is attributable to the fatigue crack which initiated at the thread root and propagated. Observation by SEM (scanning electron micro-scope) revealed the striation peculiar to fatigue (see **Fig.2.4**). After repair, the stresses were measured by strain gauges (single axis×5mm in length, four gauges) which were attached to the body of the tie rod. As a result, a maximum repeated stress amplitude σ_{amax}=1.23 kgf/mm^2 and a mean stress σ_m=17.7 kgf/mm^2 were obtained. When the coefficient of internal force φ is assumed to be about 0.2[(8)], the amplitude of external force, F_{amax}, is estimated to be about 6.2 kgf/mm^2. As the tensile strength σ_B of the material is 80.7 kgf/mm^2, the fatigue limit is as low as about 1/50—1/60 of the actual tensile strength. The reason why the fatigue strength of large diameter bolts decreases sharply is explained later.

In addition, **Fig.2.5** shows the relation between nominal diameter and tensile fatigue limit of bolts. This figure has been presented for the convenience of the engineers related to design of bolts. As shown in this figure, the horizontal axis means the nominal diameter of bolts and the vertical axis means the tensile fatigue limit of bolts expressed by stress amplitude, which will be easy to compare with general fatigue strength of materials. As the original data in this figure have been conducted under the partly pulsating stress, these are re-calculated into the case of completely reversed stress condition considering the mean stress and using modified Goodman diagram. As is apparent from **Fig.2.5**, the size effect is remarkable in comparison with the general fatigue properties and this reason will be clarified in the latter report. Some of designers may hesitate to apply the bolt connection into the structures by noticing such low fatigue strength of bolts. Generally speaking, the connected structure with bolts can stand several times larger than the applied stress of the fatigue strength of bolts. The composition connected with anti-fatigue bolts can endure more than 10 times larger than that of the general fatigue strength of bolts (see later report).

2.2 Failure of a cylinder rod

The cylinder rod of a hydraulic upsetter broke from the threads. The cylinder rod is shown in **Fig.2.6.** The macroscopic fracture surface of the rod is shown in **Fig.2.7.** The fracture occurred at the end of the engagement with internal threads. The material of the rod is S50C (quenched and tempered steel). As is apparent from the macroscopic fracture surface, the ratio of the fatigue fracture surface is very high. It is therefore estimated that the repeated stress amplitude σ_a is close to the fatigue limit of the bolt. The number of cycles to failure actually measured, Nf, is 25×10^4 cycles. With QT steels, striation is not always clearly observed on the fracture surface under SEM. Accordingly, an example of analysis from the fatigue strength (S-N diagram) is described below.

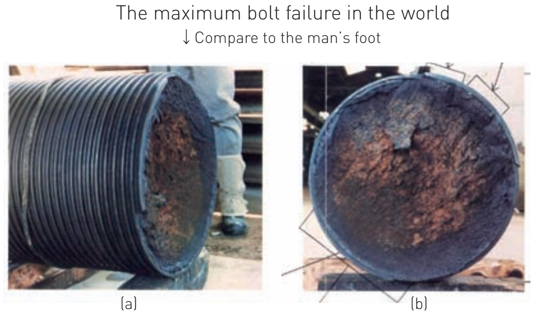


Fig.2.3 Fracture surface of tie rod [(b):Fatigue cracks are initiated inside of the frame]

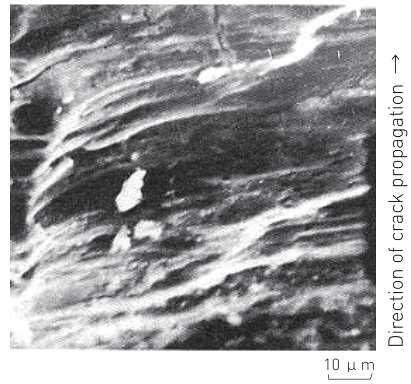


Fig.2.4 Results of observation of fracture surface by SEM

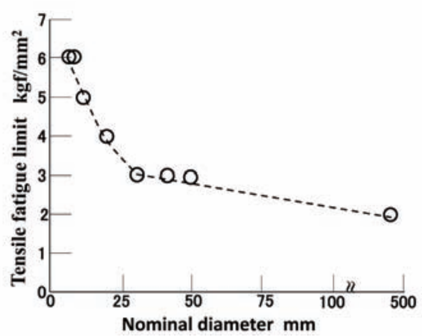


Fig.2.5 Relation between nominal diameter and tensile fatigue limit of bolts

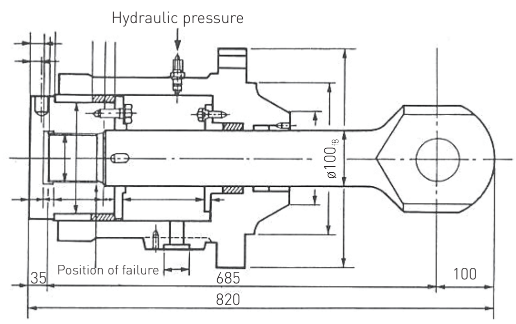


Fig.2.6 Schematic representation of cylinder rod (QT steel of S50C)

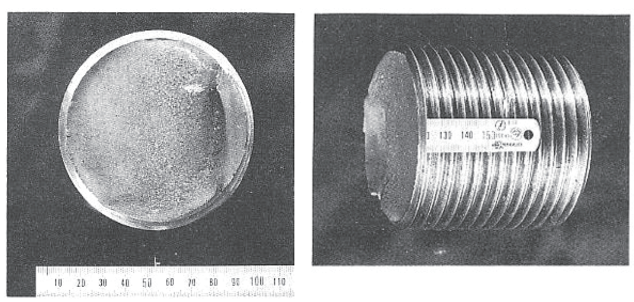


Fig.2.7 Failure of cylinder rod of upsetter

First, the fatigue limit of the screw now in use is estimated. In the case of screw M90, the root diameter of the thread is φ83.5 mm. As a load P of 0-57.4 tf (a constant amplitude of load generated by hydraulic pressure) is repeatedly applied, the nominal stress amplitude σ_a is calculated as shown below:

σ_a=57.4 ×10^3/2A=5.24 kgf/mm^2....................(2.1)

where A is the root area.

Taking the size effect into account, it is estimated that the fatigue limit of the screw is lower by about 20% than that of a standard bolt M24. If the value calculated by equation (2.1) is converted into the value for an M24 bolt, the stress amplitude

σ_{a1}=5.24/0.80=6.55 kgf/mm^2...............................(2.2)

The S-N curve of a normal bolt is shown in **Fig.2.8.** When the stress level is as calculated by equation (2.2), the number of cycles to failure, N, is 40×10^4 cycles. The order of this number is the same as that of the number of cycles to failure actually measured, $N_f= 40\times10^4$ cycles.

2.3 Failure of grinder set bolts

There are cases in which repeated stress is not apparently applied to the bolt or in which it is difficult to predict the stresses to be applied to the bolt at the design stage. An example of bolt failure in such cases is described below. A grinder is shown schematically in **Fig.2.9.** Bolts are used in many places in the grinder. The bolt most likely to be broken is the bolt (M20×160mm in length, six bolts) fixing the motor. A grinder wheel is located beneath the motor (DC110kW). The motor is connected to the grinding wheel with four V-belts. The motor and the grinding wheel are fixed on a common slider which is designed to move up and down. The billet is sent under the grinding wheel as if it crosses the wheel, and the billet surface is partially ground by the wheel.

Apparently, little repeated load is applied to the motor fixing bolts. In practice, however, the impact force produced when the grinding wheel comes into contact with the billet is transmitted through the V-belts to the motor, as a result of which fluctuating loads are applied to the bolts. Moreover, the vibrations resulting from the rotation of the motor, V-belts, and grinding wheel are applied to the bolts in addition to the fluctuating loads.

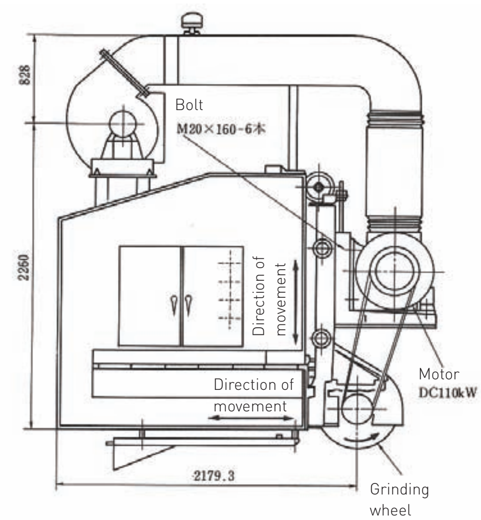


Fig.2.9 Schematic illustration of grinder (side view)

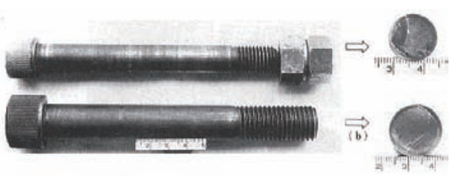


Fig.2.10 Example of broken fixing bolts for grinder

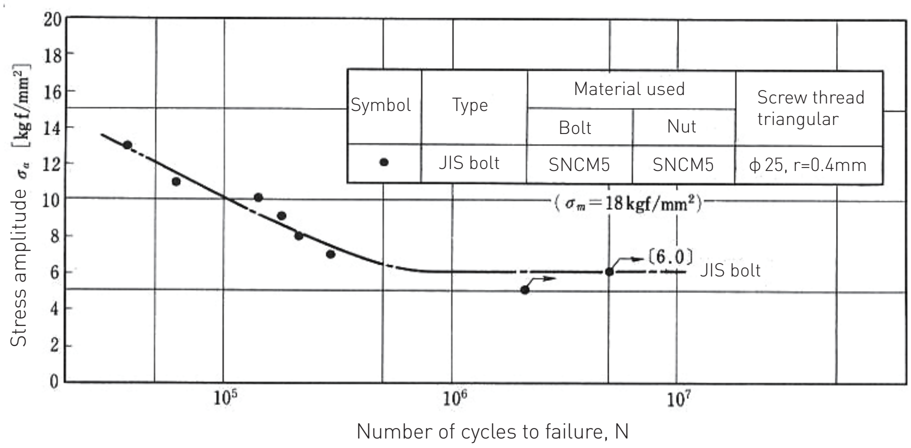


Fig.2.8 S-N curve for normal bolt

An example of failure of a grinder set bolt is shown in **Fig.2.10.** Almost the entire surface is occupied by the fatigue fracture. Judging from the above description and the high ratio of the fatigue fracture surface, it is estimated that the level of repeated stress was close to the fatigue limit of the bolt.

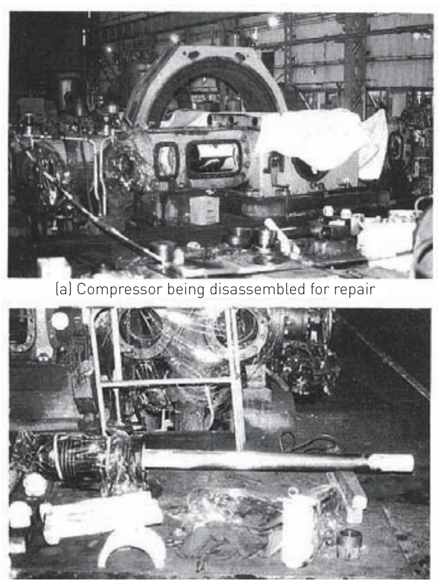
When bolt failure started to increase, the set bolt was replaced by a new bolt with higher tensile strength σ_B of 80 kgf/mm^2, but the fatigue life of the new bolt was nearly half that of the old bolt. Accordingly, the material of the bolt was changed to soft steel (SS400) as a drastic measure. As a result, the fatigue life of the bolt was prolonged by about 50% compared with that of the initial old bolt.

As described above, even bolts for which the generation of only little repeated stress is expected at the design stage may be broken due to fatigue. Depending on the individual case, bolts with low strength may have a longer life. As these points are contrary to common sense, they will be explained in more detail in latter report.

2.4 Failure of a compressor piston rod

If one thread of a bolt is broken, the breakage may spread to other parts in succession. A good example is the failure of a compressor piston rod. The compressor is of the double acting type (about 2,000 kW). As the screw (M90) of the piston rod on one side was broken, the crank shaft lost its balance, resulting in failure of the balance weight shear pin, bearing clamp bolt, connection rod, and compressor casing bed in the order mentioned.

The compressor piston rod (reciprocating type) is shown in **Fig.2.11.** Shown here is the piston rod on the side which was not broken. The color check of the rod did not reveal fatigue cracks. The fracture surface of the piston rod is shown in **Fig.2.12.** **Figure 2.12(c)** is the longitudinal cross section of the rod shown in **Fig.2.12(b).** The failure of the piston rod occurred from the end section of the nut. As the piston rod is of the reciprocating type, its fracture surfaces were severely struck by each other and could not be used for observation. Quite a long crack was observed at the root of the twelfth thread, counting from the end section of engagement with the nut (see **Fig.2.12(c)**). It may be said that the design of the threads of the piston rod is quite reasonable. The material of the piston rod is SNCM625 (quenched and tempered steel, the tensile strength σ_B=94.4 kgf/mm^2). When the rod was broken, about five months were required for complete repair.



(a) Compressor being disassembled for repair

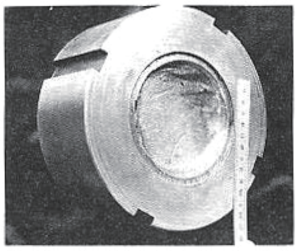
(b) Unbroken compressor piston rod

Fig.2.11 Outer view of compressor piston rod

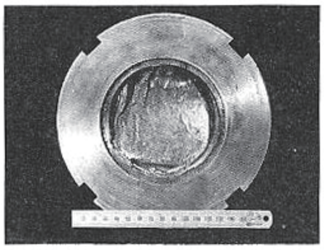
2.5 Failure of the chisel holding bolt of a large machine drill

An example of the failure of bolts for machines used in the civil engineering and construction fields is described below. **Figure 2.13** shows a large machine drill in

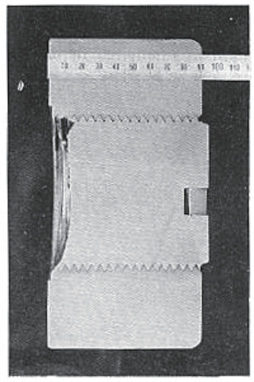
Fig.2.12 Outer view of fracture surface of compressor piston rod



(a) Broken piston rod



(b) Fracture surface of (a)



(c) Vertical section of (b)

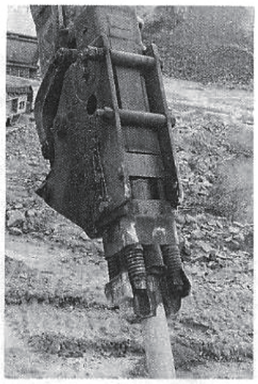


Fig.2.13 Outer view of chisel holding bolts of a large stone crusher

(a) Appearance of bolt

(b) Broken position

(c) Fracture surface

Fig.2.14 Chisel holding bolt of large stone crusher

which the chisel holding bolt was broken. **Figure 2.13(b)** shows the setting condition of the bolt (M50×length 1,200 mm). Figure 2.14 shows the appearance and fracture surface of the bolt. Four bolts make one set. It is considered that the reciprocating motion of the chisel and the impact force transmitted through the chisel are applied to the bolts. The bolts were broken during a period of six months to a year, although the duration varies depending on the method of use.

The beach mark which is characteristic of fatigue is clearly seen in the fracture surface shown in **Fig.2.14.** The ratio of the fatigue fracture surface is higher than 80% and the fracture surface is smooth and nearly free from steps. It is therefore, considered that the repeated stress is close to the fatigue limit.

Failure of the set bolt of a rod mill used for crushing

The rod mill consists of a horizontally installed cylinder in which a rod of length nearly equal to the mill length is inserted. As the cylinder is rotated around its axis, the rod is raised and dropped to crush the stone material. A steel plate with excellent wear resistance is attached with bolts to the inside wall of the rod mill. The bolt which was broken is the liner set bolt (M40×length 120 mm) of the rod mill which is used for crushing the stone material for cement. The impact resulting from dropping the rod is transmitted to the mill liner, causing failure of the bolts fixing the mill liner.

The fracture surface of the liner set bolt is shown in **Fig.2.15.** The fracture surface is a typical fatigue fracture surface and the ratio of the fatigue fracture surface is nearly 100%. It is therefore considered that fatigue cracks initiated and propagated at some distance and that the external force was decreased because of shifting part of the load to other bolts. In such cases, fatigue fracture spreads from one bolt to another in succession.

The bolt is made of SCM435 (quenched and tempered steel, the tensile strength

σ_B=100 kgf/mm^2). Failure occurred at the end section of the nut. As lime powder is adhering to the bolt, the whole bolt looks whitish.

Failure of the set bolt of an universal fatigue testing machine

There is a proverb that the shoemaker's wife goes barefoot. The universal testing machine is used to evaluate the fatigue characteristics of test specimens. Accordingly, the testing machine receives the reaction force of the load applied repeatedly to the specimen. Although test specimens are changed one after another, the testing machine itself is not changed. When the testing machine is used for a long period of time, therefore, failure of the parts of testing machine occurs frequently.

Figure 2.16 shows the hydraulic actuator of a universal fatigue testing machine. In the actuator, eight bolts each are used for the top and bottom covers (double end, W1-1/4). As oil leakage from the bottom cover was detected, the bolts for the bottom cover were checked. As a result, failure of three out of eight bolts was detected. The fracture surface of the set bolt of the actuator holding cover is shown in **Fig.2.17.** A fatigue fracture surface is clearly seen all over the surface. The failure occurred from the end of the engagement with internal threads. The material of the bolt is SCM435 (quenched and tempered steel).

2.8 Failure of the anchor bolt of a fatigue testing machine

Figure 2.18 shows the fracture surface of an anchor bolt of an universal fatigue testing machine which is of the same type as that shown in **Fig. 2.16.** The failure of the bolt occurred from the end section of the nut. The material of the bolt is SS400. Failure occurred in one of four bolts (M24). This type of fatigue testing machine is so constructed that the external force and reaction force are received within the frame. So far as desk calculation is concerned, the

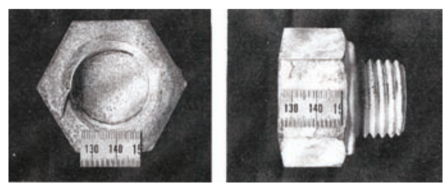


Fig.2.15 Fracture surface of fitting bolt for crushing rod mill

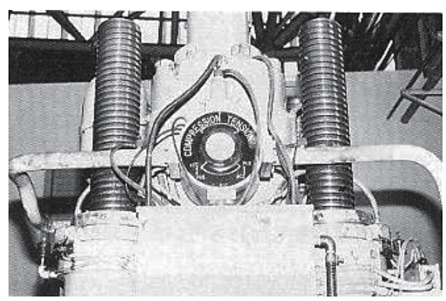


Fig.2.16 Hydraulic actuator of universal fatigue testing machine

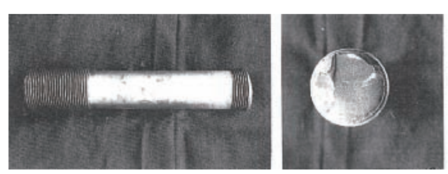
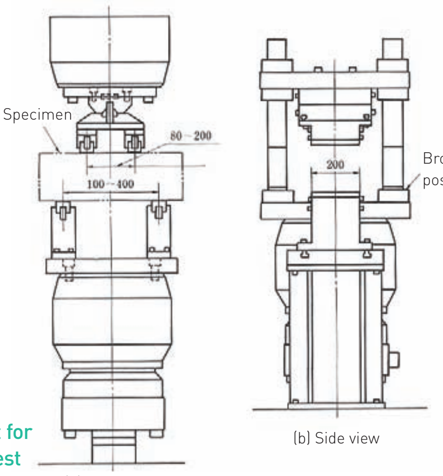


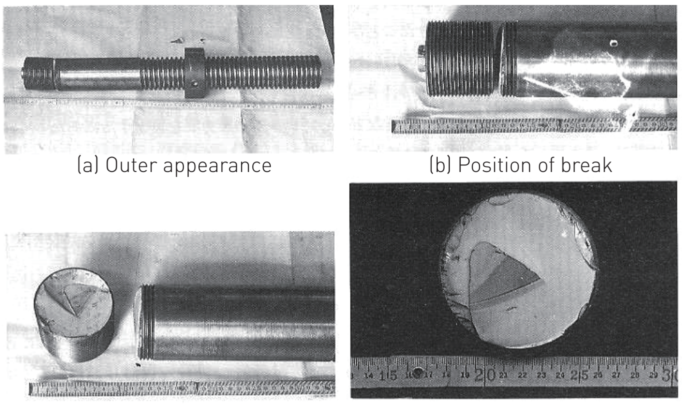
Fig.2.17 Fracture surface of set bolt of hydraulic actuator holding cover of universal fatigue testing machine (thread:W1•1/4)

Fig.2.18 Fracture surface of anchor bolt of fatigue testing machine



(a) Front view (b) Side view

Fig. 2.19 Equipment for repeated bending test



(a) Outer appearance (b) Position of break

(c) Fracture surface (d) Enlarged view of (c)

Fig.2.20 Broken position of repeated bending equipment (column)

force is not applied to the anchor bolts at all. As the testing machine had been in use for 12 years, the failure of the anchor bolt may be attributed to the vibration of the testing machine properly, which was caused as the hydraulic actuator becomes loose. As described above, the deterioration of machine with age is one of the causes of bolt failure.

2.9 Failure of a jig (column) for the reversed bending test

As described in 2.7 above, fatigue failure of the members may occur even in the fatigue life is closely examined at the design stage A jig for the reversed bending test and an example of failure of the jig are shown in **Figs.2.19** and **2.20**, respectively. The bolt is M85×750mm in length (root diameter:φ78.5mm). Failure occurred from the rod end section of the internal threads. The material of the jig is SCM435 (quenched and tempered steel).

As the reaction force in three-point bending is applied to the bolt (column), it is considered that not only a tensile stress but also a bending stress were applied to the threads. This is evident from the fracture surface shown in **Fig.2.20(d)**. The failure occurred on the triangular thread side. The reason why failure did not occur on the square thread side (right-hand side of **Fig.2.20(a)**, root diameter:φ72.4mm) in spite of the smaller root diameter is that the position of engagement with the nut on the square thread side is changed at regular intervals for adjustment. When a repeated load is applied, one of the simplest methods for improving the fatigue strength is to change the position of engagement with internal threads at regular intervals, although this method is not widely employed. A beach mark was not observed on the fracture surface of this bolt. This shows that the test was conducted with nearly constant stress amplitude.

2.10 Failure of a track bolt for the fish plate of a rail

At rail joints, a clearance of several millimeters is provided for rail

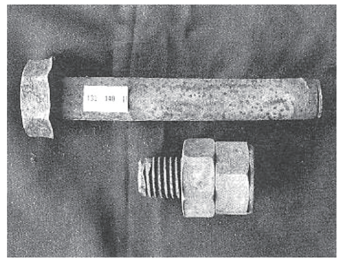


Fig.2.21 Track bolt for fish plate of rail (failure from incomplete threads)

expansion and contraction due to differences in temperature. Fish plates are used to reinforce the rail joints. The fish plate are clamped with four or six track bolts (M24×about 180mm in length). When a wheel rolls on the rails, an impact force is applied to the rails at the joints. Accordingly, tensile and shear stresses are created in the bolt. An example of failure of a track bolt (material:SS400) is shown in **Fig.2.21.** The failure initiated at incomplete threads and is a fatigue failure. Generally, the failure of bolts occurs at a three points, i.e. the end of engagement with internal threads, incomplete threads, and the under-head fillet. The probabilities that the bolt is broken from the three points are said to be 65, 20 and 15%, respectively[5-7]. However, so far as the fatigue failure of clamping bolts is concerned, more than 80-90% of failures occur from the end of engagement with internal threads unless special means for improvement of fatigue strength are taken. The probable reason why the failure of this track bolt occurred from the incomplete threads is that not only a uniaxial tensile force but also a shear force were applied to the bolt.

Summary of fatigue failures of fastening screws

The fastening screw which is represented by the combination of bolt and nut is an important part of machines and equipment. However, it seems that this importance is not fully realized, but they are regarded as one of the simple consumable parts. In practice, however, the failure of even a single bolt may have a great effect depending on the purpose of its use. In the preceding sections, several representative examples of bolt failure have been described. The importance of function and safety design of fastening screws should be emphasized once again. The foregoing description may be summarized as follows.

(1)In the relation between the nominal diameter of bolts and the tensile fatigue limit of bolts expressed by stress amplitude, the size effect is remarkable in comparison with the general fatigue properties and this reason will be clarified in the latter report.

(2)Even in case where little repeated load is apparently applied to the bolts, the bolts may break because they vibrate as a result of their looseness or age deterioration of machine part connected to a source of vibration.

(3)It is important to prevent the looseness of fastening screws. It is quite effective for the extension of fatigue life to use fastening screws made of a comparatively soft material (internal threads in particular) or to shift the position of engagement with internal threads at regular intervals.

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