Among lots of reasons for thread failure, the one that most troubles technicians in charge of bolted joint design is the “rupture due to metal fatigue”, because the problems of thread fatigue failure frequently occur at the places that were initially considered properly designed. Metal fatigue failure occurs at the places where stress exerts repeatedly. In that case, the numerical value for judging fatigue strength is not the absolute value of stress, but the “magnitude of stress fluctuation” due to repeated loading. Such stress fluctuation occurs in not only machines with movable portions but also computers and electronic devices that are basically used in a stationary state. If an electric apparatus repeats on/off state or its load is fluctuated, the value of heat generation from the integrated circuit board changes. Consequently, precision electronics instruments could break in the form of fatigue failure due to the repeated exertion of thermal stress. This article first explains the fundamentals for understanding metal fatigue, and then illustrate the phenomenon of fatigue failure inherent in threaded fasteners.

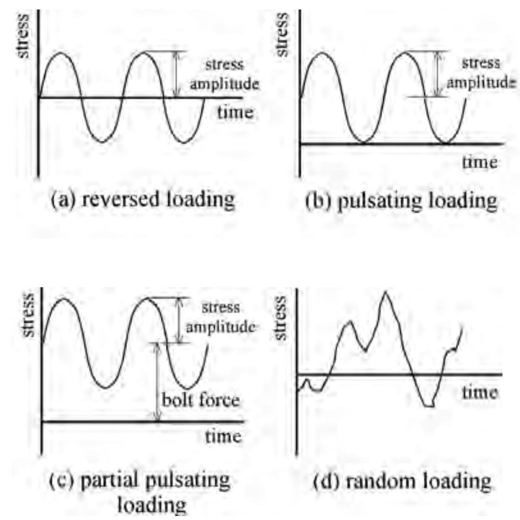

Fig. 2

(a) rupture due to fatigue failure (a) rupture due to plastic deformation

Fig. 3

Fastener Expert 101

Fatigue Strength of Threaded Fasteners- The Biggest Reason for Thread Failure

by Fukuoka Toshimichi

Metal Fatigue and Thread Rupture

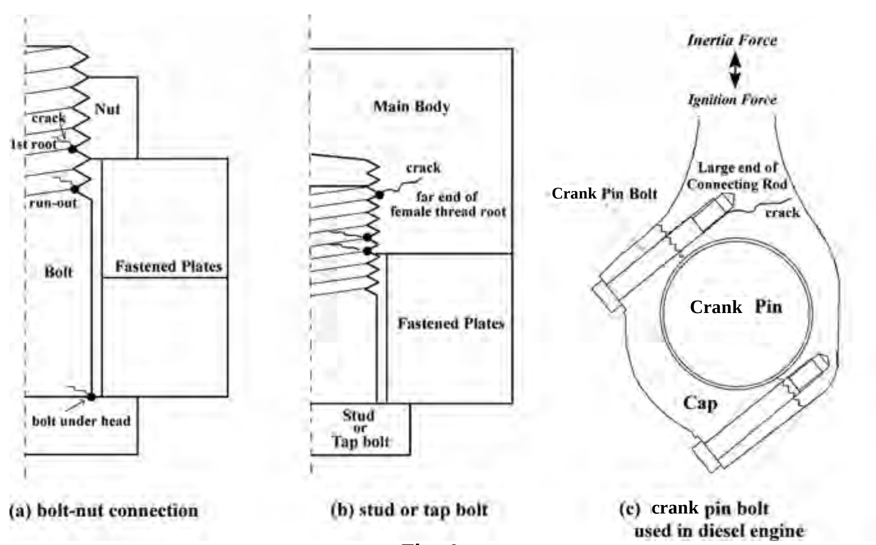

Fig. 1

Figure 1 shows the position where rupture driven by metal fatigue occurs in threaded fasteners. In a bolted joint clamped by a bolt and nut, metal fatigue mostly occurs from the first thread root of the bolt nearest to the bearing surface of nut. Additionally, it could occur in the runout portion of the threads. As for the bolt underhead portion, if it has an appropriate size of R and the material is homogeneous, rupture scarcely occurs. As shown in Figure 1(b), when female threads are manufactured in the main body and they are fastened with a stud or hexagon head bolt, the bolt could break in the same manner shown in Figure 1(a), or it sometimes could break from the innermost female thread root of the engaged threads. In the case of a medium speed diesel engine used for a ship propulsion or as a prime mover for electric generator, crack could initiate from the corresponding position in a connecting rod as shown in Figure 1(c), and finally it causes rupture, resulting in a fatal accident.

Figure 2 shows the variations of stress with time, generated in a component, during the repeated exertion of various loads. In the case of bolts, the repeated external force exerts on the initial axial force, and therefore it is termed “partial pulsating load”. A key feature of metal fatigues is that it is primarily influenced by stress amplitude, which is the amount of stress fluctuation, than the absolute value of the stress component. Fatigue failure occurs when the stress amplitude exceeds a critical value called “fatigue limit”. Fatigue limit is fairly smaller than the tensile strength of materials. As in a train axle, there is a load form called “rotating bending” where the axle rotates while bearing a bending load. In this case the fatigue limit is about 50% of tensile strength. Therefore, fatigue failure could occur without plastic deformation. **Figures 3**

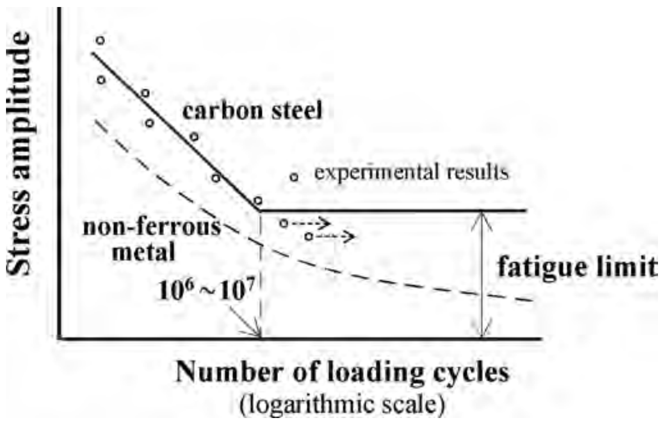

Fig. 4

(a) and **(b)** show ruptured bolts caused by fatigue failure and a great deal of plastic deformation. Here, it is found that in fatigue failure the bolt ruptures in the manner retaining its original shape without large deformation.

Since the magnitude of fatigue limit changes according to the way of applying loads, fatigue limits are usually obtained through the fatigue test corresponding to the load form shown in **Figure 2.** S-N curve shown in **Figure 4** is a diagram widely used to evaluate fatigue strength, where the ordinate represents stress amplitude and the abscissa is the number of loading cycles until rupture occurs. In the case of carbon steel materials, the S-N curve approaches a horizontal straight line after 106-107 cycles. The stress amplitude at that cycle represents the fatigue limit. **Figure 5** shows the relationship between tensile strength and the fatigue limit when repeated loading, as shown in the figure, is applied to bolt-nut connections. The data in the figure are creditable ones carried out by noted researchers of pertinent fields on various specifications of threads with different materials or thread root radii. Thread fatigue limit changes roughly from 1/5 to 1/20 of the tensile strength of materials. Due to the influence of sharp notch, it is much smaller than the fatigue strength of round bars used in general fatigue tests. Although fatigue limit shows higher values in materials with higher tensile strength, the rate of increase is small. In other words, we can say that fatigue strength is limitedly improved even if we use materials with higher tensile strength. Additionally, the correlation between the two is weak. Accordingly, in **Figure 6** using the same data the abscissa has been changed into the ratio of thread pitch P to nominal diameter d. Within a certain range, fatigue limit gets smaller with larger nominal diameter and smaller pitch. Furthermore, if P/d gets further smaller, fatigue limit drastically increases and afterwards decreases with larger rate comparing to that of the right portion. Here, the influence of thread root radius is scarcely observed. As shown above, thread fatigue limit shows a very characteristic behavior. Therefore, it is

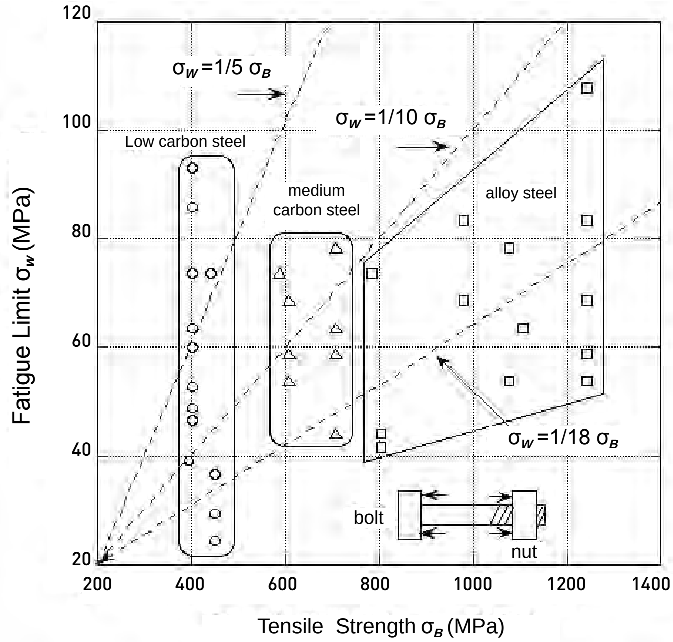

Fig. 5

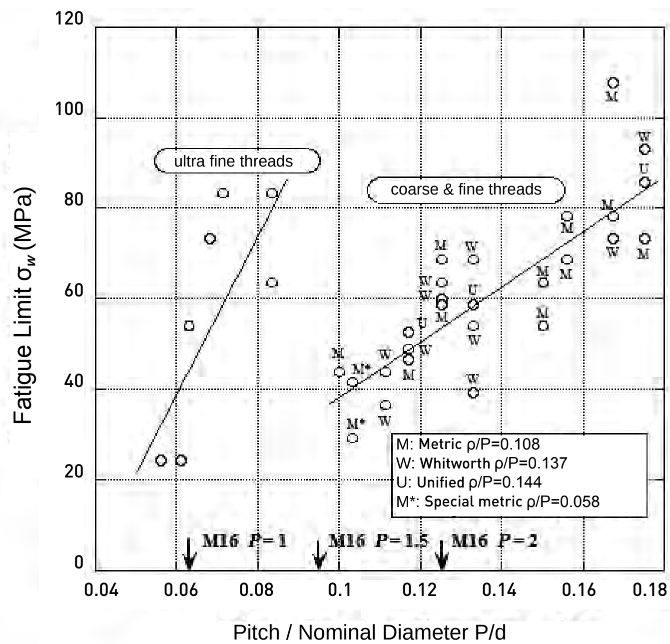

Fig. 6

considerably difficult to precisely estimate the fatigue limit of the actual bolted joints subjected to complicated loads.

External Force Exerting on the Bolted Joint and Load Factor

When the bolted joint is subjected to external force, the axial force of the bolt changes. Stress amplitude is calculated by dividing half of the increased amount of axial force by cross sectional area. In order to study the behavior of the bolt under the external force, in **Figure 7 (a)** a simple example of bolted joint is shown, in which the external force exerts axi-symmetrically around bolt axis and the axial bolt force is increased. It does not mean that the external force here exerts wholly on the bolt. Hence, the proportion of increased axial bolt force to the external force is defined as "load factor". As shown in Figure 7(b), the load factor is not constant and usually increases as the external force is increased. That is due to the progress of the separation of contact surface of the fastened objects. Accordingly, as shown in the figure, if the initial axial bolt force is increased, the load factor decreases. As a result, under the same magnitude of the external force, fatigue strength increases because the stress amplitude becomes smaller. On the other hand, if very large external force exerts, the contact surface completely separates and the axial bolt force changes along the 45-degree straight line in the figure. In this case, the whole external force exerts on the bolt and therefore the value of load factor becomes 1, which leads to a dangerous state of fatigue failure being likely to occur. A technique called "joint diagram" is sometimes used to evaluate the fatigue strength of the bolted joint, which shows the relationship among axial bolt force, bolt elongation and shrinkage of the fastened object. This method is widely introduced in mechanical design textbooks. However, as predicted from the above explanation, the diagram can only be applied to the cases when the external force exerts axi-symmetrically, and since the maximum value of load factor is 1, it is not necessarily possible to correctly evaluate the fatigue strength of the actual bolted joint.

External Force and Increase of Axial Bolt Force in Actual Machines

In actual machines or devices, as shown in Figure 7 (a), external forces rarely exert axi-symmetrically around bolt axis. As an example of actual machines, Figure 8 (a) shows a bolted joint having the shape similar to a cylinder cover. If the external force becomes very large, the separation of the contact surface of the fastened objects progresses. As an extreme case, Figure 8 (b) shows the equilibrium of forces for the case when large separation occurs at the contact surface. Considering the balance of moments, it is found that the external force is magnified by a factor of L/La, and then it is applied to the bolt. That is, in this case the load factor is larger than 1, which is very dangerous in view of fatigue strength. The mechanism of magnifying the external force is based on the same principle as in the case of nail pullers used in do-it-yourself carpenters. In other words, the magnifying rate greatly changes according to the arrangement among the fulcrum of the left end, bolt axis, and the application point of external force. This mechanism also suggests the possibility of enhancing fatigue strength by modifying the shape of bolted joints.

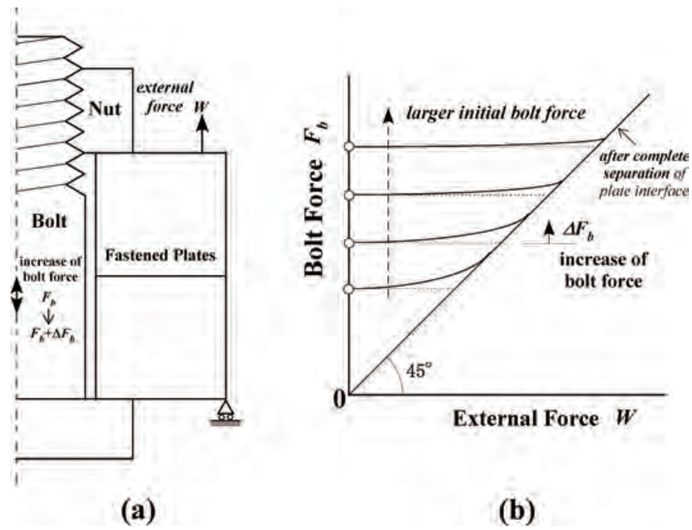

Fig. 7

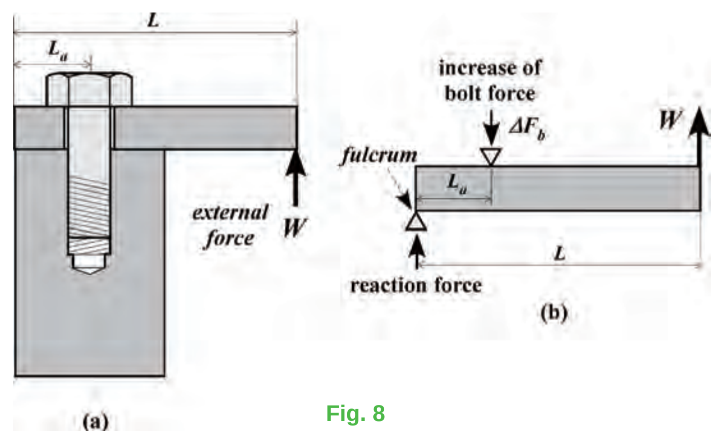

Fig. 8

Concluding Remarks

Research of metal fatigue has been started in around 1860 by Wöhler, who is famous for S-N curve introduced in this article. Even nowadays after a long trail of history, accidents and problems due to metal fatigue failure, including thread-related problems, continuously occur as before. Even if a certain problem is fixed, the other parts might fail due to fatigue failure because of the other reasons, which are possibly caused by improving the machine or device performance. This phenomenon has long been repeated. In my next article, I will prove the position where thread fatigue failure frequently occurs by using computer analysis, and introduce tangible methods for improving fatigue strength.

Reference:

Toshimichi Fukuoka, "Threaded Fasteners for Engineers and Design – Solid Mechanics and Numerical Analysis –", pp.166-200, Corona Publishing Co., Ltd. (2015)