"Fastener Troubles, Causes & Solutions" Series

# Failure of Propeller Shaft Couplings—Fatigue Failure of Reamer Bolts

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## 1 Introduction

A variety of loads are exerting on bolted joints. For example, when they are subjected to shear loads, slippage occurs on the interface and it sometime causes loosening or fatigue failure. Reamer bolts are used in the bolted joints subjected to large shear loads. For that purpose, the diameter of the bolt cylindrical portion is larger than the nominal diameter, and when the fastening is completed, the cylindrical portion is usually pressed onto the bolt hole. Consequently, the shear loads exerting on the bolted joints are supported by the force perpendicular to the cylindrical portion of reamer bolt, in addition to the friction force on the interface of the fastened object. Using the results by three-dimensional finite element analysis, this article explains the basic characteristics of the loads exerting on the reamer bolts, and the mechanism of fatigue failure occurring when the bolts are used in fastening shaft couplings.

## 2 Evaluation Method of the Strength of Reamer Bolts

Geometric characteristic of reamer bolts is that, as a reference dimension, the diameter of bolt cylindrical portion is equal to that of the bolt hole. Accordingly, JIS proposes the following expression for evaluating the strength of reamer bolts used in flanged shaft couplings. The symbols in the expression correspond to the ones in Figure 1 in my last article.

$$\tau = \frac{T}{\left(B_p/2\right)\cdot\left(n/2\right)\cdot\left(\pi d_{rm}{}^2/4\right)} \quad (1)$$

$\tau$ is the shear stress exerting on the cylindrical portion of the reamer bolt due to the torque T transmitted through the shaft. $B_p$ is the diameter of the circle on which multiple bolts are aligned. $d_{rm}$ is the diameter of the cylindrical portion of reamer bolt. n is the number of reamer bolts. Expression (1) indicates that the product of $\tau$, the cross section area of the bolt, the moment arm length and the number of bolt is equal to the torque. However, the number of bolts is half of the actual number, n/2. Thus, it is possible to take into account the influence of machining error on the fit between reamer bolts and bolt holes. However, this expression involves two problems. First, the transmission of torque is contributed not only by the contact around bolt cylindrical portion, but also by the friction on such contact surfaces as the interface between couplings. In that sense, the effect of friction is not taken into account in Expression (1). Another problem is the appropriateness of the assumption of n/2. The value of 2 can be regarded as a kind of safety factor. In order to clarify the above problems, it is necessary to systematically evaluate the influences of the fit and the coefficient of friction on the interfaces by numerical analysis. Expression (1) is widely used to design actual shaft couplings, which seemingly causes few troubles. However, if the value "2", which corresponds to a safety factor, can be a little smaller, it is expected that more efficient design can be achieved.

## 3 Evaluation of Shear Force Transfer Ratio by Finite Element Analysis

Shear forces exerting on the reamer bolts used in shaft couplings are supported by the force perpendicular to the bolt cylindrical portion and the friction force. The ratios of the perpendicular force and friction force to the shear force are defined as shear force transfer ratio and are obtained from three-dimensional finite element analysis. Denoting the ratio of shear force sustained by the bolt cylindrical portion as $R_{rm}$, and the ratio sustained by the friction force on the interfaces as $R_\mu$, the sum of the two ratios naturally becomes unity.

$$R_{rm} + R_\mu = 1 \quad (2)$$

Figure 1(a) shows the load exerting on a reamer bolt. The shear force due to the torque exerts in the circumferential direction, through which the bending load is applied to the bolt. Since our purpose is to clarify the basic mechanical properties of reamer bolts, a finite element model, shown in Figure 1(b), was prepared corresponding to the case of the shaft coupling diameter being infinite. A set of M16 bolt and nut is used to fasten two plates, and the tensile load is applied to the plate end. Then, the shear force exerts in the direction perpendicular to the bolt cylindrical portion. The magnitude of the exerting load is changed on the basis of the average shear stress, which is defined by dividing the shear force by the cross section area of bolt cylindrical portion. This value corresponds to the shear stress $\tau$ in Expression (1). Figures 2 (a) and (b) show the analytical results of shear force transfer ratio, for the cases of axial stress of the reamer bolt being 100MPa and 300MPa. The vertical axis is the shear force transfer ratio, and the horizontal axis is the fit between the bolt cylindrical

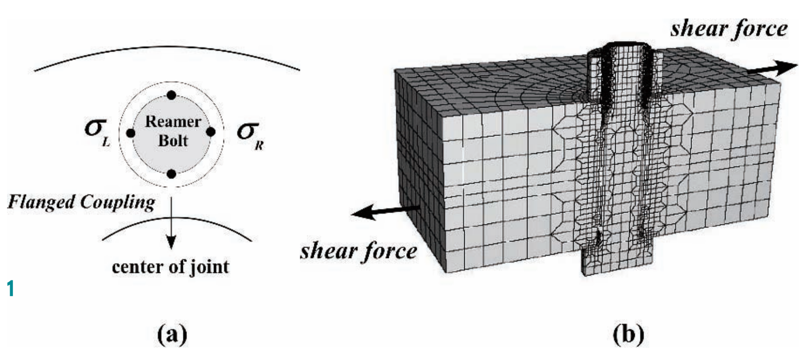


Figure 1

portion and bolt hole. The positive values imply interference fit and the negative values clearance fit, respectively. The parameter is μ, coefficient of friction on the contact surfaces. The shear load is applied so as to generate the average shear stress of 50MPa. The coefficient of friction is changed as 0.1 and 0.2. From the figures, it is found that as the friction coefficient gets smaller and more tighter interference fit is attained, $R_{rm}$ increases. Additionally, as the axial bolt stress increases, the value of $R_{\mu}$ becomes higher because the slippage is unlikely to occur owing to the effect of friction. Although the two figures seem to exhibit completely different results, the tendencies regarding to the variations in the fit and coefficient of friction are the same. In any event, the shear force capacity that reamer bolts can sustain is largely contributed not only by the force perpendicular to the bolt cylindrical portion but also by the action of friction force.

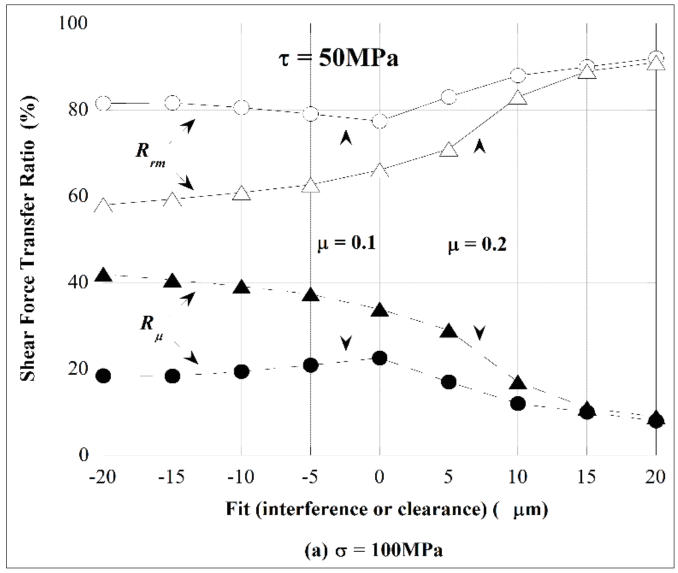


Figure 2 (a)

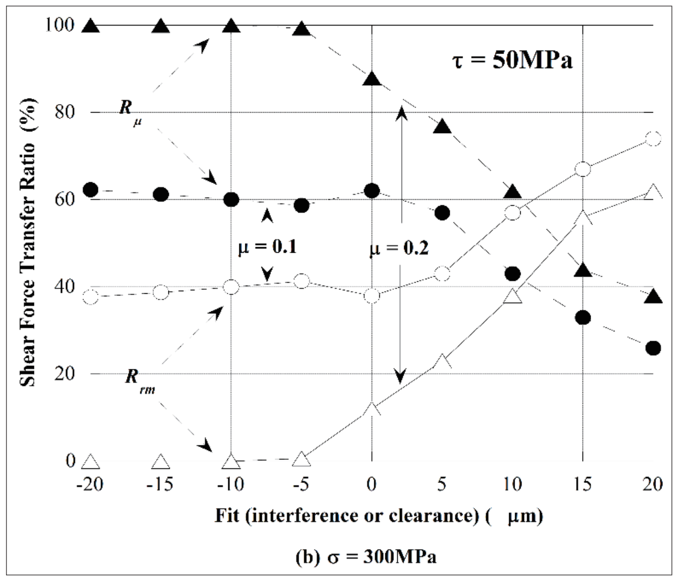


Figure 2 (b)

## 4 Fatigue Failure of Reamer Bolts

Figure 3 shows the fatigue failure of reamer bolts used in propeller shaft couplings of ships. Despite few cases of accidents, the accidents, if once occurring, could lead to a critical one such that makes the ship navigation impossible. A propeller shaft transfers the power generated in the main engine to the propeller. As shown in the figure, the rupture of reamer bolts does not occur at the interface of the coupling, but mostly on the bolt surface a short distance to the propeller side. Additionally, the bending load is found to be the cause, judging from the shape of the ruptured surface. Incidentally, the fit is extremely small and therefore it is impossible from the practical point of view to systematically change its size and conduct comprehensive experiments. Therefore, we used the finite element model in Figure 1(b) to change the fit in various levels, and obtained the bending stresses occurring in reamer bolts when subjected to the shear force generated by the torque. Figures 4 (a) and (b) show an example of the distributions of axial stress and bending stress along the cylindrical portion of reamer bolt. The two components of axial stresses are σL and sR at the two surfaces which are 180 degrees apart from each other, shown in Figure 1 (a). The horizontal axis represents the distance from the interface of the couplings, and the value of zero corresponds to the position of the coupling interface. As for the analytical conditions in the figure, the fit was -10mm clearance fit in both cases, and only the values of coefficient of friction are different. When a reamer bolt is subjected to bending load, the tensile and compression stresses occur on the bolt cylindrical surfaces that are 180 degrees apart from each other. The bending stress is calculated by dividing the difference between the two stresses by 2. When the coefficient of friction is 0.2, the bending stress is small. However, If the coefficient reduces to 0.1, the peak of the bending stress appears at the position approximately 13mm to the propeller shaft side from the interface. This position almost coincides with the ruptured position of reamer bolt shown in Figure 3.

Although not shown in the figures, the fit and coefficient of friction are changed in various levels in finite element analysis. As a result, the conditions for Figure 4(b) produced the maximum bending stress at the same position as the ruptured surface of the actual reamer bolt. This result implies that, in the state of clearance fit, large bending stresses would occur when the coefficient of friction is small. When a ship goes astern, the main engine uses about 70% to 80% of the power necessary for the case of going ahead. That is, the direction of shear loads changes repeatedly. Therefore, the fit of the reamer bolt possibly changes from the interference fit in the initial condition to the clearance fit, and at the same time the coefficient of friction is likely to decrease. This phenomenon seems to be the primary cause for high bending stresses to occur at the position away from the interface of the shaft coupling.

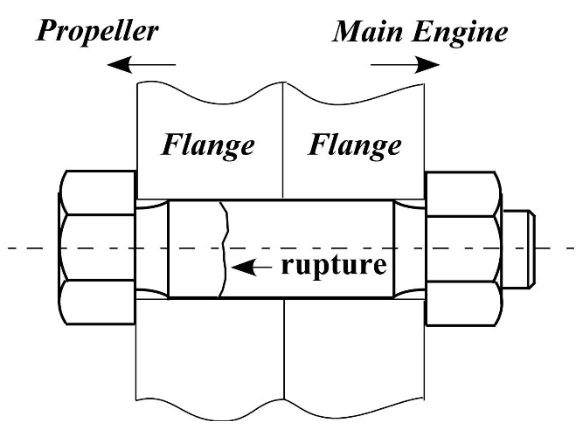


Figure 3

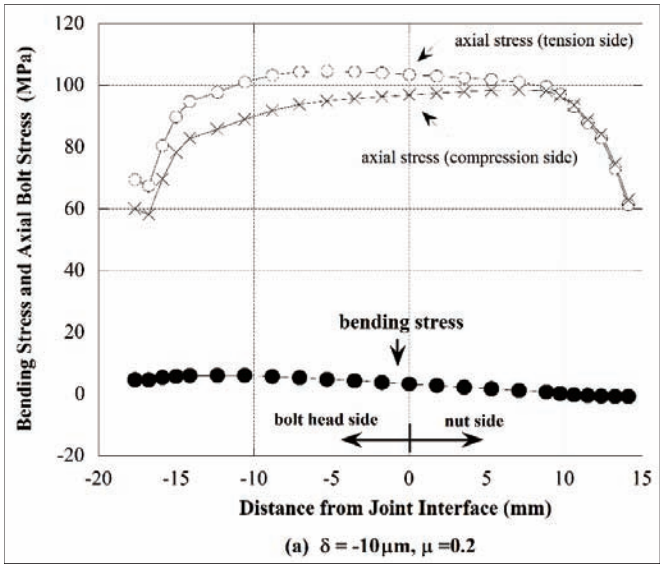


Figure 4 (a)

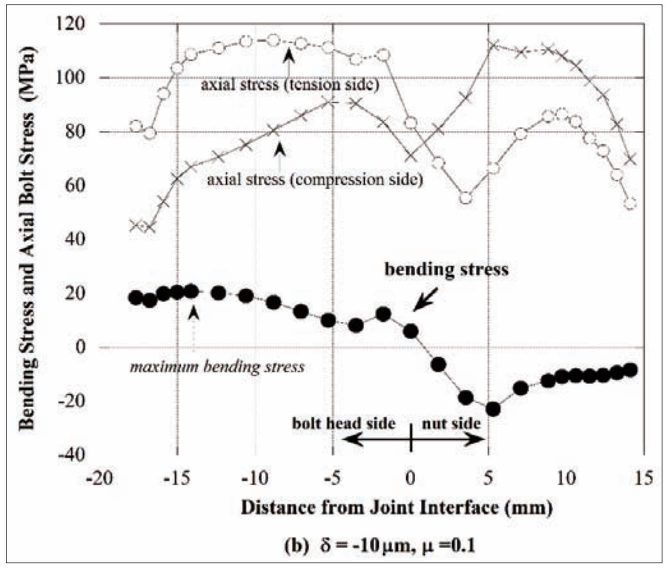


Figure 4 (b)

## 5 Conclusion

In this article, characteristic mechanical properties of reamer bolts are clarified by finite element analysis, and it is indicated that there is some room for improving the design formula currently used for shaft couplings. Furthermore, the article clarifies the mechanism of the fatigue failure of reamer bolts that occurs at the position to the propeller side away from the interface of the coupling. It is considered that the factors affecting failure of reamer bolts, which clamp shaft couplings, are the fit around the bolt hole, friction of the contact surface, and, in addition, the precision of alignment between the driving shaft and driven shaft connected to the coupling. In my next article, I will explain the relationship between the shaft alignment and the fatigue failure occurring in reamer bolts.

Reference

1. Toshimichi Fukuoka, "Threaded Fasteners for Engineers and Design – Solid Mechanics and Numerical Analysis –", pp. 290-296, Corona Publishing Co., Ltd. (2015)