1. Introduction

A reamer bolt, the diameter of which is equal to the bolt hole diameter, is widely used in shaft couplings transferring great power. A typical usage of the shaft coupling clamped with reamer bolts is a propeller shaft coupling, which transfers the power generated by the main engine of a ship to the propeller. In such shaft couplings, only the rupture of a single reamer bolt causes major accidents making the ship unable to navigate. In my preceding article, the focus was placed on the fit between the bolt body and the bolt hole, which greatly affects the rupture of reamer bolts. In this article, I will explain the effect of shaft misalignment, which is considered to be another primary reason for the rupture of shaft couplings. The role of shaft couplings is to transfer the power between the driving shaft and the driven shaft. In that case, the two shafts must be aligned along the same axis. In actual shaft couplings, however, a certain extent of misalignment inevitably occurs. As a consequence, the reamer bolts fastening the shaft coupling could possibly be subjected to large stress amplitudes. Considering the above phenomena, the relationship between stress amplitude and misalignment, which is the dominant factor of the fatigue strength, is explained based on the results obtained by three-dimensional finite element analysis.

“Fastener Troubles, Causes & Solutions” Series

Failure of Propeller Shaft Couplings: Shaft Alignment and Fatigue Failure

by Toshimichi Fukuoka

2. Misalignment of Shaft Couplings

When shafts are tightened with flanged fixed shaft couplings, misalignments shown in **Figure 1(a), (b), (c)** may occur. In sequence, they are called parallel misalignment, axial misalignment, and angular misalignment, or alternatively, offset, endplay, and angle of deviation. In those cases, the mechanical behavior of shaft couplings is influenced by the stiffness of the whole bolted joint, and therefore it varies not only with the extent of misalignment but also with the length between the coupling and the bearing and the axial bolt stress. With respect to parallel misalignment and angular misalignment, as they could be the cause of the exertion of bending stress on the shaft system in the running condition, the two shafts are carefully aligned along the same axis. However, when the shaft system has a large overall weight like the propeller shaft coupling of ships, certain extent of parallel misalignment and angular misalignment would inevitably occur due to the shaft weight and the deflection of the foundation of bearings. On the other hand, with respect to axial misalignment, the problems induced in the actual couplings seem relatively fewer; however, it is important to clarify the limit value of misalignment that affects the mechanical behavior of couplings.

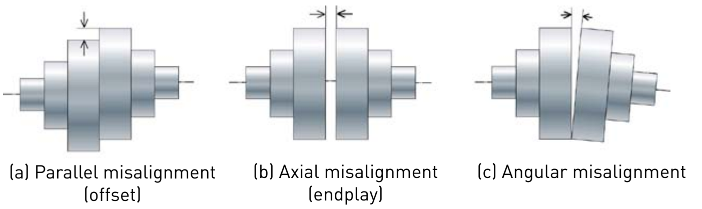
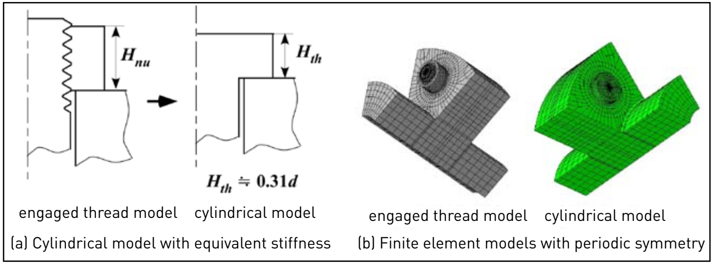

(a) Parallel misalignment (offset)
(b) Axial misalignment (endplay)
(c) Angular misalignment

Figure 1



(a) Cylindrical model with equivalent stiffness
(b) Finite element models with periodic symmetry

Figure 2

3. Calculation Efficiency Improvement Using Equivalent Model of Bolt and Nut

To evaluate the effect of shaft misalignment on the mechanical behavior of couplings, the analyses must be conducted using the whole model or half model of the couplings. In that case, if the shape of the engaged thread portion were precisely modeled, the number of finite elements of the analytical model becomes very large, and it makes the calculation difficult. To cope with the problem, the engaged thread portion is replaced with a cylinder which has equal stiffness against the the external force applied as the shear load. The cylinder diameter is equated to the average outer diameter of the nut, and the height is varied to match the stiffness. **Figure 2(a)** illustrates the idea of equivalent height H_{th} of engaged threads model. H_{nu} in the figure represents the nut height which is equal to the length of engaged thread portion. **Figure 2 (b)** shows the analytical model of shaft coupling used for evaluating H_{th}. The left one depicts the model of the engaged thread portion, and the right one is its equivalent model. The nominal diameter of the bolt is M16, and the dimensions of each part of the model are in accordance with JIS B1451. In the next section, the full model of the shaft coupling is constructed using the equivalent model. Additionally, the axial bolt stress is set to be 100MPa, the coefficient of friction of contact surfaces is 0.2, and the fit between the bolt body and the bolt hole is ±0μm. The magnitude of shear force applied to the couplings is set to be the value that generates the average shear stress of 20MPa on the cross sections of each bolt. The height of the cylinder portion was varied in the analyses for deriving the equivalent height H_{th}. From the model shape, which produced the same amount of shear force transfer ratio as the one by the analytical model having the engaged thread portion, H_{th} is set to be 0.31 times the nominal diameter.

4. Effect of Misalignment

To evaluate the effect of misalignment, analyses are conducted using a model with two shafts being mounted on both sides of the shaft coupling. As shown in **Figure 3**, the two shafts are solid with a diameter of 48mm. Contact conditions are given so that the shaft portion inserted into the flange consists one body with the inner surface. The analytical model is bilaterally symmetric with a total length of 1,000mm. With respect to the amount of misalignment, the offset is set to be 10mm, which is one hundredth of the total shaft length. The endplay is changed in 3 levels, i.e., 0.2mm, 0.6mm and 1mm, which correspond to 2/10000, 6/10000 and 10/10000 of the total shaft length, respectively. The amount of angle of deviation is changed in 6 levels, i.e., 0.01°, 0.03°, 0.05°, 0.07°, 0.1°, and 0.3°. The analytical results are shown below.

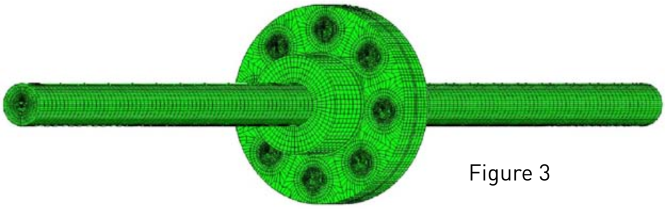


Figure 3

First, with respect to parallel misalignment, no significant effect was observed on the shear force transfer ratio and bending stress. In other words, for shaft couplings with relatively long distance between the adjacent bearings, it is considered that parallel misalignment seldom causes serious problems. Next, regarding the effect of endplay, the values of 0.2mm, 0.6mm, 1mm employed here correspond to the states of "perfect contact on the flange interface", "intermediate condition between contact and separation", and "perfect separation" in the initial fastening state, respectively. **Figure 4** shows the results of the shear force transfer ratio R_{rm} sustained by the cylindrical body of reamer bolt. The figures in the parenthesis represent the amount of endplay, where 0mm implies the state without misalignment. Compared with the state without misalignment, R_{rm} wholly exhibits larger values in the case of 0.2mm endplay. With further increase of endplay, it is observed that R_{rm} drastically increases due to the lost of contact around the flange interface. Then, raising the axial stress three times as high, i.e., 300MPa, the effect of misalignment almost disappears because the contact surfaces are closely in contact in the initial fastening state. In other words, it means that the effect of endplay is lowered with increase of axial stress.

Regarding flanged fixed shaft couplings, it is extremely important to align the two shafts to be connected along the same axis. However, in the case of the stiffness of the foundation, on which the bearing is set, being low, there are cases with the state equivalent to angular misalignment due to the effect of its deformation. **Figure 5** shows the effect of the magnitude of deviation angle on the shear force transfer ratio. $\alpha = 0°$ indicates the case without deviation angle. If α exceeds 0.03°, the effect of angle deviation significantly appears. Although not shown in the figure, bending stresses also increase when α exceeds 0.03°, corresponding to the shear force transfer ratio. Then, the axial bolt stress is raised from 100MPa to 300MPa; however, beneficial effects could be obtained unlike the case of endplay. Furthermore, the analyses were conducted by reducing the length of the shaft system to 500mm, half of the original one, but the difference in the shear force transfer ratio was at most between 2% to 3%. From the above results, it is found that increasing axial bolt stress has a little effect on decreasing stress amplitude, and also the effect of the shaft system length is not substantial. Therefore, it can be concluded that the angle of deviation is a critical misalignment which greatly affects the strength of shaft couplings.

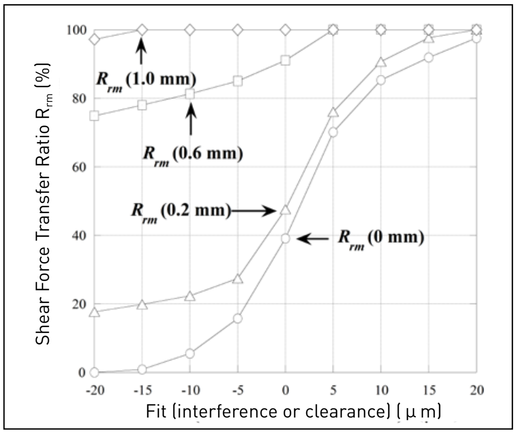


Figure 4

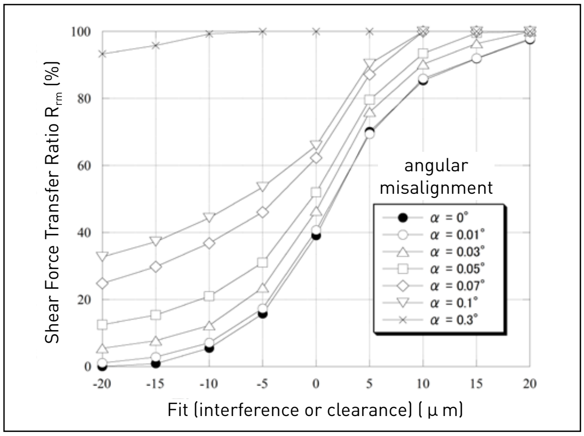


Figure 5

5. Conclusion

In this article, the effects of misalignment between two shafts were explained, which inevitably occurs when installing shaft couplings, even though there is a difference in extent. Regarding parallel misalignment, the induced problems are so limited as long as the shaft system length is long and the magnitude of misalignment remains within a certain range. As for axial misalignment, if the extent of misalignment is not so large, the effect can be eliminated by raising the axial bolt stress. However, in regard to angular misalignment, the effect of raising bolt stress is so limited, and even a long shaft with low stiffness could suffer a problem. Therefore, we can say that angular misalignment is the one to be treated with particular concern. In my next article, I will explain the resonance phenomenon occurring in the bolted joints from the perspective of natural frequency. ■

Reference

1. Toshimichi Fukuoka, "Threaded Fasteners for Engineers and Design – Solid Mechanics and Numerical Analysis –", pp. 290-298, Corona Publishing Co., Ltd. (2015)
2. Japanese Industrial Standards, Rigid flanged shaft couplings B1451 (1991) (in Japanese).
3. Mancuso, J. R., Couplings and Joints (1999), pp.23–29, Dekker.