"Fastener Troubles, Causes & Solutions" Series

Tire Falling Accident of Large Vehicles (Part 2) - Variation of Axial Force & Mechanism of Fatigue Failure

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1. Introduction

The fact that tire falling accidents of large vehicles mostly occur in rear wheels is mainly due to the variation of axial force of wheel bolts fastening the wheels to the hubs. Rear wheels have a dual-wheel structure that is inherent in a large vehicle, and the 2-stage fastening process of rear wheels causes the variation of axial force. This article starts by explaining the characteristic features of the fastening process of wheel bolts, and then accounts for the mechanism of fatigue failure occurring in the wheel bolts. Including threaded fasteners, the primary factor that dominates the failure due to metal fatigue is stress amplitude. Here, I will explain the mechanism of tire falling accident by introducing the test results of stress amplitude measured by a test device, which is manufactured from an actual machine, also by introducing the numerical results of finite element analysis conducted for evaluating the stress amplitude in detail at the thread root.

2. Fastening Process of Wheel Bolt & Variation of Axial Force

The expression between axial force and torque, when fastening common bolts and nuts, can be derived from the elementary theory of mechanics explained in my third article of the previous serial publications of Fastener World Magazine. On the other hand, in this case computer analysis is required for obtaining the expression between torque and axial force, because the rear wheels of large vehicles are fastened in 2 stages. The following expressions shows the relationships among torques T_{inn} and T_{out}, nut factors K_{inn} and K_{out}, and axial forces F_{inn} and F_{out}, in which the subscripts "inn" and "out" represent the fastening processes of inner nuts and outer nuts, respectively. "d" is the nominal diameter of threads.

$$\begin{aligned} T_{inn} &= K_{inn} F_{inn} d \\ T_{out} &= K_{out} F_{out} d \quad (1) \\ F_b &= F_{inn} + F_{out} \end{aligned}$$

As shown in the third expression, the final axial force F_b is the sum of F_{inn} and F_{out}. **Figure 1** shows the finite element model used for analysis. The obtained expressions between nut factors and coefficients of friction are as follows.

$$\begin{aligned} K_{inn} &= 0.6004\mu_{ith} + 0.8423\mu_{inu} + 0.02120 \\ K_{out} &= 3.179\mu_{oth} + 0.6198\mu_{onu} + 0.08163 \qquad (2) \end{aligned}$$

Here μ_{ith}, μ_{inu}, μ_{oth}, and μ_{onu} are, in a sequence, coefficients of friction of the thread surface and the seating surface of nut during inner nut fastening and outer nut fastening. The value of K_{inn} is comparatively smaller than K_{out}, which indicates that large axial force is produced when fastening inner wheels. As an example, we calculate the axial force Fb by assuming that both the inner and outer wheels are fastened with torque of 600Nm and coefficients of friction of 0.15. The axial force F_{inn} is 123kN when fastening inner wheels. If we then fasten the outer wheels, only 30kN of F_{out} is added and the axial force F_b increases to 153kN. Now we turn our focus on the expression of nut factor K_{inn}. It is found that the constant that precedes μ_{inu}, coefficient of friction of the seating surface of inner nut, is 0.8423. On the other hand, its value is 0.65 for ordinary bolts and nuts. In other words, μ_{inu} has a large influence on the axial force to be produced. Therefore, if coefficients of friction were changed due to the repetition of fastening and disassembly of bolted joints, the axial force of wheel bolts is more likely to change than ordinary bolts and nuts. This mechanism implies that one must pay particular attention to the fastening operation of large vehicles, where the tire replacement is carried out every year in snow season between ordinary tires and winter ones.

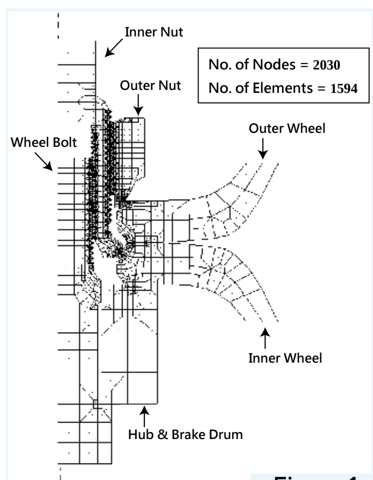

Figure 1

Then, we measured the coefficients of friction by repeating fastening and disassembly of bolted joints. It is found that the coefficients of friction are to be changed significantly beyond fifteen times repetition, even if we use lubricants having the effect of stabilizing its values. In that case, the seating surfaces of the inner nut and outer nut are too rough to receive the action of the lubricant. The above considerations suggest that for large vehicles, in which bolt fastening and disassembly are repeated, it is desirable to regularly replace threaded parts and wheels of the jointed portions.

3. Mechanism of Wheel Bolt Fatigue Failure

Figure 2 shows the mechanism of cyclic loading on the wheel bolt. As shown in the figure below, the cargo weight loaded on the large vehicle acts upon the tires. The stress in the wheel bolt carrying that load changes with the tire rotation of the tires. As shown in the bottom left figure, assuming that the vehicle runs on the flat road at a constant speed, we focus on a specific bolt. It is found that a certain amount of stress amplitude acts on the bolt for each rotation. If the stress amplitude exceeds the fatigue limit, crack will initiate and in the worst case result in rupture. Since the shape of the bolted joint is complicated, it is necessary to conduct fatigue test or computer analysis in order to know the magnitude of stress amplitude.

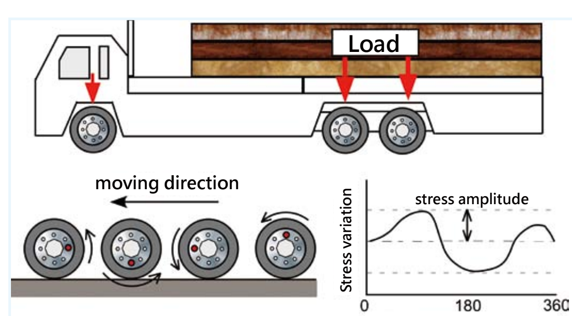

Figure 2

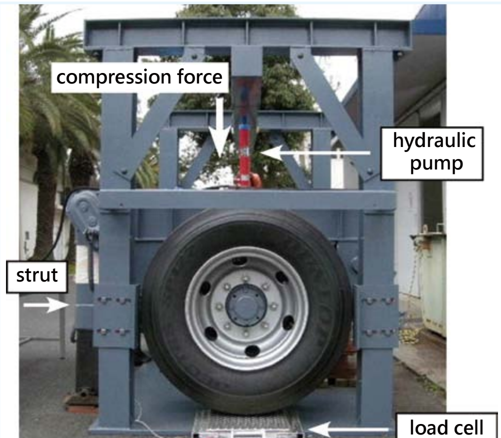

Figure 3

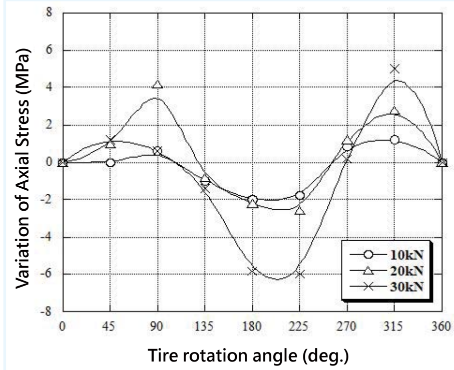

Figure 4

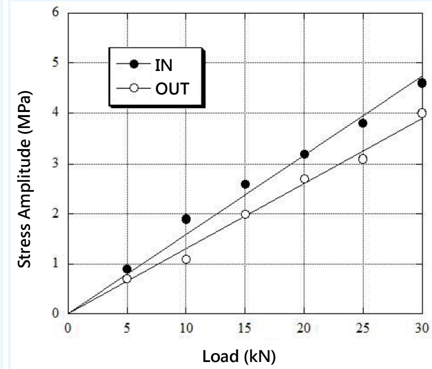

Figure 5

4. Measurement of Stress Amplitude Using a Device Manufactured from an Actual Machine

Figure 3 is a photo showing a test device manufactured using the rear part of a trailer. It is extremely difficult to measure the stress amplitude of a wheel bolt in the running condition. Here, we use a hydraulic pump to apply a force equal to the load exerted by the loaded cargo, and measure the compression force acting on the tires by means of the load cell placed beneath them. Strain gages are attached onto one of eight wheel bolts to measure its stress amplitude. The test sequence is as follows. First, use the hydraulic pump to apply the compression force equal to the loaded cargo and measure the stress currently exerted on the bolt cylindrical portion. Then, rotate the tire by 45 degrees and measure the axial stress for the same compression force. Repeating this operation eight times, with increment of 45 degrees rotation, we can obtain the stress amplitude for one rotation of the tire. An example of the test results is shown in **Figure 4**. The vertical axis is the variation of the axial bolt stress, and the horizontal axis is the rotation angle of the tire. The parameter is the live load, and the maximum live load of the trailer used here is 25kN. **Figure 5** shows the relation between stress amplitude and live load, which is almost linear. The notations "IN" and "OUT" indicates the positions of the bolt surface, each of which represents the surface closer to and the surface further away from the tire center. On the whole, the stress amplitude of "IN" is a little larger, and it is not so large even if the tire is loaded to the maximum specified load . This figure shows the results of the standard bolt force. On the other hand, if the axial force decreases to around 30% of the standard one, the stress amplitude produced against the maximum live load increases to about 25MPa. According to these results, we find that the stress amplitude drastically increases with decreasing axial bolt force. Additionally, since the stress amplitude at the thread root becomes even larger because of the notch effect, fatigue failures are likely to occur at these locations.

6. Evaluation of Stress Amplitude at the Thread Root Using Finite Element Analysis

Figure 6(a) is a finite element model made to analyze the stress amplitude produced in the jointed portions of wheel bolts. Only one side of the rear wheel is modeled, and the compression load is applied to the axle on which the live load acts. Figures (b) and (c) are the finite element models of the wheel bolt and inner nut. For efficient calculation, only one of 8 bolts is modeled using fine mesh division and the remaining 7 bolts are modeled with coarser mesh division. Figure (d) is the model with fine mesh division, and figure (e) is that with coarse mesh division. In the analysis, we focus on the bolt with fine mesh division, and obtain the stress amplitude for one rotation of the tire by changing the direction of applying compression load and the position of the modeled ground in contact with the tire. From the above finite element analyses, it is found that, as long as about 50% of the target bolt force is retained, the stress amplitude will not reach the value causing fatigue failure. However, if the axial force drops to 30% of the target one, the bolt may be in a fairly dangerous state.

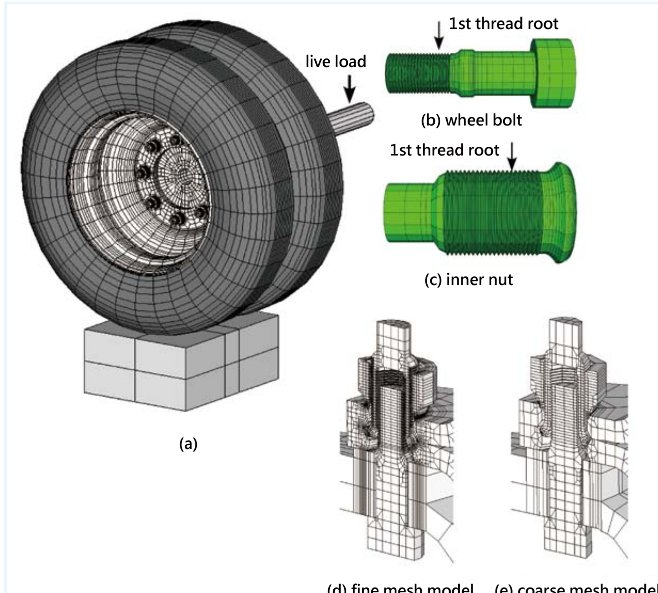

Figure 6

7. Conclusion

Because the rear wheels of a large vehicle have a dual-wheels structure, the axial bolt forces are intrinsically likely to vary. However, if we fasten the wheel bolts to the specified torque value, there is almost no chance that tire falling accidents will occur. On the other hand, from the onsite operation point of view, there are various problems to overcome for fastening multiple wheel bolts with specified torque values. My next article will explain high precision fastening device manufactured to reduce the variation of axial bolt forces.

Reference:

1. Toshimichi Fukuoka, "Threaded Fasteners for Engineers and Design – Solid Mechanics and Numerical Analysis –", pp.264-280, Corona Publishing Co., Ltd. (2015)