"Fastener Troubles, Causes & Solutions" Series

Failure of Roller Coaster Shaft: A Single Failed Thread Brought a Theme Park to a Complete Shutdown

by Toshimichi Fukuoka

1. Introduction

Threaded fasteners are the most widely used machine elements. In comparison with gears, bearings, springs and other machine elements, threaded fasteners have a specific characteristic in terms of the form of load exertion. In other words, the direction of load exertion on the other machines elements is predetermined. Journal bearings, for instance, support the loads in the radial direction, and helical springs are subjected to compression or tensile loads. In contrast, threaded fasteners are usually subjected to different forms of load exertion for each bolted joint. Some threaded fasteners are mainly subjected to bending, shearing and twisting separately, and others are subjected to those loads simultaneously. That is, it is considered that bearing more complex loads than other machine elements is the primary reason that makes thread strength evaluation difficult. My new series of articles for Fastener Magazine this year focuses on the incidents that I have been associated with so far. The purpose of this series is to offer effective information to technicians working in various fields pertaining to threads, by explaining the causes for various thread troubles and their countermeasures.

2. Overview of the Roller Coaster Accident

There have been multiple reports on major troubles caused by just a single damaged screw. Among them, the roller coaster accident that took place in Expoland (Osaka Prefecture) on May 5, 2017 became an object of public concern. It is noteworthy that the accident led to the shutdown of such a large theme park as Expoland.

Figure 1 shows the roller coaster course where the accident took place. It had a maximum height of 40 meters, and a drastic spiral at the middle of the course. Top speed was 75 kilometers per hour. The coaster was highly popular especially among the youth, as an attraction that provides high speed and thrills. This course was run by two roller coaster trains named "Wind God" and "Thunder God" that were alternately put into service condition. The former one, "Wind God", caused the accident. The threaded portion machined on the shaft end ruptured, which caused the falling off of the module that connects the wheels and car body. Finally, it resulted in a painful accident of the death of one passenger.

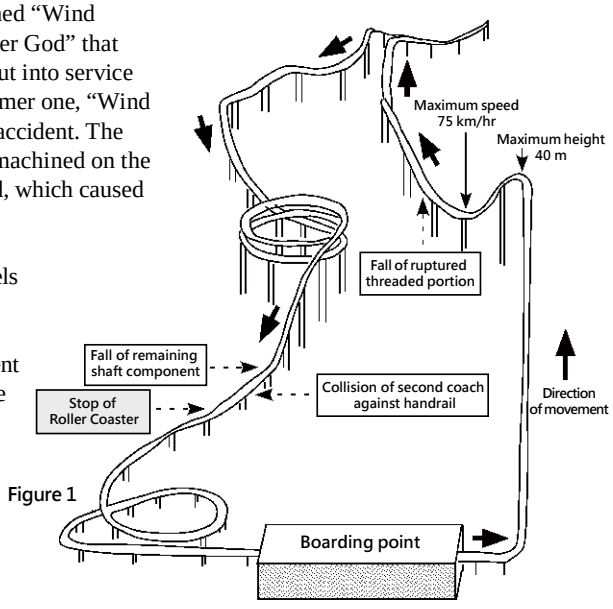


Figure 1

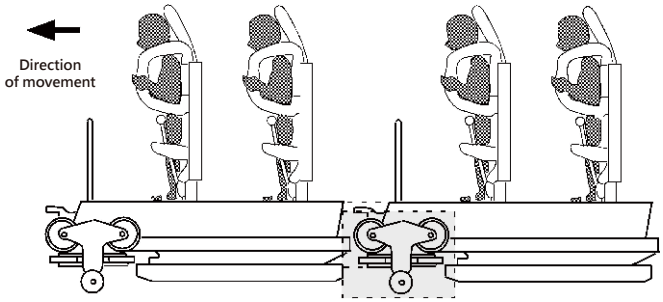


Figure 2

Figure 2 shows the state of the passengers boarding the roller coaster train. Since the passengers are boarding while standing, they can feel a strong physical sense of force owing to acceleration and deceleration. The lower part of Figure 2 represents the module. Figure 3 is the side view of the module, which is composed of 5 wheels gripping the rail. The center part of the figure is the ruptured shaft. Figure 4 shows the detailed structure of the module. The ruptured shaft had been designed to attach the module to the car body through the threads machined onto the shaft ends. Although the threads were machined on both the shaft ends, what ruptured was the inner one.

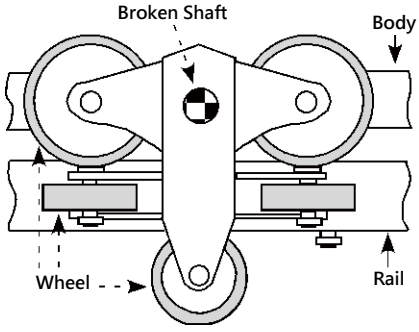


Figure 3

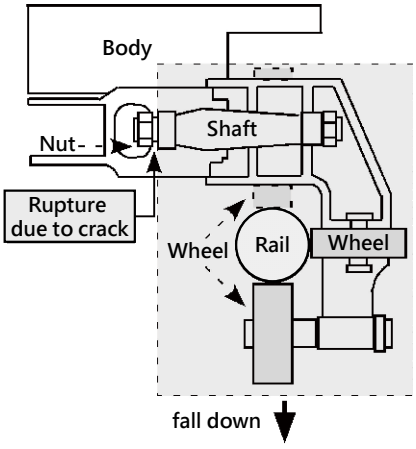
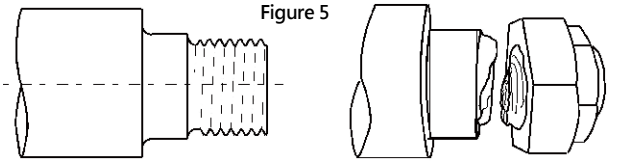


Figure 4

3. Cause of the Accident of Thread Rupture and Its Mechanism

An investigation on the accident determined that the cause of the shaft rupture was the fatigue failure due to the repeated loads exerting on the threaded portion. Figures 5 (a), (b) respectively show the shapes of the thread portion on the shaft ends before and after the rupture. This shape of the ruptured portion is similar to the case of being subjected to "axial repeated tensile load" in standard thread fatigue tests. The picture indicates that the loads exerting in the axial direction of the shaft have a large influence. From the above considerations, it is presumed that the rupture is caused not only by the bending load exerting on the car body, but also by the tensile load due to centrifugal force. Although detailed analyses are required to explain how the load exerts on the running shaft, it is considered that the spiral portion placed in the latter part of the roller coaster course would have exerted quite an amount of axial load.

Figure 5



(a) threaded end of stepped shaft (b) rupture due to crack propagation

4. Why did the Accident Occur?

Considering the Problems Involved in the Roller Coaster

In addition to the critical bolted joints in machines and structures, it is indispensable to check amusement facilities like roller coasters, focusing on the heavy loaded portions, regularly and closely, since they involve the issues on the security of human life. The Wind God that caused the accident as well as the Thunder God had been put on regular checks.

Please take a look at Figure 4 again. The portion where rupture occurred is located inside the car body, and has a shape that is difficult for visual inspection. On the other hand, it is clear that if the car body bears the load in the horizontal direction of the Figure, all the loads exert on the ruptured threaded portion. From this standpoint, it can be said that the difficulty in visual inspection indicates a problem in the design process, regardless of a dangerous portion being involved. At the time of the accident, the responsible engineer of the amusement facility manufacturer said that the fatigue failure was unexpected. Judging from this, we can make a conjecture that the responsible inspector did conduct only a simple check of the ruptured portion. If the shape of this module is necessary from the strength design point of view, the module should have been disassembled and checked regularly, even if it demands some cost.

Another thing is the problem with shaft shape. As shown in Figure 5(a), the threaded portion has a stepped shape in two stages, so that its diameter is fairly smaller than that of the car shaft itself. Furthermore, this portion with thinner diameter is very short for the total length of the shaft. Employing such a shape, the "ability to absorb strain energy" becomes extremely low when subjected to axial load. I will explain this phenomenon by means of simple solid mechanics.

Figure 6 shows how much strain energy is accumulated and degraded in partly stepped bars, assuming that the strain energy for a straight round bar, with length L and diameter d, under tension being U. In case of the bar on the far right in Figure 6, for instance, it can only absorb one fifth of the strain energy of a perfectly straight round bar.

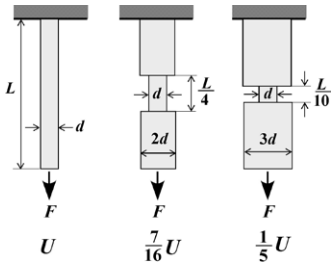
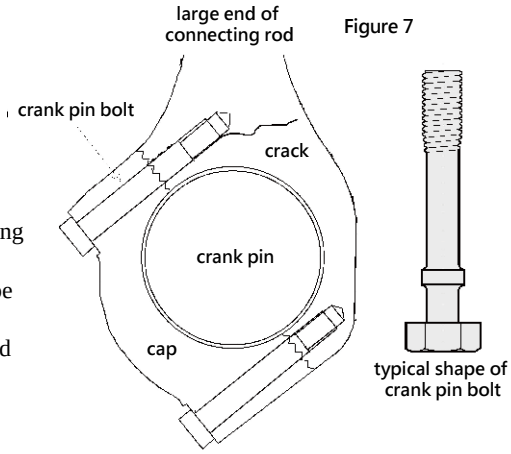


Figure 6

The shaft of the roller coaster is similar in shape to the ones at the center and the far right of the Figure, in which the shafts have partly thinner portions. That is, in the case of the shaft of this type, the ability of the whole bar for accumulating the strain energy decreases, because the stress of the thicker portions is low and the shaft scarcely elongates even under axial load.

Figure 7



As a contrasting example, Figure 7 shows the shape of the large end of connecting rod used for middle-speed diesel engines and the crank pin bolt used for fastening. Because the crank pin bolt is subjected to a large amount of bending load, the bolt is wholly machined thinner for easy bending. As a result, it is possible to suppress the amount of stress variation caused by the external force, namely the "stress amplitude", which is the major cause for fatigue failure. From the above considerations, we can conclude that the shape of the threaded portion of the roller coaster train shaft, which caused the tragic accident, is not preferable from the standpoint of solid mechanics.

5. Afterword

A month and a half after the accident, a first-rate Japanese news publisher made this accident the top story again on the first page of its Sunday morning newspaper. It was an exclusive scoop that cracks were found on the same spot of the shaft in another roller coaster train, "Thunder God". I already knew this case in advance because the news publisher got in touch with me a little while ago. The article surely proved that there was a problem with the car structure. However, design problem is not the only cause for the accident. If the maintenance such as a close check had been conducted on the ruptured threaded portion, it would have been highly possible to successfully prevent the accident. Anyway, the fact is that the occurrence of the accident and the news scoop, which was announced next, became the trigger that led a large theme park to a complete shutdown.

Reference

Toshimichi Fukuoka, "Threaded Fasteners for Engineers and Design – Solid Mechanics and Numerical Analysis –", pp.280-282, Corona Publishing Co., Ltd. (2015)