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A Fatal Accident Case and Lessons for Entertainment Engineering

Kenji Iino, SYDROSE LP, San Jose, California, USA
Masayuki Nakao, The University of Tokyo, Tokyo, Japan

ABSTRACT

On May 5th, 2007, a six-car stand-up roller coaster Fujin-Raijin II, during a ride, dropped one of its two wheel assemblies from the second car. Losing its balance, the second car tilted to the left by about 45 degrees. The rider in the left side of the front row jammed her head between the passenger support structure and the handrail of the maintenance walkway and was killed instantly. The next day, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) instructed a nationwide inspection of similar attractions.

Investigations revealed that the main axle had a crack caused by metal fatigue and the owner of the amusement park, bankrupt in 2009, had been running the coaster for 15 years without changing the axle and reporting “in good condition” upon visual inspection only. The applicable law required, and still does, annual testing with magnetic particles, ultrasound, or liquid penetrant. The axle, at the time of its failure, had only about 25% of cross-sectional area remaining intact where the crack had grown. A maintenance worker later reported looseness with the axle fit in the pressure-receiving hole. The fit was originally designed tight to receive the bending force.

People pay and wait in long lines for the excitement of unusual thrill from short amusement rides. The rides take passengers through unusual movements and G-forces to make them scream and laugh. Mechanical parts of the vehicles thus are subjected to unusual loading conditions. Machine design for such rides requires serious design reviews, failure analysis, frequent inspection, and thorough maintenance. Engineering ethics call for amusement park owners' and workers' awareness of design and operations for an unusual environment.

1. INTRODUCTION

Dyrehavsbakken, about 10 miles north of Copenhagen, Denmark claims the world's first amusement park opened in 1583 [1], however without rides, it was the natural springs that attracted the people of Copenhagen. The first mechanically designed ride was a giant swing built in the 17th century [2][3]. Fig. 1 shows an illustration by Peter Mundy in Ref. 2. Then railway companies put up a carousel in Coney Island, NY to attract people in 1875, followed by a roller coaster like switchback gravity train in 1884 [4]. The first modern amusement ride was probably the Ferris wheel designed and built by George Washington Gale Ferris, Jr. for the 1893 World Expo in Chicago [5] (Fig. 2).

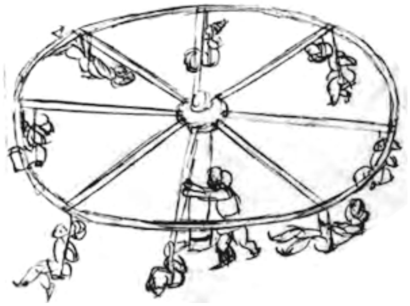

Fig. 1 Peter Mundy's illustration of a giant swing

We cannot trace the history of accidents that probably took place back in the early days, however, the US Consumer Product Safety Commission has records of a fatality count of 3 in as early as 1973 [6]. The count was 5 in a more recent year of 2004 [7] (Fig. 3).

Fig. 2 Ferris wheel at the 1893 Chicago Expo

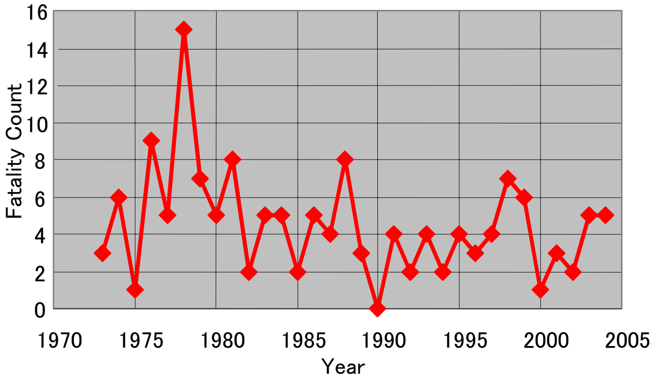

Fig. 3 Amusement ride-related deaths in the US

Fig. 4 shows the weighted counts of injuries with fixed-site (e.g., a theme park), mobile (e.g., carnival), and inflatable (e.g., moon bounces) rides. The weighting deals with ambiguity of the raw data from National Electronic Injury Surveillance System (NEISS) [7].

Observing Fig. 3 and 4, we see that the number of deaths does not show significant change over the years, however at the same time, it means that we have not been able to significantly drop the number despite the advancement of technology. Injuries, on the other hand show significant increase in those associated with inflatable rides.

The engineering community spends a major portion of its activities in efforts for accident prevention. We have seen much progress in ways of identifying what the real cause was, e.g., forensic engineering, root cause analysis (RCA) [8], and so on. These methods deal with precisely identifying “what happened and how.” That information is inevitable for us in devising ways of preventing accidents of similar nature from happening again. Armed with more knowledge of how past accidents happened, the designer uses tools like fault tree analysis (FTA) or failure mode and effects analysis (FMEA) [9] in efforts to foresee problems with the design so he can make modifications to avoid them. These methods identify the most damaging scenarios based on probability assessment of elementary events that lead to accidents. Leveson developed System Theoretic Process Analysis (STPA) [10] for handling more complex systems including human factor. Visnepolschi extended TRIZ into I-TRIZ [11] to find failure mechanisms that are hard to recognize by asking the designer “how can the system accomplish the failure?”

All the above methods for accident prevention, however, are based on human knowledge, insight, and new viewpoints for identifying what can go wrong. If the analyzer or risk assessor has limited knowledge or ability, he is likely to miss the bad scenario. To overcome this limitation, we suggest new research direction for an automated mechanism to ring the bell for the designer.

We pay large entrance fees to enter theme parks and patiently wait in long lines just to get the thrill of short amusement rides. They are perhaps the last type of “rides” we would imagine that we could get injured or even killed in. This paper reports about a specific roller-coaster accident that took place in 2007 in Japan, and what it taught us in terms of engineering, and engineering ethics. We also discuss about the concerns we have about entertainment engineering in Japan, and how we can make use of failure information in the general field of engineering.

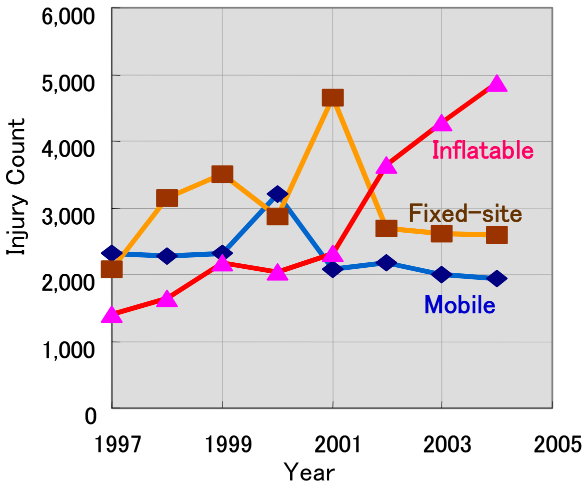

Fig. 4 Amusement Ride-Related Injuries in the US

2. FUJIN-RAIJIN II

Background Information

Fujin-Raijin II was a stand up roller coaster in Expoland, which was an amusement park that started operations in 1972. Within a few years of the accident, the amusement park went bankrupt and closed. It started as the amusement area for the Osaka Expo in 1970 [12]. The original coaster Fujin-Raijin, built by an amusement ride manufacturer Togo, had two tracks; one for the stand-up and the other for a regular seated ride. The two rides ran in parallel except some sections of the tracks. Fujin-Raijin moved to Kumamoto prefecture after the expo and is still in operation, now with a different name. Expoland had its sequel built by the same company Togo, and named it Fujin-Raijin II that started running in 1992. The name comes from imaginary Buddhism gods Fujin, the god of wind and Raijin, the god of thunder. These gods are well known for the painting by the 17th century artist Sotatsu Tawaraya (Fig. 5).

Fig. 5 Fujin-Raijin painting by Sotatsu Tawaraya

The track

Unlike its predecessor, Fuji-Raijin II ran two trains, the blue Fujin (Fig6) and red Raijin alternately. Fig. 7 illustrates the entire 985m long track with some information associated with the progress of the accident. The trains are pulled up by a chain to the highest point of 40m above ground and released into a free fall on the track. The trains completed a run in about 2 minutes and 20 seconds. The maximum speed was 75km/hr.

Fig. 6 Promotional poster of Fujin-Raijin II (part)

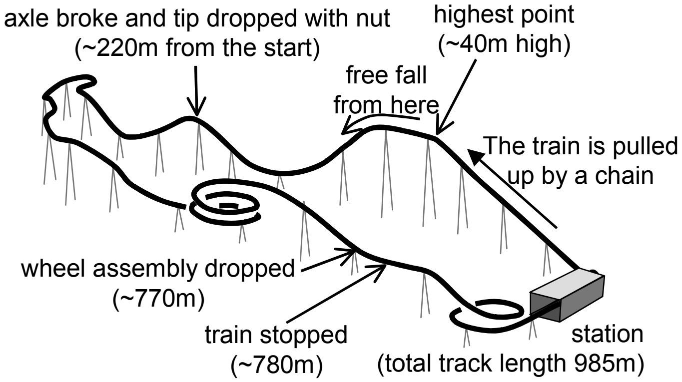

Fig. 7 Track of Fujin-Raijin II with major events during the accident

The cars

Unfortunately, there were no thorough investigation report by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of the Japanese government other than press releases and statistical reports on investigations of other amusement rides in the country, e.g., [13]. With the attraction closed, we can only judge from pictures about the cars as we explain here. Each train had six cars. Each of the first five had two wheel assemblies in the left and right front and was connected to the trailing car. The connection was attached to the trailing car in a way it was free to rotate in all directions so the train could follow the twisting and swirling track. The last car had another pair of wheel assemblies in the back. Fig. 8 shows the front view of a car of Fujin.

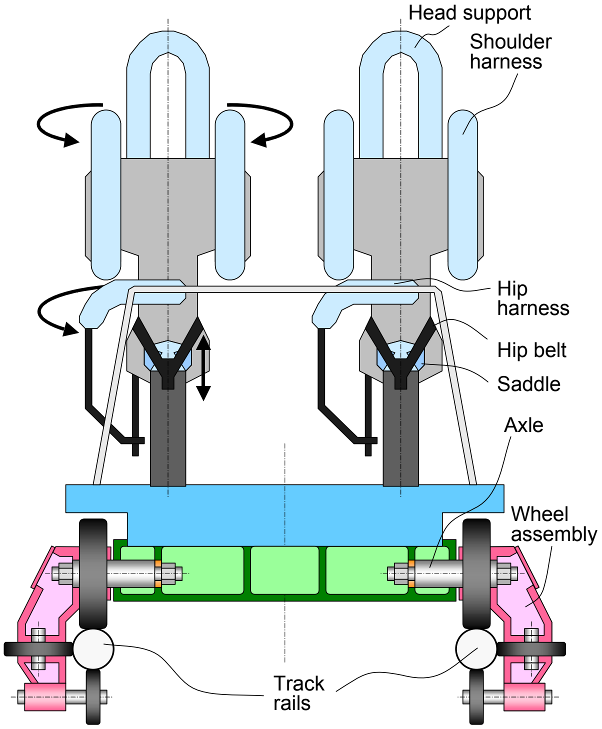

Fig. 8 Front view of a Fujin car

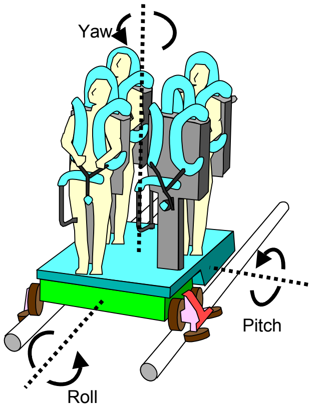

Fig. 9 Roll, Yaw and Pitch

Wheel Assembly

Figure 9 shows our convention of roll, pitch and yaw, for the following discussion.

The Osaka Prefecture Police (OPP) released a series of photographs of the damaged car. Fig. 10 shows the wheel assembly that fell off the car. It broke at the top of the photograph where an M32 thread extended up to engage a nut. The photograph views the assembly from above with the thread and nut missing.

The assembly had two main wheels on the top, two side wheels to prevent yaw [14], and a bottom wheel to keep the car on track without letting it jump up off the rail. Fig. 11 shows the assembly, in which the failed axle is drawn with dotted lines. The five wheels rotate individually around their own axles, and in addition, the entire assembly rotates about the axle shown in dotted lines.

Even though we could not get our hands on a complete drawing of the machine, subassemblies, or its parts, there was some information available on the Internet. With the penname SUBAL, an unidentified person runs a BLOG [15] which has a series of articles of his conjecture about the cause of the accident. The articles give valuable information and suggestions about analysis into the cause. He claims that he obtained a copy of the drawings of the wheel assembly without identifying the source, however, we will rely on this information for further discussions. The dimensions available from SUBAL's BLOG prove fairly adequate when compared with photographs from other sources. Fig. 11 shows the axle which we concluded its configuration in this manner.

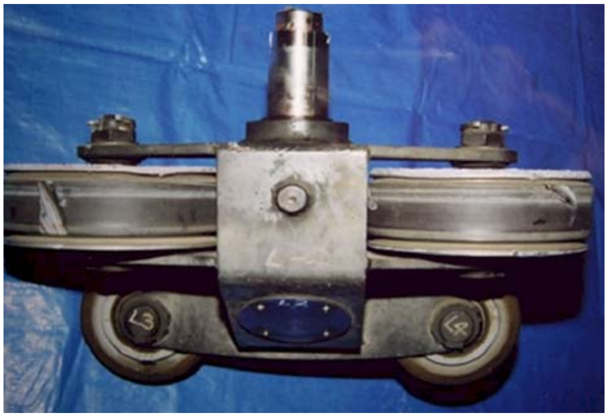

Fig. 10 Wheel assembly that fell (Top view)

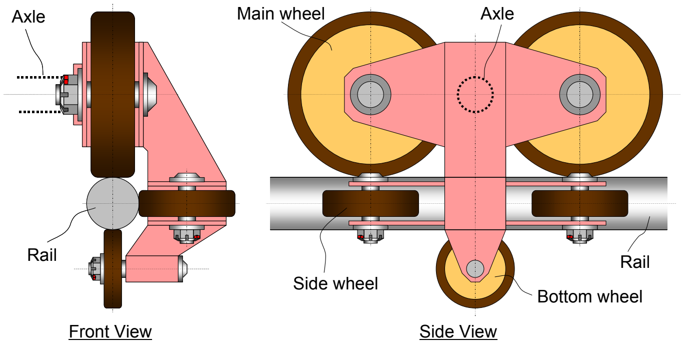

Fig. 11 Wheel assembly

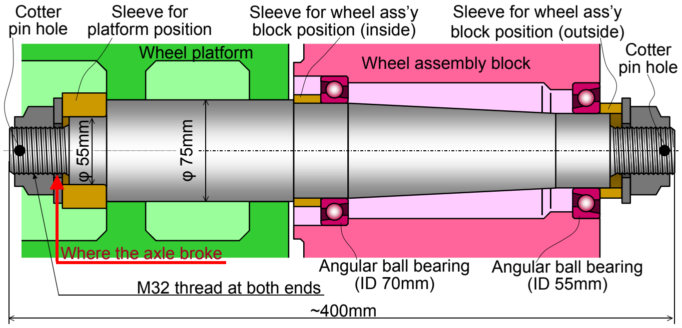

Fig. 12 Wheel assembly axle

3. THE ACCIDENT

It was almost 1 o'clock in the afternoon on Saturday, May 5th, 2007. It was the Children's day national holiday and the second last day of the 9 days Golden Week in Japan that year.

The first peak of the ride was a slow climb to the highest point. Then when the latch disengaged from the chain that was pulling the train up, it entered the free gravity fall on the track. The second high peak was immediately after the first valley, and at its top, the left side axle on the second car, Car-2, broke where indicated with a red arrow in Fig. 12 [16]. It dropped with the nut fixed on the thread with a cotter pin. While the wheel assembly lost its constraint to keep its axle pinned into the wheel platform, it survived another relatively calm 500m section but as the train exited the double-loop climb, the entire assembly fell of Car-2. Car-2's connections to Car-1 and 3 had no constraints against roll, and when the left-side wheel assembly was gone, the entire car rolled around the right side track rail for about 45 degrees.

The passenger on the left side of the front row, a 19-year-old female, in Car-2, constrained to the standing seat, tilted with the car and her head was jammed at high speed between the maintenance catwalk handrail and the head support behind her head. Fig. 13 shows how the car and the standing seats were when the emergency rescue workers were trying to remove the body. The figure is a trace of a photograph that shows all other passengers still stranded in their seats and the victim with her upper body lying on the catwalk. Bodies of the rescue workers block some of the structures in the background.

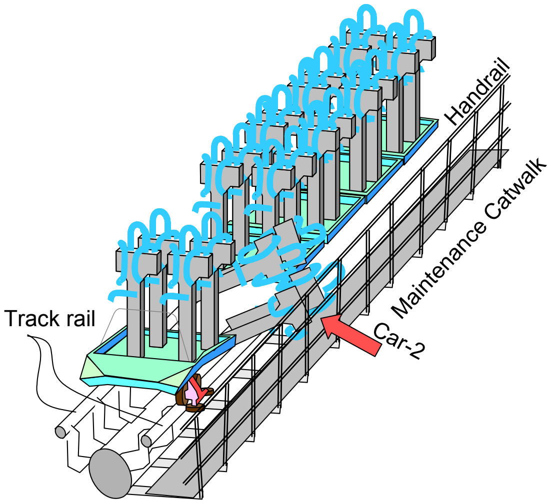

Fig. 13 Car-2 after rescue workers had arrived

The impact was immense. The passenger in the left-side back row of Car-2 was also badly injured and taken to the hospital together with the other 18 that were on the same ride. Some of the 18 were slightly injured. The ride had 4 vacant seats. Fifteen bystanders were also taken to the hospital for getting sick when they saw the accident.

The head support seen bent backwards behind the handrail in Fig.12 was for the second passenger. That for the front row passenger that died is not seen in the picture. It was most likely removed by the rescue workers. The stand-up seat itself was pushed backwards. No question it was an immediate death.

4. CAUSE ANALYSIS

Maintenance

OPP immediately started a criminal investigation for misconduct, and then on June 4th, a month from the accident, it released a series of photographs of the failed wheel assembly including Fig. 9. Figure 13 shows the axle where it broke. Although it is hard to tell from the second photograph, specialists say the cross section showed beach marks over the upper 2/3 area of the cross section. This means at the time of failure, the axle had only 1/3 of the original cross section intact to hold onto the wheel assembly. What we can see from Fig. 13 is that the crack initiated at the bottom of the minor diameter at the upper side of the axle. As figures 8 and 11 show, the wheel assembly does not turn at high speed like wheels. It may rotate for a few degrees to keep itself on the track, nonetheless, the axle is subject to repeated stress cycles as the cars travel on the twisted track.

Note from Fig. 7 that the axle broke when the train reached the top of the first hill after the initial drop. Fig. 14 shows our conjecture of how the axle eventually broke at this location. The upward inertia put bending force on the axle.

(a) Side view

(b) Straight view at the two broken faces

Fig. 13　Photos of the broken axle
(orientation is the same as when installed)

Due to gravity on the car and wheel assembly, the bending force is greater at track valleys rather than hills, however, as the crack was initiated at the high end of the axle neck, bending force when the rising car was forced to turn down worked to spread the crack.

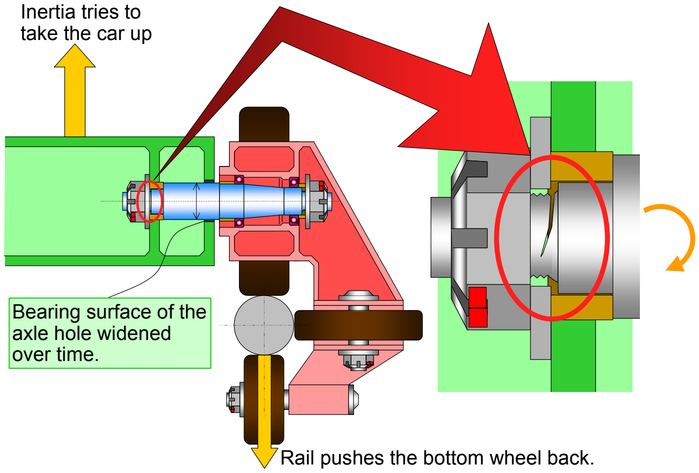

Fig. 14　Mechanism of axle failure

When a structural member is subject to repeated stress cycles, metal fatigue is always a concern, not only to the designer but also to servicemen and equipment owner.

In Japan, amusement rides are subject to Building Standards Law [17], which requires conformance to Japan Industry Standards. The applicable standard, JIS A 1701: Inspection Standards for Amusement Facilities specifies that such equipment shall have annual inspection for cracks by either the magnetic-particle, ultrasonic, or liquid-penetrant method.

It was later disclosed that Expoland, the owner of the park, never exchanged the axles on the cars throughout the 15 years of operating Fuji-Raijin II. Their annual inspections took the wheel assembly apart, however, only made visual observations of the parts. The park continued to report "nothing to report, in good condition" to the administration. Poor maintenance, or perhaps a better word is, negligence was a large cause of this accident.

Design

The initial design intended the mating hole in the wheel platform (bearing surface on axle hole in Fig. 14) to carry most of the bending force. Iino estimated the bending stress in the axis in this case not to exceed 6kgf/mm^2 [16]. We can easily guess that the axle would hardly rotate because the wheel assembly is attached to it via two ball bearings. Over time, however, with pulling it out for inspection and pushing it back in, the surface will wear. A maintenance worker later confessed that within 5 to 6 years, the axles' fits were loose and they used glue to keep them tight [18].

Iino estimated the maximum bending stress to exceed 100kgf/mm^2 at the neck [16] when the train was subject to 3G at the bottom of the first valley, assuming there was no support at the axle hole. He also estimated the bending stress, when the car was banked by 45 degrees, to be at the same level. Iino's analysis, however, had to assume quantities like the car's dead weight, velocity, and track's bank angle from photographs. Again, it was unfortunate that no formal report was published other than police's press releases about the physics of the accident.

The axle was made of nickel-chrome alloy with tensile strength of 75kgf/mm^2. When material is subject to repeated stress cycles, the design textbooks recommend keeping the stress below 25 to 48kgf/mm^2 by multiplying a factor of 0.35 to 0.64, e.g., [19]. The factor of safety in this case is the reciprocal of the multiplying numbers, thus 1.6 to 2.8. Although conservative and rough, the bending stress in excess of 100kgf/mm^2 clearly violates this requirement.

During a DFMLC panel of Entertainment Engineering in 2011 IDETC/CIE, Sywak of McLaren Engineering that built machines for the Cirque du Soleiu's show KA and Rinke of Walt Disney Imagineering both said the factor of safety for their designs is 10 [20]. A common factor of safety by Unwin for steel when the load may involve impact conditions is 12 [21]. If we apply these factors of safety, we find that even the stress of 6kgf/mm^2 at the original bearing surface on the wheel platform was marginal. Due to unavailability of the design documentation, the above estimations are rough, however, we find that the original design itself to be at least questionable.

Dimensional Tolerance

After reviewing the photograph in Fig. 9, we were puzzled with the wide wear mark on the main wheels. Since the track rails are swept circles (cylinder when straight), the contact with the main wheels should be a point and thus, leave a straight-line mark on the center of wheel width (Fig. 15).

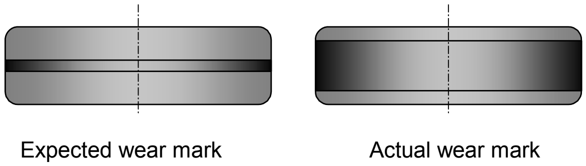

Fig. 15 Wear mark on main wheel

We then realized for the rigid wheel assembly in Fig. 8, it is practically impossible to keep tight contact of the side wheels for the entire length of the 985-meter ride. Instead of keeping contact all the time, the side wheels on the left and right side assemblies would alternate which side was in contact depending on where the car was on the track. The broken axle thread was M32, so from Fig. 9, the wear mark was about 50mm, thus the biggest gap between the track rail and side wheels was about 50mm.

In May 1990, the predecessor Fuji-Raijin had an incident of getting stuck on the track in the middle of a ride. This was probably due to the warm weather expanding the width of the two track rails wider than what the narrowest wheel assembly pair could handle. Mechanical engineers are good at managing microscopic tolerance of machines, however, when it comes to large structures, we tend to forget that they also have building tolerances as well, and they are much lager than what we are used to. Although we cannot estimate the resulting impact forces upon the cars swaying sideways and hitting the rail, they must have been quite significant.

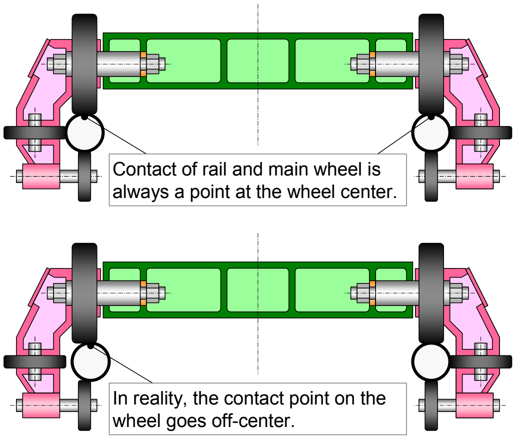

Fig. 15 Gap between side wheels and rail

5. AFTERMATH

On May 6th, the day after the accident, MLIT instructed all the local governments in Japan to have amusement park coasters (defined to have a track with a maximum inclination of 5 degrees or more) inspected for damages and cracks in the axles [22], in a way conformant to JIS A 1701.

On July 31st, about 2 months from the accident, MLIT ran a press release that there were 307 such rides in the nation and 14 were still under inspection. Of the 293 that filed reports, 15 had problems, and 12 of the 15 had been fixed.

The Ministry of Internal Affairs and Communications (MIC), however, in October of the same year made an admonition that the emergency investigation was incomplete [23]. MLIT followed up with another emergency investigation that revealed that 40% of the amusement rides had not conducted the crack inspection with magnetic-particles, ultrasonic, or liquid-penetrant method over a year [24].

The finding led to revising the applicable law to require attaching results of crack inspection to the annual reports to the local governments for amusement rides that run at 40km/h or faster [25]. In revision included a monetary penalty of 1 million Japanese Yen (about US$10K) or less for violation. Business owners were not required to attach results of the inspection before. With this strict revision, many of the small amusement park owners decided to close their businesses.

6. DISCUSSION

The mass media and the police blamed the inappropriate crack inspection as the cause. Expoland closed after the accident but restarted in August of 2008 after settling civil matters with the family of the deceased. People, however, did not return there for amusement and the company was forced into bankruptcy in October of the same year. On September 28, 2009, three board members of Expoland and the company itself were found guilty of criminal charges.

Police investigation tends to close, as soon as it finds evidence of malpractice to accuse a responsible person. The authors, however, question the design itself in addition to the poor ownership. The manufacturing company, at the time of the accident, had already been gone, filing bankruptcy in 2004. The lack of documentation about the design of the machines and insufficient investigation into the failed hardware hampered us from backing up our point.

We wrote this paper in hopes of preventing similar mishappenings in Japan as well as in other parts of the globe. One of the effective ways of preventing failure is to learn from failures happened elsewhere.

On December 2, 2012, concrete slabs inside a highway tunnel dropped killing 9 and injuring 2. As we write this paper, the owners are busy taking the existing concrete slabs down. We then learned about an almost identical accident near Boston Logan Airport in 2006 [27]. The cause of the Boston accident has been identified to the use of inappropriate type of epoxy [28]. Investigation for the one in Japan is underway [26]. The two designs are almost identical. If we had learned from the 2006 accident in Boston, and the owners in charge of Chuo Highway in Japan more keen on accidents elsewhere, the inspections could have been made more thoroughly. The mass media again blamed the accident on poor inspection.

After all, it is each business owners to keep their eyes open for accidents with facilities similar to those of their own. We, however, may be able to contribute by making such information readily available and find ways to push the information to those in need.

Our analysis of the failed Fujin-Raijin II design shows that amusement rides are not necessarily 100% safe. Of course, nothing is 100% safe. The consumers may want to understand the risk involved with it before taking an exciting ride. We are now armed with the tool Internet, and we would like to share valuable information with as many people as possible. The fun with taking this type of rides is great and we are probably not ready to give them up entirely. We would like to realize a world where such rides are closer to 100% safe.

In terms of social behavior, we found the following:

- People tend not to follow regulations unless there is a penalty for violation
- Japanese industries tend to lack or have poor design documentations
- Police investigation and the mass media tend to blame maintenance, however, we need to look at the design to see if the original idea had some flaws

The authors have made studies in documenting and making failure information available on the Internet [29,30]. Our current research focuses on a tool that warns the designer that has a risky configuration in his design. Such situations will happen with lack of knowledge or experience. At times, it can be a total surprise even with a skilled designer. To realize such an automated warning system, we have to work with what the designer has configured without knowledge of a possible failure scenario.

Designing rides for the Entertainment Engineering is different from other practices of mechanical engineering because it tries hard to give the user the sense of “danger” rather than “safety”. The user is happier if he senses “danger” in his rides. Loading conditions are often extreme. Looking at statistics of injuries and fatalities, the numbers have not changed much in the past several decades, meaning that despite the recent vast advancement of technology, safety with rides have not improved much.

Because the number of ride accidents is small compared to, say, automobile accidents, a local region of the world probably have not accumulated enough information associated with large number of accident cases. There are two possible development directions for Entertainment Engineering that we suggest. They can run conjointly. One is to gather accident information and build an information repository on the Internet about entertainment accidents. The other is to develop mechanisms to warn the designer of possible design flaws. This is especially important for Entertainment Engineering because machines operate in manners different from usual design.

One might say that such developments are not special to entertainment and they are what everybody in engineering is looking for. So far we have seen new developments and tools that have made progress, however, they are not perfect; that is why we continue to see accidents. If we try to cover the entire engineering community, we can easily get lost in the overwhelming amount of information. A small size community of Entertainment Engineering is a good starting point and we can plan about expanding the coverage later.

7. CONCLUSIONS

Industries worldwide will benefit from having a mechanism for sharing accident information. The Internet offers a good foundation for information sharing, however, it is hard for the designer to constantly monitor the Internet searching for accident information with resemblance to his design.

Accident investigation shall not close with identifying who is responsible. It is easy to blame the maintenance because that is the cause in many cases. Our further evaluation, however, of the hardware involved with the Fujin-Raijin II accident identified possible flaws with the design. Without knowing the real cause of accidents we cannot prevent their repetition.

The designer, despite failure analysis tools, will embed risks in the design without knowing it. It is easy to point fingers with detail analysis that takes place after the accident. What we need are ways to warn designers of possible flaws in his design that he has not recognized before the design is put in shape.

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