EFFECT OF WHEEL IMPACT LOADING ON SHATTERED RIMS

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SUMMARY

This paper reviews proposed formation mechanisms for shattered rim defects in railway wheels and describes past research efforts that were conducted to better understand such defects. It appears that impact loading, among other factors, is a major factor in the initiation of shattered rim defects in wheels.

Association of American Railroads (AAR) MD-115 form failure data and AAR 1999 Car Repair Billing (CRB) data are discussed to provide information on the service frequency of shattered rim defects. Railroad wheel impact data, generated from wheel tread defects and recorded by wayside impact detectors in service is presented and is used to estimate shattered rim crack fatigue life.

Key Words: Shattered Rim Defects, Wheel Impact, Wheel Tread, Wayside Impact Detectors

INTRODUCTION
Shattered Rim Defects in Railway Wheels

Shattered rims, which rarely occur in North American railway service, are still an important safety concern for railroads. Such defects can lead to train derailments at high speed, and therefore are worthy of further study to better understand the mechanisms and the conditions under which they initiate. Once shattered rims initiate in the wheel rim, propagation occurs rapidly under normal wheel loading. To initiate cracking, however, a large load, such as an impact, may be required.[1]

Shattered rim fatigue cracks historically have initiated at voids and porosity in cast wheels and at aluminum oxide inclusions in forged wheels. Initiation depth is typically 12 to 20 millimeters (1/2 to 3/4 inches) below the wheel tread surface, and propagation occurs roughly parallel to the wheel tread surface. Shattered rims are often noted when cracking exits the front rim face. Complete fracture of a section of the wheel rim can also occur. An examination of shattered rim fracture surfaces normally reveals obvious fatigue crack "beach marks," also referred to as a "clamshell pattern." If service damage is not too extensive, the crack initiation site is often clearly visible as Figure 1 shows.

Figure 1. Typical Shattered Rim

Recent attention has centered upon the size of discontinuity that will be sufficient to initiate a shattered rim, and to the types of stresses that are responsible for the cracks.[2,3,4,5] This paper focuses primarily on the role of wheel/rail impacts caused by shells/spalls, slid flats, built up tread and out-of-round wheels on shattered rim initiation.

AAR MD-115 DATA

The AAR wheel failure database, consisting of MD-115 failed wheel reports submitted from field railroad locations, can be used to determine the occurrence of shattered rims in North America. Figure 2 shows the number of shattered rims reported on AAR MD-115 forms in 1999 as a function of percent remaining in rim thickness. Note that the failure distribution for shattered rims is bimodal, with most failures occurring when the wheels have greater rim thickness and thus are newer. This suggests that most shattered rims are infant mortality failures that occur primarily due to a void or inclusion of the critical size necessary to cause initiation.

However, an important additional related factor is the phenomenon of "bonus metal" being supplied on new wheels. Although the AAR minimum rim thickness for new wheels is a fixed measurement, added rim thickness metal may be present on new wheels. Thus, if the percentage of remaining rim thickness on shattered rim wheels is calculated using the AAR minimum value instead of a larger "actual" value, higher percent remaining rim thickness values will result. This skews results somewhat showing failures occurring in "new" wheels.

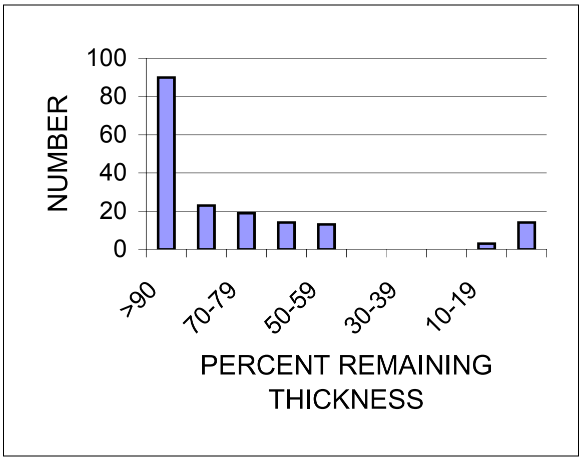

Figure 2. Distribution of MD 115 Shattered Rims vs. Percent Remaining Rim Thickness

Also noted in Figure 2 is a second peak of shattered rim failures that occurred when the percent remaining rim thickness was much less, thus later in wheel life. Recent research work, described later, has suggested that these late-life failures may be due to impact-related cracks forming in wheels and not being removed by subsequent tread re-profiling operations.[6] When wheels are returned to railroad service, the already initiated cracks propagate to form shattered rims.

A graph of Standard Steel's 1999 MD-115 report wheel failure data showing the number of shattered rims versus percent remaining rim thickness has a similar appearance to the graph shown in Figure 2. However, there are no Standard Steel shattered rim failures seen at low percent remaining rim thickness values, and the distribution is not bimodal.

AAR CAR REPAIR BILLING DATA

AAR's car repair billing data (CRB) is also useful in examining the frequency of the shattered rim problem. CRB data consist of those freight car repairs made between railroads as "foreign repairs" or by railroads on privately owned cars. In general, repairs made by private car shops are not included in CRB data and similarly, railroad home-line "system" repairs are not included. It is estimated that only 40% of the total number of North American wheel change-outs are included in CRB data. Shattered rims totaled 301 wheels in 1999; and 511,299 CRB wheel removals occurred. This means that shattered rims accounted for only 0.059% of all removals during 1999.

Shattered rims are identified in the CRB data as why made code 71 repairs. However, it is believed that some number of why made code 68 (cracked rims) repairs (531 total in 1999) are actually shattered rims due to misidentification in the field. The cracked rim category will contain other defects that are not shattered rims. Thus, the actual number of CRB shattered rims is likely somewhat higher, although still a small percentage of total wheel removals. Other issues related to 1999 AAR CRB data are reviewed in a recent paper presented by the Railway Wheel Manufacturers' Engineering Committee (RWMEC).[7]

A review of 1999 CRB wheel removal data by job code was conducted for 289 why made code 71 wheels. The data shows that for the shattered rim wheels, 179 were heat-treated wheels and 110 were the no longer produced untreated wheels. Further, 230 of them were curved plate while 59 were straight plate. These data show that straight plate wheels, though a diminished portion of the total wheel population due to accelerated removal efforts, comprise approximately 20% of shattered rim wheels.

Since the AAR estimates that approximately 5% of all wheels currently in service are straight plate, these wheels appear to fail more frequently for shattered rims and cracked rims. Similarly, untreated wheels are shown to make up around 40% of both cracked rims and shattered rims whereas their AAR estimated population is only 15% of all wheels in service. Both straight plate and untreated wheels have been in service for many years and are nearing the end of their useful wear life.

An analysis of 1999 AAR CRB data by car type was conducted for shattered rims (see Figure 3).

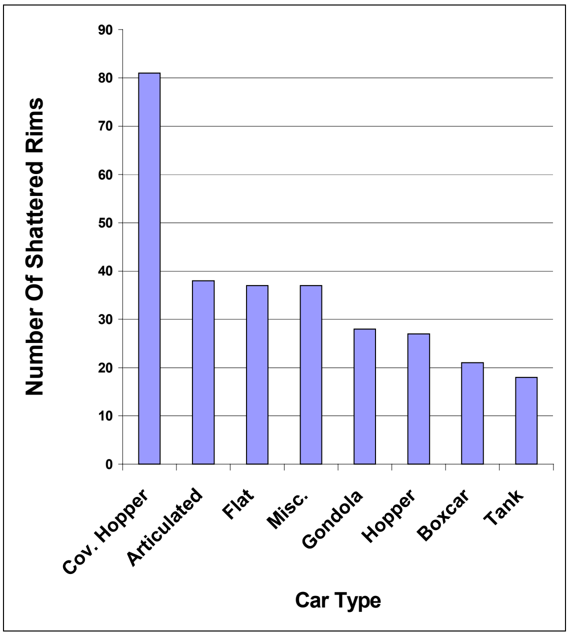

Figure 3. 1999 CRB Wheel Removal Data for Shattered Rims by Car Type

It is interesting to note that covered hoppers have more wheels removed for shattered rims, which may be attributed to the cars being moved with their hand brakes applied. The trends are not so clear for other types of cars and definitive conclusions are hampered by the following factors:

- CRB repairs tend to include a greater percentage of private car repairs (tank cars, articulated cars, flatcars) than railroad-owned cars.

- The mileage traveled per car (fatigue cycles) can be very different depending on the type of service, particularly for intermodal flatcars, articulated container cars, and unit-train coal cars. Covered hoppers and tank cars that represent the largest numbers of cars in the fleet are typically low mileage cars.
- CRB repairs tend to include fewer system hopper and coal gondola repairs since these repairs are often made by home railroads and thus are not reported to the AAR.
- Although some cracked rims are likely misreported as shattered rims, other causes (such as brake system problems) can contribute to the incidence of cracked rim wheel defects.
- Certain types of low-mileage cars are known to have a greater percentage of older, inferior straight plate wheels.

Figure 4 shows graphical 1999 CRB data for the number of shattered rim wheels removed versus the year the wheels were manufactured. Note that there is a large peak of removals that grew from 1986 to 1992. This is probably associated with the discontinuation of periodic air brake testing, which resulted in an increase of wheel flats. The implementation of an improved repair track air brake test in 1992 and periodic single car air brake testing in 1992 has resulted in a continued reduction. Additionally, this peak may be associated with the extensive car building boom in the early 1990's that would result in a greater population of wheels being put into service. The graph also has a second peak in the early 1980's, and this suggests that these wheels are nearing the end of their useful wear life. CRB data was then analyzed to see if the frequency versus percent remaining rim thickness trend shown for AAR MD-115 data was consistent. AAR minimum rim thickness was assumed for the initial rim thickness value, and rim thickness at removal was obtained from the database. Figures 5 and 6 show the results for shattered rims in one- and two-wear wheels, respectively.

Note that the one-wear wheels in Figure 5 do not show as strong a bimodal distribution as either the MD-115 data or the two-wear wheel data in Figure 6. The reason for this difference remains unexplained.

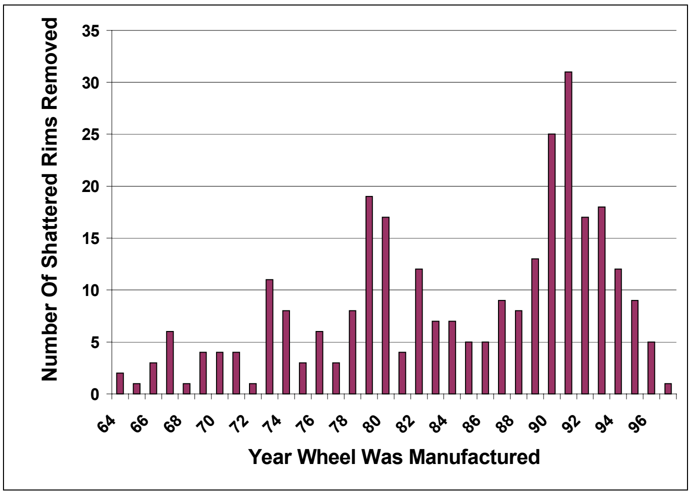

Figure 4. Number of 1999 CRB Shattered Rim Wheels vs. Year Manufactured

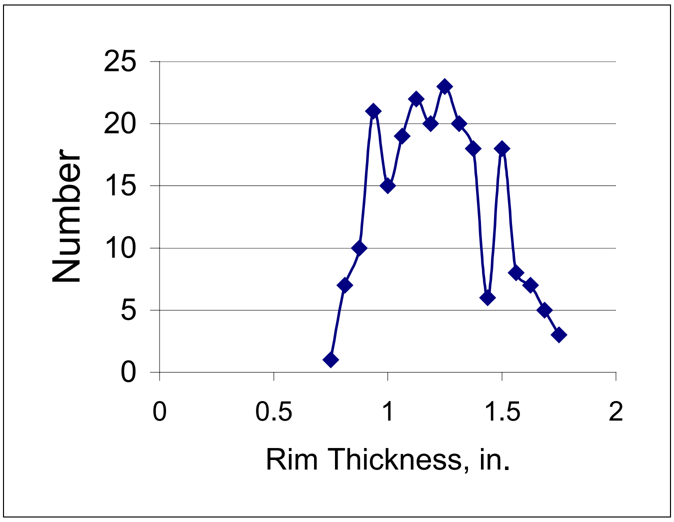

Figure 5. Distribution of CRB Shattered Rims vs. Rim Thickness for One-Wear Wheels

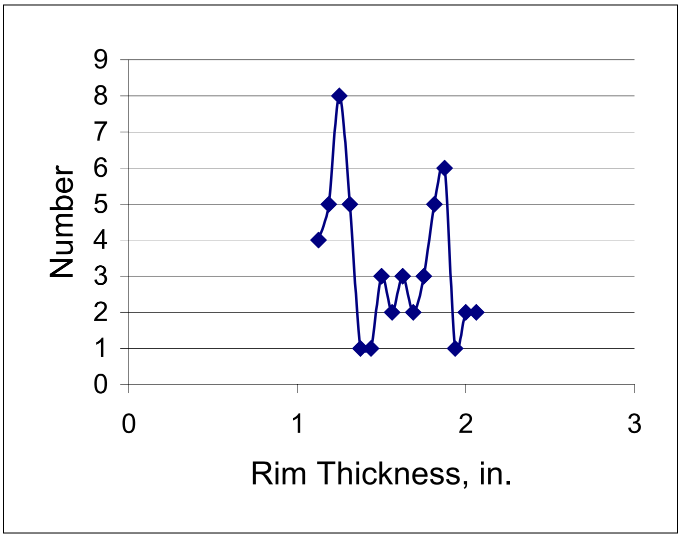

Figure 6. Distribution of CRB Shattered Rims vs. Rim Thickness for Two-Wear Wheels

WAYSIDE IMPACT DETECTOR DATA

Use of wayside impact load detectors by North American railroads has resulted in the removal of high impact wheels that damage bearings, lading, rail, other mechanical components, and the wheels themselves.

Current AAR rules allow wheels to be removed for "why made code 67 (out-of-round)," if a wheel impact load detector reading greater than 40,800 kg (90,000 pounds) is noted, and if verified out-of-round "runout" exceeds 1.8 mm (0.070 inches).[8] Such defects are the responsibility of the car owner. However, slid flats, built up tread and shells/spalls can also lead to high impact loads being imposed upon the wheel tread. Table 1 shows 1999 AAR CRB data for wheel defects that can cause tread impacts. Shelling/spalling defects have increased dramatically in recent years and thus the number of wheels that have experienced high impact loads has similarly increased.

Table 1. 1999 CRB Wheel Removal Data for Wheels that Cause High-Impact Loads

AAR Why Made Code	Number Of Wheels
67 = out-of-round	2,554
75 = shelling	80,298
76 = tread built-up	9,131
78 = tread slid flat	27,018

The Canadian National (CN) Railway has seen that out-of-round wheels with "healed" shells, where tread metal flows over and smoothes tread craters, can lead to impacts as high as 90,300 kg (199,000 pounds).[9] They also note that wheel impacts over 45,400 kg (100,000 pounds) are 10 times more common in winter than in summer. CN found that 87% of their wheel impact readings (for 32,040,106 total wheels examined) were less than 17,700 kg (39,000 pounds). The highest impact wheels, with 68,000 kg (150,000 pounds) impact and above, made up only 0.0007% of the total. However, as noted by the authors, 0.0007% still represents a significant number of wheels. Since the CN impact detectors evaluated 32,040,106 wheels, 0.0007% wheels with the highest impact translates to approximately 225 wheels. Further, it was noted that approximately 0.038% (more than 12,000 wheels) of the total CN wheels had impacts greater than 45,350 kg (100,000 pounds). Approximately 3.5% of the wheels (more than 1.1 million wheels) had impacts greater than 22,700 kg (50,000 pounds). All of these wheels experienced stresses well above loads associated with the normal static wheel load 16,200 kg (35,750 pounds) for a 129,700 kg (286,000 pounds) gross rail load car.

Early experience with wheel impact load detectors showed that a large percentage of high impact wheels were not condemnable under AAR rules,[10] although such detectors were effective at finding high impact wheels. More recent testing at TTC's Facility for Accelerated Service Testing using condemnable and non-condemnable service worn wheels and wheels with manufactured defects produced additional data. Sizes of tread defect and train speed were found to be very important.[11] Larger flat spots and higher speeds led to higher impact loads.

PAST SHATTERED RIM RESEARCH AND ALLOWABLE DEFECT SIZE

Recent technical papers have suggested that the critical defect size necessary to initiate a shattered rim is 1 mm (0.04 inch) in diameter.[2,3] Marais of Spoornet applied a local strain approach to the problem of shattered rim growth in cast wheels.[2] Spoornet's field experience has been that shattered rims have been caused by 1-mm (0.04 inch) voids and a tightening of ultrasonic requirements is said to have eliminated their occurrence. Lunden calculated the size of a "safe" crack length in the wheel rim to be 1 mm (0.04 inch) in diameter.[3] His crack growth analysis was based upon use of stress intensity factors and took into account crack surface friction and wheel/rail friction. Lixian et al.[4] proposed a crack initiation process for shattered rims in forged wheels and use of the Murikami criterion[12] for crack initiation calculations. In their initiation model, the wheel rim crack first forms at the inclusion/matrix interface of a ball-shaped aluminum oxide inclusion.

DYNAMOMETER RESEARCH

Researchers at the technical facility of a major cast wheel manufacturer have been successful in creating "shattered rim like" defects on a laboratory dynamometer.[6] Shattered rims have been generated at very low-mileage levels, less than 24,000 km, (15,000 miles) for applied rolling wheel loads above 63,500 kg (140,000 pounds). In one test case, 16,300 kg (36,000 pound) wheel loading was applied for 64,000 km (40,000 miles) and was followed by 49,900 kg (110,000 pound loading) for 9,600 km (6,000 miles). Since an internal flaw was discovered at 9,600 km (6,000 miles) using ultrasonic testing, wheel loading was then returned to the 16,300 kg (36,000 pound) level for 10,700 km (6,700 miles) until failure occurred. Although the applied load was not a dynamic one as would be experienced by a wheel with a flat spot in actual railroad service, the results suggest that higher load levels can influence shattered rim initiation.

IMPACTS AND SHATTERED RIM LIFE

A 914-mm (36 inch) diameter freight car wheel (H36) has a circumference of approximately 2.87 m at the tread surface. Therefore, a point on the wheel tread experiences approximately 350 cycles per km traveled. Using the data from the dynamometer experiments,[6] we note that shattered rim failure for three data points occurred at an approximate average of 16,000 km (10,000 miles or 5,620,000 cycles) for an applied dynamometer loading of 150,000 pounds (68,000 kg).

In another paper analyzing the crack growth rate of shattered rims, two calculations were made.[1] The first calculation used the rolling contact shear stress at 12 mm below the surface, and the second used an alternating stress equal to the endurance limit based on the Murikami criteria.[12] The results gave a first approximation of the growth rates of a shattered rim crack. The alternating shear stress gave a life of 24,000,000 cycles or 69,000 km (42,700 miles). The calculation assuming an alternating stress equal to the Murikami endurance limit gave a life of only 11 cycles to grow a 10-cm (3.5 in.) crack that is clearly incorrect for crack propagation. Therefore, it would appear that wheel impacts may be the major contributor to crack initiation while normal rolling load stresses can produce crack propagation.

IMPACT FATIGUE - INITIATION AND GROWTH

A recent paper by Yu et al. reviewed the effects of impact fatigue on metallic materials.[13] Impact fatigue strength, crack initiation and propagation under conditions of impact fatigue were discussed. The authors stated that crack growth rates are usually higher for impact fatigue than non-impact fatigue and that the loading time for impact fatigue is much shorter than for ordinary fatigue (0.1 to 1%). Fracture of materials under repeated impacts is said to have similar fatigue-fracture characteristics to non-impact fatigue, but stress concentrations cause impact fatigue life to decrease significantly. A graph in the paper suggests that impact fatigue endurance limit stress amplitude is approximately 1/3 lower than that for ordinary fatigue at hardness values (approximately 320 Brinell) similar to hardness values used for wheel steel.[13]

The crack initiation life of notched specimens is less for impact fatigue than it is for ordinary fatigue, but the reverse is true for smooth specimens. The authors also state that impact fatigue life increases with longer loading time for notched specimens and that impact-fatigue initiation is longer for stress ratio R=0 than it is for stress ratio R=-1 (completely reversed stress) at the same maximum stress level.

With regard to fatigue crack growth, Yu et al. state that for a greater stress range $\Delta\sigma$ there is a higher impact fatigue growth rate.[13] In the area of fatigue growth associated with the higher ΔK region, a longer loading time speeds up the impact fatigue crack growth rate. This implies that impacts with greater magnitude and greater size will be more damaging (in terms of remaining life reduction) for a wheel nearing brittle fracture at the end of the fatigue growth process. A larger defect will spend more time delivering the wheel/rail impact force than a smaller defect that causes a quick "spike."

The paper also reported that the transition from "tough" to brittle fracture takes place at lower values of ΔK (hence earlier in the fatigue growth process) for impact fatigue than for non-impact fatigue in a Fe-3Si steel.[13] This transition means that the steel's impact fatigue strength is lower, the fatigue crack growth rate increases for impact conditions, and the tendency to fracture in a brittle manner is greater. In this earlier stage of the fatigue crack growth process, increasing the loading rate and decreasing the temperature increases the brittle fracture trend. For wheels, this means that higher speeds, greater impacts, and colder temperatures provide the worst conditions with respect to impact fatigue crack growth.

IMPACTS AND ENDURANCE LIMIT

The question now becomes how to account for the more damaging effects of impact loading on the wheel rim, particularly when a stress concentration such as a void or inclusion is present within the volume. Clearly the presence of a stress concentration in a wheel rim is more similar to a notched impact fatigue specimen than a smooth one. The modified Murikami equation[14] allows for calculation of the fatigue endurance limit for steels with internal three-dimensional defects and is shown below:

$$\sigma_w = (1.56\ (H_v + 120)/\ (\sqrt{area})^{1/6}) \times ((1-R)/2)^{\alpha}$$

where, σ_w is the fatigue endurance limit, H_v is the Vickers hardness, area is the cross sectional area of the inclusion in μm^2, R is the stress ratio, and $\alpha = 0.226 \times H_v \times 10^{-4}$.

As a first approximation, we can reduce the "ordinary fatigue" endurance limit by a factor of 1/3 to estimate the effect of impact fatigue on endurance limit reduction. This will also allow for estimation of the effect of impact loads on allowable discontinuity size. Table 2 shows the results.

Table 2. Endurance Limit and Defect Size

Diameter inches	Diameter mm	Ordinary Fatigue Strength, MPa	Impact Fatigue Strength, MPa
1/8	3.18	159	106
0.088	2.24	169	113
1/16	1.59	179	119
0.039	1.0	194	129
1/32	0.79	201	134
1/64	0.40	226	150

This simple treatment does not take into account the difference in material response between static loading and dynamic, high strain rate loading, but again will serve as a first approximation. We also note that the Murikami equation was designed for tensile loading, not shear loading as would be found below the tread surface in rolling contact fatigue.

CONCLUDING REMARKS

! It appears that impact loading is the major factor in the initiation of shattered rim defects in wheels.

! The high strain rate effect of impact loads probably reduces the endurance limit. It is not known if a simple reduction factor can be applied to the Murikami criteria to account for impact.

! As the inclusion or void increases sufficiently to a large size, the necessity of a impact load for crack initiation diminishes.

! Once formed, the normal rolling contact stresses are sufficient to produce crack propagation.

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