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## Axle Fatigue: 315,000-pound Capacity Cars at FAST

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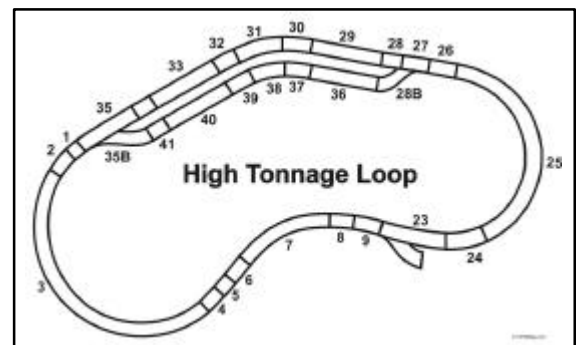
### Summary

Transportation Technology Center, Inc. (TTCI) has used strain/stress measurements and finite element analysis of axles to estimate the fatigue life for Class G, 7×12 axles operating at 78,750-pound axle loads (315-pound gross rail load) on a test loop at the Facility for Accelerated Service Testing (FAST). Life estimations were completed for axles with no surface defects as well as for axles with the following surface features:

- A “V” notch on the surface, 0.0625 inch deep by 0.0625 inch wide.
- A “V” notch on the surface, 0.125 inch deep by 0.125 inch wide.
- A 0.125-inch deep “blended” area resulting from grinding to remove a 0.125-inch deep notch.

This analysis demonstrated that with no surface defects, the life until crack initiation should be essentially infinite. With notch defects present, however, the predicted life until crack initiation is reduced significantly to approximately 2,600 to 12,000 miles (960 to 4,440 train laps at FAST) depending on the size of the notch. A repair that grinds away a 0.125-inch deep notch and leaves a smooth transition would increase the estimated fatigue life again to a value that could be considered infinite (2.64 to 7.54 million miles).

The axle stress environment created by the FAST loop was shown to be somewhat more severe or accelerated when compared with that of normal revenue service. The primary reason for this is the presence of a much larger percentage of curved sections per mile traveled than that in most service environments. Over 60 percent of each FAST lap is spent on a 5- or 6-degree curve (right). Since the lateral forces imposed on the outside wheel of the lead axle set in a truck group are significantly higher while traveling through curves than those present on tangent track, the stress levels in that lead axle are also significantly higher in the curved sections. Change in path resulting from traveling through turnout sections that transition from the main loop to the bypass loop, and bypass back to main (Sections 28B & 35B), also results in significant increases in dynamic stress levels above those seen on tangent track. However, dynamic stress levels due to other special trackwork such as flange bearing frogs, crossing diamonds, bridge decks, and a concrete slab track section are of secondary importance in the creation of axle fatigue damage.



## INTRODUCTION

Since 1998, there have been three axle failures within the consist operating on the High Tonnage Loop (HTL) at FAST, located at the Federal Railroad Administration's Transportation Technology Center (TTC), Pueblo, Colorado. All three axle failures resulted in the derailment of one or more cars. All failures were also characterized by fatigue cracks that progressed through 40 to 60 percent of the axle cross-section prior to final fracture. In all three cases, it appeared likely that crack initiation was caused by a surface discontinuity. All axles were in average used condition. The axles that failed in 1998 and 2001 were manufactured in 1969 and 1970, respectively. The axle that failed in 2002 was manufactured in 1989.

The FAST course is a 2.7-mile closed loop used primarily for research of the effects of heavy axle loads on rail, tie, track base structure, and bridge durability. Each time the train completes a lap, it can travel over the main section of the rail or the bypass section. Within each lap there are four 5-degree curved sections (Sections 3, 7, 31, or 38) and one 6-degree curve. Normal travel speed on this loop is 40 mph. The balance speed for the curves is about 33 mph.

The failures have all occurred on Class G, 7x12 axles loaded to 78,750 pounds per axle. After three failures, the obvious concern was that the stress environment created on axles of this size during operations on the FAST loop was resulting in excessive fatigue damage and short service life. Initial manual calculations of loads and stresses in these axles indicated that even in the curved sections the maximum axle stress would not be high enough to create significant fatigue damage. It was realized, however, that actual dynamic stress levels could likely be significantly higher and tests measuring those levels would have to be conducted to determine their true magnitude. If dynamic stresses were significantly higher than the values derived from hand calculations, fatigue damage could be occurring.

## PROCEDURE

In order to confirm the stress levels estimated using manual calculations and measure the peak dynamic axle stresses due to the special features of the FAST course, strain gages were mounted on the two Class G axles of one truck. Gages were mounted near each wheel seat area and at the centerline of each axle (Figure 1). The four gages at each location were connected in a full bridge circuit to measure bending stress only. These instrumented axles, with 38-inch wheels and carrying a load of 78,750 pounds each, were then tested on the FAST course on two different occasions. The stress values recorded during each test period were similar in magnitude and character. This *Technology Digest* addresses the results of the second test. During the time period of the second test, axle strain data was recorded for at least two laps under each of the following operating conditions.

- Counterclockwise on the main loop
- Clockwise on the main loop

- Counterclockwise on the bypass loop
- Clockwise on the bypass loop

Each sequence was run initially at 40 mph and then repeated at 50 mph. The 40-mile per hour sequences were also repeated on a second day to determine if compaction of the approaches to a newly constructed concrete slab track section significantly influenced the peak dynamic stresses recorded.

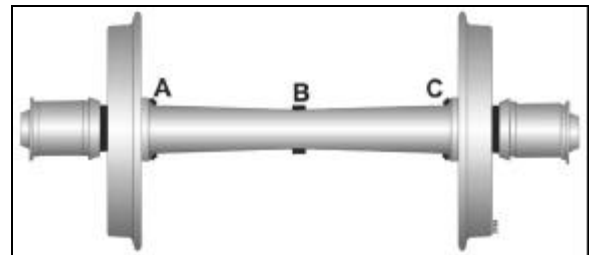


Figure 1. Strain Gage Locations on Axles

The recorded strain data was converted to stress-versus-time data. With the use of Rainflow cycle counting techniques, the time history stress data was then converted into stress range-versus-mean stress histogram files. Using Miner's Linear Cumulative Damage Technique these histogram files were then used to complete the fatigue life estimations for axles with no surface flaws or imperfections. Data from past fatigue tests conducted on full size axles was used to construct the component stress-life curve (S-N curve) used for the life estimations.<sup>1</sup> Histogram creation and fatigue life estimation was completed using nCode Fatimas™, a PC-based fatigue analysis software.

Since it was important to estimate as accurately as possible the stress concentration effects of surface damage, finite element models incorporating the geometry for surface discontinuities were created. Three models, created using ANSYS™ software, included the following surface features:

- A semi-circular "V" notch on the surface: 0.125 inch wide by 0.125 inch deep by 0.43 inch long. The bottom of the notch has no radius (see Figure 2 for typical configuration).
- A semi-circular "V" notch on the surface: 0.0625 inch wide by 0.0625 inch deep by 0.22 inch long. The bottom of the notch has no radius.
- A 0.125-inch deep depression on the surface of the axle simulating the removal of a 0.125-inch deep defect by grinding and blending. The depression was 1.9 inches long by 1.5 inches wide and had a 2.5-inch radius about an axis that is perpendicular to the rotational axis of the axle (see Figure 3).

The stress versus time data collected during the testing on the FAST course was modified by the concentration factors calculated using the finite element analysis. Following the steps used previously with the stress data for an axle with no surface defects, fatigue life was again estimated for axles containing the defects investigated with the finite element analysis.

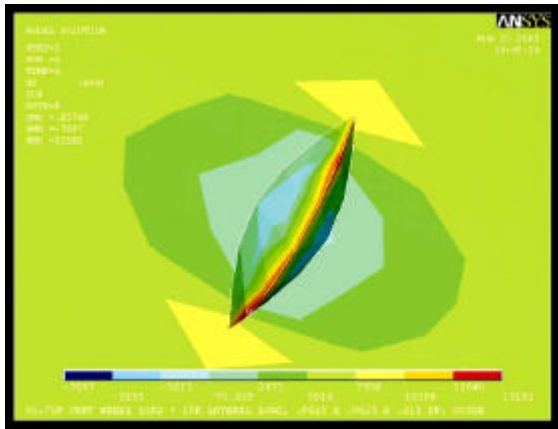


Figure 2. Typical Notch Geometry

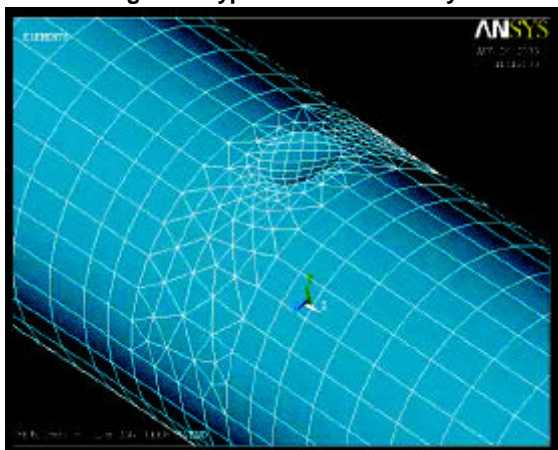


Figure 3. Blended Repair

**RESULTS**

**FAST Axle Stress Levels**

Study of the axle stress vs. time data collected revealed key characteristics regarding the environment at FAST:

- The highest stress levels occurred on the lead axle in a truck pair at locations A or C (Figure 1). The location of maximum stress was always on the high rail end of the axle.
- The highest peak stress levels occurred during transient change of course or turning maneuvers and were as follows:
  - Entering 5- or 6-degree curve: 15,000-16,000 psi
  - Turnout sections that transition from main to bypass loops: 16,400-16,600 psi
- Typical steady state stress levels at Gage Locations A and C were as follows:
  - Tangent track: 8,000-10,000 psi
  - Steady state curving: 12,000-14,000 psi
 (These stress values agreed well with theoretical values derived from manual calculations.)
- Axle stress due to special trackwork such as flange bearing frogs, crossing diamonds, and bridge approaches was less than that measured due to curving or turnout transitions.

- Measured stress did not indicate any significant effects due to the differences in stiffness between the slab track section and its approaches. After one day of activity, the settlement of these approaches did not result in any significant dynamic load effects.
- The increase in travel speed from 40 to 50 mph resulted in an increase of about 7 to 10 percent in stress due to curving forces. There was no significant, speed-related increase in axle stress due to other special features of the FAST course (flange bearing frogs, slab track, bridges, crossing diamonds or turnout transitions). Figures 4 and 5 illustrate a comparison of the stress range histograms for two counterclockwise bypass laps at 40 mph versus two similar laps at 50 mph.
- Using the stress data collected in this test and comparing the amount of curving per mile traveled at FAST with similar information for revenue service routes, it is estimated that the axle fatigue damage on the HTL was at least three times higher per vehicle mile compared to a typical eastern route and at least 3.4 times higher compared to a typical western route.

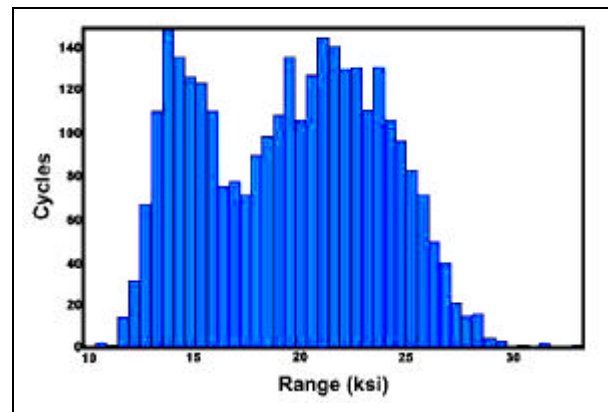


Figure 4. Stress Range Histogram, 40 mph

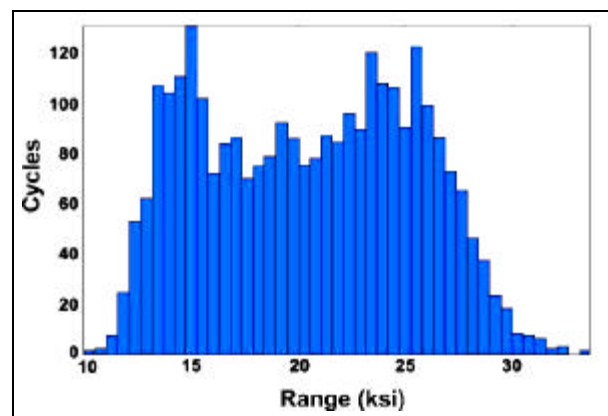


Figure 5. Stress Range Histogram, 50 mph

- Direction of travel (clockwise versus counterclockwise) had little significant effect on the levels of stress and fatigue damage.

- Maximum measured stress at the center of the axle length (Location B) was about 10 percent less than that measured at Locations A or C.

**Effects of Surface Defects on Axle Stress**

The stress concentration factors due to surface defects calculated by finite element analysis are shown in Table 1. The maximum stress was at the base of the notch. These factors are similar in magnitude to those estimated using approximation techniques listed in mechanical engineering literature.<sup>2</sup>

**Table 1. Stress Concentration Factors Due to Surface Defects**

Type of Surface Feature	Stress Concentration Factor
“V” notch – 0.125” deep × 0.125” wide × 0.43” long	2.66
“V” notch – 0.0625” deep × 0.0625” wide × 0.22” long	2.02
“Blend” – 0.125” deep × 1.5” wide × 1.9” long	1.25

**Predicted Fatigue Life in FAST Environment**

If there are no defects on the surfaces of the Class G axles, calculations estimate the fatigue life under the FAST load environment to be essentially infinite. The presence of surface defects or damage, however, reduces the estimated fatigue life significantly. Most of the fatigue damage is a result of the considerable amount of time spent in curving maneuvers. Turnout transitions from main loop to bypass loop and back again also contribute significantly to the total fatigue damage of each lap. The primary contributors to damage in these sections are transient, lateral forces created at the wheel flange-rail interface. Special trackwork (e.g., frogs, crossing diamonds, bridge approaches, and the slab track) is a relatively insignificant contributor to fatigue damage. Table 2 summarizes the estimated fatigue life until crack initiation at Locations A or C in 3 percent of an axle population operating at 78,750-pound axle loads in the FAST environment traveling 40 mph. It is important to remember that these life estimations are for crack *initiation*. Even after crack initiation, the axle could travel for a significant amount of time before the crack grew to a length that would result in total failure.

As shown in the table, the “repair” of a damaged axle surface by a blend and grind operation can return the estimated fatigue life of the structure to the essentially infinite range. An increase in travel speed to 50 mph would result in a decrease in fatigue life of about 17 percent if a surface notch was present and about 80 percent if a surface repair were present. The reason for the significant decrease in predicted life for the surface repair is that many cycles that did not cause fatigue damage at 40 mph have increased enough in stress level to cause damage at 50 mph.

**Table 2. Estimated Fatigue Life to Crack Initiation at FAST**

Surface Defect	Minimum Estimated Life (miles)
None	Infinite
“V” notch – 0.125” deep × 0.125” wide × 0.43” long	2,120
“V” notch – 0.0625” deep × 0.0625” wide × 0.22” long	9,800
“Blend” – 0.125” deep × 1.5” wide × 1.9” long	2.64 million

**CONCLUSIONS AND RECOMMENDATIONS**

Fatigue analysis using measured stress/strain data indicates that Class G axles without surface defects can be used in the TTC FAST load environment without the concern of short life. It is critical, however, that care be taken to eliminate surface damage on these axles. It is also clear that a program of frequent, thorough inspections is very important. Currently, inspections include visual methods to detect surface damage as well as nondestructive testing methods (ultrasound, liquid dye penetrant, or magnetic particle) to locate cracks that cannot be detected visually.

Regularly scheduled, comprehensive inspections of axles used in the FAST consist are of critical importance in the prevention of axle fatigue failures. Currently, 100 percent of the axles in the FAST consist are inspected every 6 months. This work requires the effort of two people for a 2-week period. In order to promote a more efficient inspection program, the following additional work should be undertaken:

- Research on methods of nondestructive testing that can detect cracks on axles without removing them from the car. Ideally, such procedures could be effectively used even while the car is in motion. Such an effort will be undertaken by TTCI in 2004.
- Conduct crack growth analyses to estimate time or miles from crack initiation to axle failure. This additional information could help determine the most effective frequency for axle inspections.

As part of a comprehensive program to monitor, maintain, and control axle integrity, it would also be beneficial to develop more stringent yet practical specifications and practices for the handling of axles and wheelsets to limit or eliminate surface damage while these parts are being transported. Manufacturers have started programs to increase the strength of axle steels through new alloying techniques. It is not certain, however, that the fatigue strength of axles with improved steels will really be improved significantly if surface defects or damage exist. More research in this area is needed.

**References**

1. R. Byrne, 1967, “Railroad Axle Design Factors,” American Society of Mechanical Engineers (ASME), No. 76-RR-3.
2. “Failure of Materials in Mechanical Design,” John Wiley & Sons Inc., New Jersey, p. 406.

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