

The research described was performed by Transportation Technology Center, Inc., a wholly owned subsidiary of the Association of American Railroads.

Key Findings:

- Preliminary results show samples from modern (2015) high strength (HS) rails tend to withstand more fatigue cycles at similar stress levels than samples from an HS rail manufactured in 1992.
- Probability of one premium rail reaching infinite fatigue life is 75 percent at 45 ksi or lower. The probability of the same rail type to reach infinite fatigue life decreases to 31 percent as the stress increases to 54 ksi.

Rotating Beam Fatigue Testing of Rail Steels: Preliminary Results

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[Transportation Technology Center, Inc. \(TTCI\)](#) is conducting rotating beam fatigue testing to determine the stress (S)-number of cycles (N) behavior of rail steels in the form of S-N curves and threshold fatigue stress levels of selected rail steels. Three rail types were selected for comparison to modern rails: two new high strength (HS) rails manufactured in 2015, and an HS rail manufactured in 1992. Numerous samples cut from the three types of rails were subjected to various stress levels in the rotating beam fatigue tester; an apparatus that rotates each sample while applying a consistent bending stress. Once the sample fractures, the number of cycles is recorded for that stress applied. When a sample does not break after passing 100 million cycles, it is said to have reached endurance limit for that stress applied or it is presumed that the material can endure an infinite number of cycles without failure. The highest stress level in which a sample has a high confidence of reaching the cycle limit is considered to be the threshold stress level. Results from these tests will be used to supplement finite element analysis (FEA) models of rail.

FINITE ELEMENT ANALYSIS STUDY

Figure 1 shows alternate compressive and tensile bending stresses on a 141RE rail from the leading and trailing axles of two railcars. The range of stresses from red to blue in the two rail images shown at the bottom of Figure 1 give a general idea of the distribution of tensile (red) to compressive stresses (blue) under the leading and trailing axles.

The plot in the middle of Figure 1 shows under the assumption of zero gage wear in a 141RE (141 lbs./yd.) rail, the highest stress in the head of the rail under the axles of the leading and trailing trucks can range from 40 ksi at zero vertical wear to 120 ksi at 1.1 inches of vertical wear. This (141RE rail) is one of the different scenarios that was examined in this FEA study.

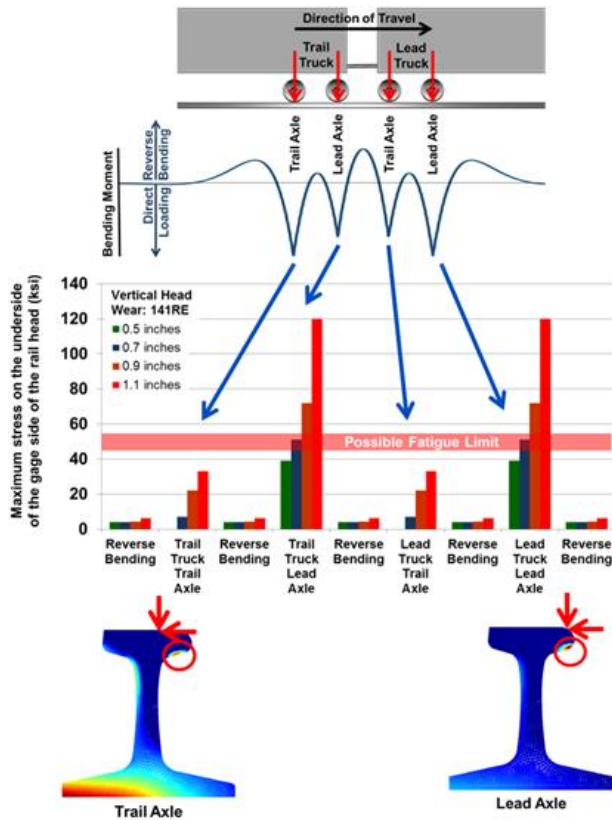


Figure 1. Typical longitudinal tensile stress amplitudes (x-y plane) on the underside of the head of a 141RE rail under direct and indirect bending cycles from leading and trailing axle loads

LITERATURE REVIEW

In the past, work was performed to determine infinite fatigue life of rail steels. Rotating beam fatigue tests generate data that can be plotted on a semi-logarithmic plot where the x-axis is the number of cycles to failure (N) on a logarithmic scale (to the power of 10) and the y-axis represents the various nominal stresses (S) at which the tests are run. The curve generated by plotting the data is known as an S-N curve. Figure 2 shows an example of this S-N curve, which has the stress amplitude plotted versus the number of cycles to failure for a rail steel.¹

At lower levels of stress, metals can endure a high number of cycles, but as stress levels increase, the metal starts to develop fatigue damage. For steels, under constant-amplitude loading, the S-N curve becomes horizontal at a certain stress range known as the fatigue limit or endurance limit. It is presumed that the material can endure an infinite number of cycles without failure below this endurance or fatigue limit. S-N curves generated

in earlier works^{1,2,3} have shown this “possible fatigue limit” to fall anywhere between 40 ksi and 60 ksi and can be considered in Figure 1 as represented by the pink horizontal band. It was therefore important to conduct rotating beam fatigue tests of modern rail steels to find the possible fatigue limiting stress range to apply in the FEA models.

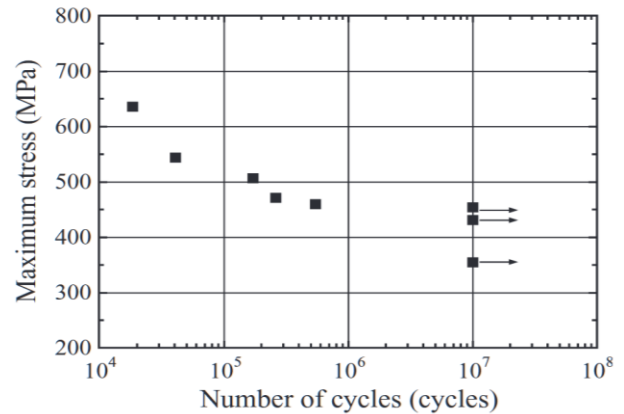


Figure 2. S-N curve of a rail steel obtained by a uni-axial fatigue test¹

Using earlier studies on rail steels, a stress range from 30 to 110 ksi was selected for testing. At each stress level a high level of variation is expected, which can be addressed by testing multiple samples at each stress level. ASTM standard⁴ E379 states that six samples be used for testing of this kind, with at least two samples per each stress range (using at least four stress ranges) based on a minimum level of replication. For this program, TTCI tested rail samples at more than four stress levels and more than two samples at each stress level.

ROTATING BEAM FATIGUE TESTING

Figure 3 shows the rotating beam fatigue tester. The sample is placed between the spindle housing and the loading holder. The motor spins the sample at the desired revolutions per minute (rpm) and a load is applied to the loading holder creating the stress on the sample at constant amplitude. Maximum operating speed of the machine is 5,000 rpm. S-N curves of rail steels have been obtained at testing speed range of 2,500 to 6,000 rpm (on other machines).² The value of 3,000 rpm was chosen as the speed for all tests TTCI conducted.

The equipment has a loading ratio of 1:5, which means an application of 3 kg (6.6 lbs.) shown in red circle in Figure 4 amounts to a 15 kg (33 lbs.) load applied to the sample.

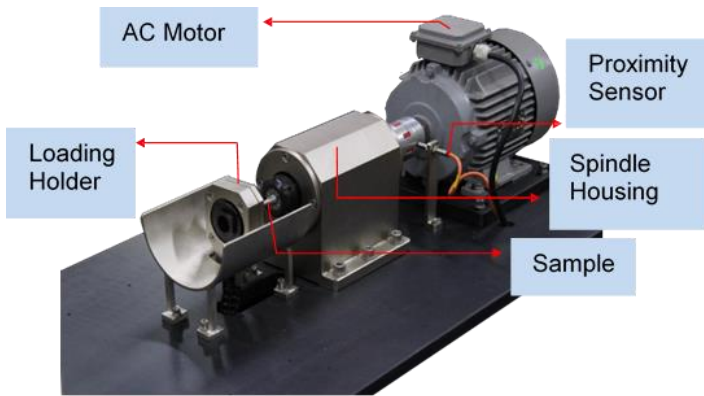


Figure 3. Rotating beam fatigue tester



Figure 4. Loading location (red oval) for rotating beam fatigue tester

The bending stress applied to each sample is calculated based on the bending moment applied and the sample dimensions.

A two-part testing plan to determine maximum rail stress endurance limit was developed using legacy and contemporary testing methods. The standard testing method, while good for locating the appropriate stress levels at which a sample would break, lacked the robustness of a fully randomized testing regimen. Part one is a series of samples tested in a random order to locate the appropriate stress levels at which samples would break; too low of a stress and samples will reach the cycle limit, and too high of a stress and the samples will break quickly. Using the data from part one, part two was developed as a fully randomized test but adjusted to be at the appropriate stress levels.

S-N CURVE DEVELOPMENT AND FATIGUE LIMIT DETERMINATION

Three rail steels were tested so far in this test program: two new HS or premium rail steels (denoted as HS1, HS2) manufactured in 2015 were compared to one HS rail steel (with vertical wear) manufactured in 1992. To eliminate any interference of stress conditions due to top of rail wear, samples were machined at 0.8 inch below the top of rail surface for all test rails. The 1992 rail had unknown tonnage accumulation in revenue service, which could have altered the inherent stress and fatigue conditions. The rail was investigated ultrasonically to determine there were no inherent fatigue defects inside the head of the rail. Also from the FEA results shown in Figure 1, high tensile stresses can be expected at the bottom of gage corners. Samples were machined from the center of the head and away from gage or field surfaces. Rail samples have residual stresses that are generated during rail manufacturing, and a stress relieving cycle was done for all samples at 450°F for four hours to redistribute some of the concentrated residual stresses.

Figure 5 shows the S-N curve results for the three rail types. The 1992 HS rail sample failed at the lowest number of cycles at the 100 ksi stress level when compared to the other rail types. The new rail samples showed some variations, especially at 55 ksi for HS1. Some of the HS2 rail samples ran up to 100 million cycles at almost every stress level.

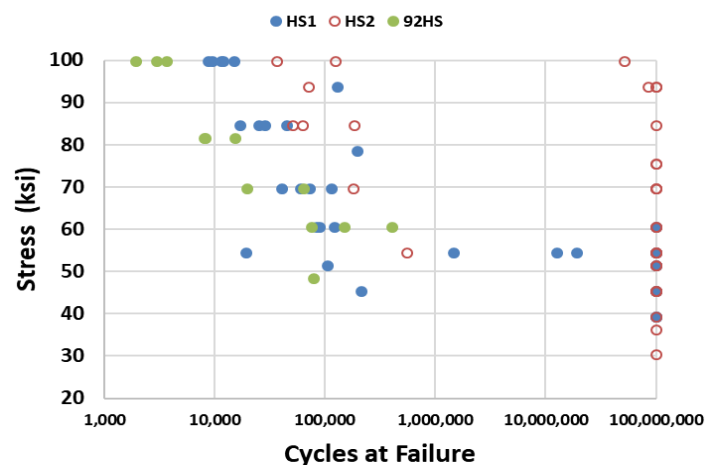


Figure 5. S-N curve results for three rail types

At each stress level below 100 ksi, at least one sample reached 100 million cycles, but other samples had much shorter fatigue lives at the same stress level. Note the time

it took to achieve the results shown in the S-N curve. While a sample that broke after 10,000 cycles took 3.33 minutes to complete, a sample that ran to 100 million cycles took 33,333 minutes (~23 days) of non-stop running to complete. Further analysis and research are being carried out to understand the behavior of the HS2 rail.

Data was collected from the first batch of tests, and a statistical calculation was done to determine the confidence of the selected fatigue limit value. Figure 6 shows the probability curve for each rail type to reach the cycle limit at each stress level.

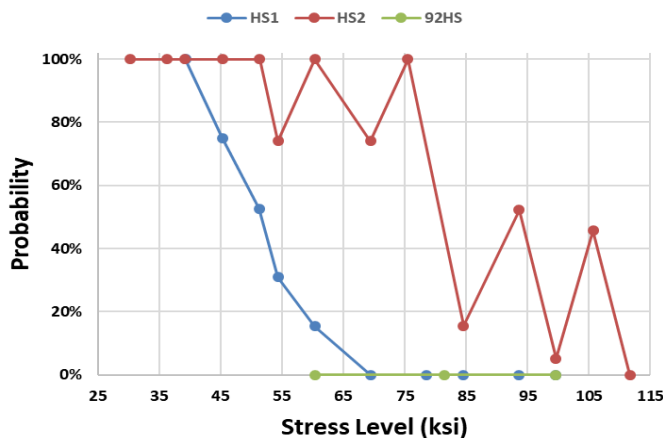


Figure 6. Probability distribution for cycle limit versus stress level

Data from each stress level was fit to a Weibull distribution to determine the probability, a sample would reach the “cycle limit” or run for infinity at that stress level. Samples that reached the cycle limit of 10^8 cycles (100 million) were right-censored when fitting to the Weibull distribution, meaning the value for the true number of cycles at failure is somewhere above 100 million. Censored values do not affect the shape or scale of the distributions but can shift the distribution. The HS2 samples that failed were roughly in the same position on the S-N curve as the other rail types. But because there were samples that reached the cycle limit at nearly every stress level, the probability is higher at each stress level compared to the other samples. Increasing the number of samples at each stress level would smooth out the curve for HS2 rail.

CONCLUSIONS AND FUTURE WORK

It is still quite early to draw conclusions about the endurance limit of 2015 HS2 and the 1992 HS rails, considering the amount of time it takes for a sample to

reach 100 million cycles and the number of samples required to get a reliable Weibull distribution. Preliminary results show the probability of HS 1 rail samples reaching infinite fatigue life is 75 percent at 45 ksi or lower. The probability of HS1 samples to reach infinite fatigue life decreases to 31 percent as the stress increases to 54 ksi. Future tests on the HS2 rail will give a better idea of the range of stresses where the probability of samples with infinite fatigue life varies between 0 and 100 percent. Preliminary results show the 1992 HS rail seems to be enduring a lower number of fatigue cycles at similar stress levels than the HS1 and HS2 rail samples.

Definitive conclusions of modern rails and their comparison of endurance limits to those of older rails will require more testing. Microcleanliness and microhardness will be evaluated and results will be analyzed to find any correlation with threshold fatigue stress ranges obtained from this testing program for all rail types. Results of endurance limit stress ranges will be compared with the highest tensile stresses obtained in the existing FEA models at various amounts of rail wear and wheel loads and will be applied in updating the FEA models.

References

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