TECHNOLOGY DIGEST

TD-08-026
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TIMELY TECHNOLOGY TRANSFER

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An Analytical Procedure for Predicting Crack Initiation in Crossing Diamond Frog Materials

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Summary

Transportation Technology Center, Inc. (TTCI), a wholly owned subsidiary of the Association of American Railroads (AAR), conducted a parametric study to predict the service life of crossing diamond frog materials. The objective of this study was to determine the amount of tonnage for certain wheel loads and train speeds that will initiate cracks in crossing diamond frog materials. Crossing diamond related train delay costs are estimated at more than $100 million annually. These costs are conservative in that they include only the direct costs and not the additional operating costs.

While lower train speeds increase train delays, higher train speeds increase maintenance costs. An optimum train speed is desirable to minimize life cycle costs. The optimal train speed may be different for each crossing diamond frog material. Full-scale testing of material is a reliable method to study the effects of train speeds, but is time consuming and costly. Computer simulations using material test data can allow multiple testing scenarios quickly and effectively, reducing the need for real time full-scale testing.

This analytical parametric study by TTCI for predicting crack initiation in crossing diamond frog materials has resulted in the following conclusions:

- The prediction of the amount of tonnage to initiate a crack in crossing diamond frog materials can be used to determine the life cycle cost (LCC) at different train speeds. This allows the development of optimal train speed policy. Optimal train speed minimizes train delays and reduces the LCC.
- The effect of train speed on the crack initiation period is significant. Crack initiation life at 60 miles per hour (mph) is less than 60 percent of the predicted life for the same frog material at 40 mph. Operating and maintenance crews can determine slow orders based on this information.
- Significant damage occurs to diamond frog material because of increased ratcheting during a few initial load cycles. Initial higher resistance to ratcheting is expected to significantly increase the crack initiation period.
- The predicted crack initiation period for a 90-degree crossing diamond frog, the demonstration case, is in line with crossing diamond service life.
- The analytical procedure used in this study can be used for any crossing diamond frog material to predict crack initiation.

This study was funded by the AAR Strategic Research Initiatives Program.

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INTRODUCTION

Impacts at crossing diamond frogs are generated as the wheels land on the downstream side of the flangeway corners. The maximum vertical load in these areas at 40 mph can be as high as 3.6 times the static wheel load with nominal conditions, and 10 times the static wheel load with worn wheel and rail corner conditions.[1] Impacts are comparatively lower at lower angle crossings and crossings with speed restricted trains.

Higher train speeds reduce the service life of crossing diamond frogs due to increased wear. Crossing diamond frogs with slower train speeds generally have longer service lives, but have a higher LCC due to train delays.

The objective of this parametric study conducted by TTCI is to determine the amount of tonnage for certain wheel loads and train speeds that will initiate cracks. The tonnage amounts can be used to determine the LCC of crossing diamond frogs. Service life is the sum of life before and after crack initiation. This study only addresses the life before crack initiation.

Ratcheting and fatigue behavior of metal was studied under different loads. The amount of tonnage for the crack initiation period was predicted at train speeds from 20 mph to 60 mph. This information was used in another study to analyze the economic benefits of higher and lower train speeds. The study shows that at lower train speeds, train delay dominates the LCC. Above track speed, the train delay costs are zero. At higher train speeds, the maintenance costs increase, but trade-off between savings from train delays and cost of maintenance is significant.[2]

This study shows that significant ratcheting damage occurs to crossing diamond material during initial cycles. Later, the damage becomes nearly linear. This shows that the initial material resistance to ratcheting damage will significantly increase the crack initiation period.

MATERIAL MODEL

Figure 1 shows the analytical procedure to predict service life. As an example, bainitic steel is used, but this technique may be used for any steel or alloy.

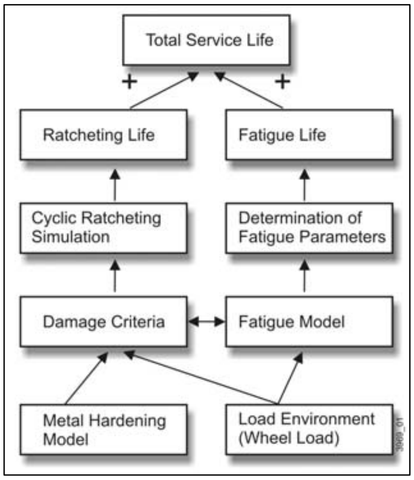

Figure 1. Procedure for Analytical Crack Initiation Prediction of Crossing Diamond Frogs

The magnitude of accumulated strain with cyclic load is approximated using Chaboche's material hardening model.[3] The model is based on experimental stress-strain data and can predict the strain accumulation due to ratcheting for any number of loading cycles. The Chaboche model was used to simulate the strain accumulation because it is compatible with Ansys©, a finite element program. Reference 3 addresses a detailed procedure to build a material hardening model.

DAMAGE MODEL

Higher train speeds increase the loads that accelerate metal flow, called ratcheting. Over thousands to millions of cycles, ratcheting strain can accumulate to reach the ductility limit of the metal, which can initiate cracking. Additionally, rolling contact fatigue (RCF) damage can accumulate within the material. In this study, a damage model is implemented that combines both RCF and ratcheting damage to predict the crack initiation period.

RCF differs from classical fatigue theory. RCF addresses the critical fatigue plane, while classical fatigue theory focuses primarily on uniaxial loading. The RCF model uses a fatigue parameter (FP), which is a function of normal strain range ($\Delta\varepsilon$), maximum normal stress (Δбmax), shear strain range ($\Delta\gamma$), and shear stress range ($\Delta\tau$). Once the FP is known for certain loading, the number of cycles to failure can be calculated directly from the relationship, as Figure 2 shows.[4] Fatigue damage (D_f) per cycle is the reciprocal of the maximum number of fatigue cycles.

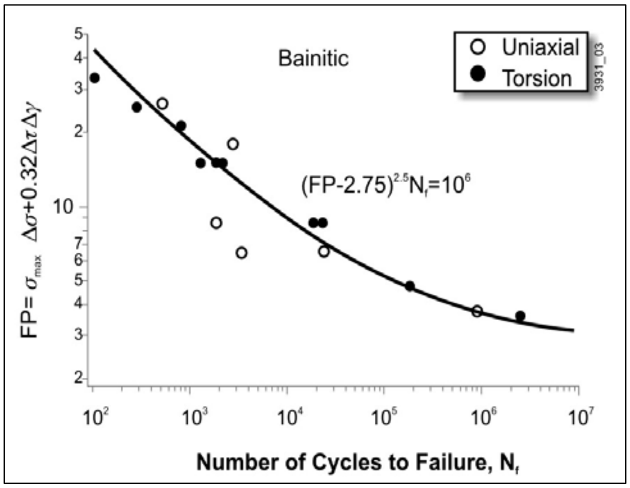

Figure 2. Test Data and Parameters for RCF

Crack initiation due to ratcheting occurs when the accumulated shear strain reaches the critical strain of the crossing diamond frog material. The critical strain is the fracture strain obtained from torsion tests and is experimentally found to be 0.57 or 57 percent.[5] Ratcheting damage (D_r) per cycle is the reciprocal of the maximum number of ratcheting cycles to reach critical strain.

The total damage due to fatigue and ratcheting is combined as $D_f + D_r$. When the total damage equals 1, diamond crossing frog material crack initiation is expected. The corresponding number of cycles is the crack initiation period of metal.

SIMULATION OF RATCHETING

Figure 3 shows the dynamic loads of high angle crossing diamond frogs from 263,000-pound cars at different train speeds, simulated in another study.[1] Critical loading on the rail end occurs when the wheel leaves one crossing frog corner and just touches the other corner. At that very moment, full static and dynamic wheel loads strike the other corner.

A finite element model is created using just the end portion of the frog and the wheel. First, the load is applied on the end of the crossing frog through the wheel. Then, the load on the contact patch is saved and used for successive loading cycles, as Figure 4 shows. This technique significantly reduces the program run time. A small routine is used to simulate the passing of the wheel over the gap. The routine applies a static load and then reduces to zero, simulating one cycle. The resulting plastic strain from each cycle is calculated for 1,000 loading cycles, as Figure 5 shows.

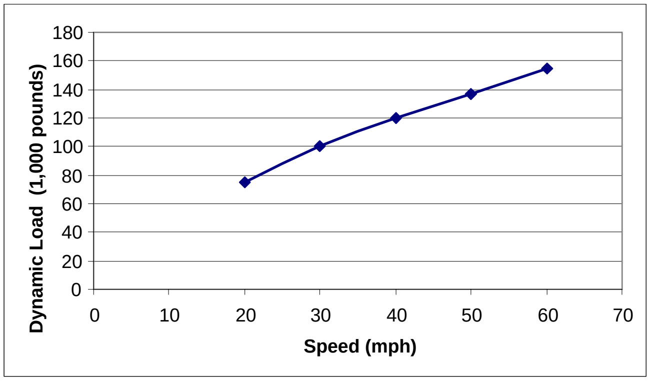

Figure 3. Dynamic Load on a 90-degree Crossing Diamond Frog

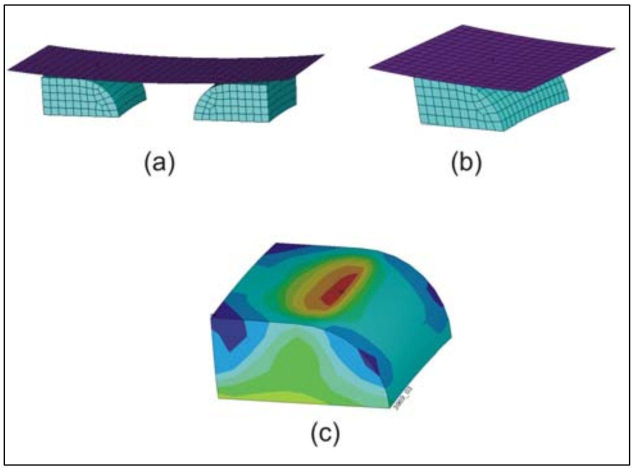

Figure 4. Finite Element Model. (a) Full Model with Rigid Wheel, (b) Half Symmetrical, and (c) Model with Contact Patch

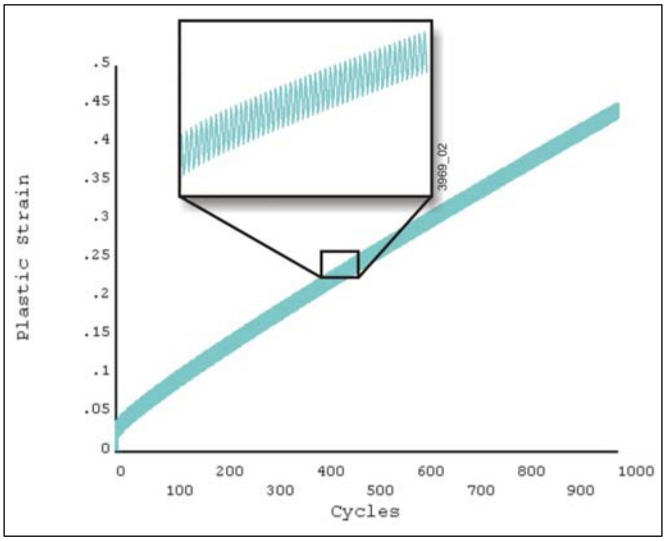

Figure 5. Typical Ratcheting Curve –– Cycles versus Incremental Plastic Strain

DAMAGE ANALYSIS

Due to computational costs, it is impractical to run the contact simulations for any more than 1,000 or 10,000 cycles. When generating fatigue crack initiation maps, it is often desired to determine the loading conditions that will lead to crack initiation at a greater number of cycles. If the logarithm of damage is plotted against the logarithm of cycles, the line is fairly linear. Therefore, 1,000 cycles is typically sufficient to determine the trend of the damage parameter, and the total damage can be extrapolated to a higher number of cycles.

The fatigue damage accumulates in a linear fashion, due to the assumption that is made in the derivation of the fatigue parameter.

The ratcheting damage does not follow a perfectly linear line. Up to 1,000 cycles, the ratcheting damage is quite significant. At the higher cycles, from 1,000 to 10,000, the ratcheting damage appears to accumulate fairly linearly. Therefore, the general trends for ratcheting and fatigue damage are apparent and can be extrapolated for the total damage for each load. Assuming a 120-car HAL train, the cycles can be converted to million gross tons (MGT). Figure 6 shows typical ratcheting and fatigue curves at 20 mph using MGT versus damage.

Figure 7 shows the crack initiation period of a 90-degree crossing diamond at different train speeds. In general, analytical results agree with experience. It appears that under the assumption and the conditions made in this analysis at 60 mph, the crack initiation period reduces to about 56 percent for the same crossing diamond frog material at 40 mph.

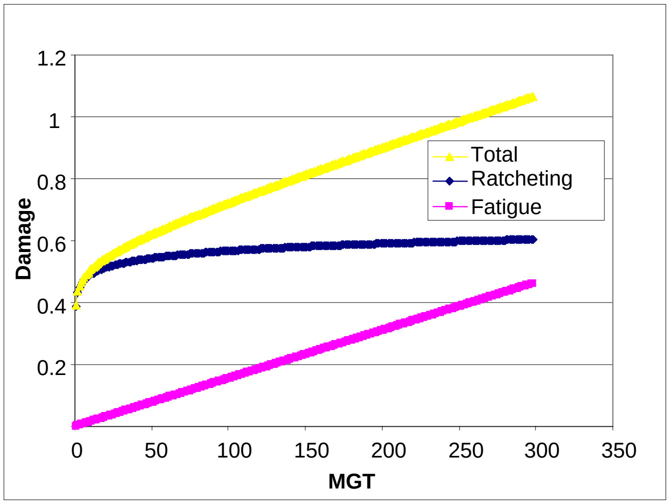

Figure 6. Typical Ratcheting and Fatigue Curves at 20 mph

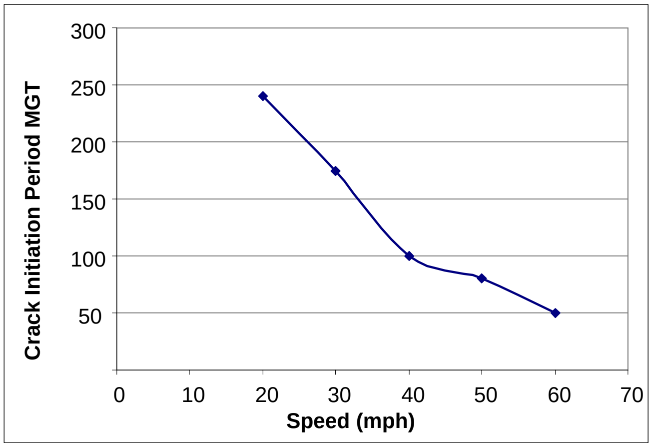

Figure 7. Predicted Crack Initiation Period versus Train Speed

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