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Overview of Rolling Contact Fatigue Prediction Models

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Summary

A literature review reveals that there are currently only two practical analytical models to predict rolling contact fatigue (RCF) initiation in wheels and rails:

- The so-called shakedown theory approach
- The surface energy approach (energy-related damage model commonly termed T-gamma)

Each model appears to have its merits and has been used in the prediction of RCF.

The shakedown model is complex and probably difficult to apply under the complex loading conditions associated with wheel/rail contact. The pragmatic approach associated with that of surface energy (T-gamma) is attractive in that it can be tested as well as "tuned" for prevailing conditions in heavy haul.

It is recommended that means and tools be developed, either in the laboratory or in service, to test the efficacy of each model.

The development of means to test each model and tune the T-gamma model will be reported in subsequent *Technology Digests*.

This review supports the development of an RCF prediction model for wheels and rails under heavy haul conditions and was conducted by Transportation Technology Center, Inc. under the direction of the Association of American Railroads as part of its Strategic Research Initiatives Program.

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INTRODUCTION

Rail and wheel life may be limited by one or a combination of the following: wear, the formation of surface and near-surface cracks, and material flow. All of these mechanisms can be generically classified under the term RCF, being associated with stresses and creep in the contact patch between wheel and rail.

In rail:

- The formation of surface and subsurface cracks may give rise to:
    - Transverse fatigue cracks resulting in rail failure
    - A noncontinuous rolling surface resulting in high vertical impact loads on track components and structure
    - Sufficient damage to the surface of the railhead reducing the effectiveness of ultrasonic testing devices
- Head wear:
    - Alters the rail profile, generally to a less effective shape for optimal curving performance and increasing the rate at which RCF damage occurs
    - Reduces the life of the rail by reducing the rail section
- Material flow:
    - Alters the rail profile, generally to a less effective shape for optimal curving performance, increasing the rate at which RCF damage occurs
    - Can reduce the life of the rail by introducing cracks under the flow lips formed at the gage corner and on the field side of the railhead

On the wheel:

- The formation of surface cracks:
    - Has been associated with the formation of high impact wheels[1]
    - May be associated with the formation of shattered rims and vertical split rims
- Tread and flange wear:
    - Alters the wheel profile, generally to a less effective shape for optimal curving performance, increasing the rate at which RCF damage occurs
    - Reduces the wheel flange and rim sections below acceptable limits
- Material flow on the wheel tread can alter the wheel profile, generally to a less effective shape for optimal curving performance, increasing the rate at which RCF damage occurs.

Rails are ground to remove RCF at an annual cost of $12 million. The annual cost of replacing worn rail in curves is over $500 million (curves are associated with the bulk of RCF encountered in service). The annual cost of gage corner lubrication and top-of-rail friction control is $25 million.

Annual wheel repair and replacement costs are $800 million, with 27 percent attributed to flange wear and approximately 67 percent attributed to tread damage. Of the latter, approximately 50 percent is attributed to RCF and the remainder is associated with unreleased handbrakes. Annual RCF-related wheel damage is estimated to be $440 million.[2]

Annual fuel costs associated with poor curving performance and wheel and rail damage associated with RCF is estimated to be $144 million.

The total annual problem size associated with RCF is estimated to be close to $700 million.

Consequently, the Association of American Railroads tasked Transportation Technology Center, Inc. (TTCI) to identify those forms of RCF prevalent under heavy haul conditions in North America, determine the root causes for this RCF, and propose means to mitigate RCF.

This *Technology Digest* (TD) reports on TTCI's review of the analytical RCF prediction models.

FOCUS OF THIS TD

This TD focuses on the mechanisms of surface crack initiation, material flow, and wear. To mitigate damage to rail and wheels, RCF-initiated surface cracks, material flow, and wear should be reduced as much as possible and controlled by maintenance such as grinding.

Subsurface crack formation resulting in shelling will not be a particular focus of attention because this failure mode has long been accepted as being a function of the combination of the subsurface Hertzian maximum shear stress, subsurface defects, and/or residual stresses. These effects result in crack formation between 0.25- and 0.75-inch deep resulting, in turn, in rail spalling and wheel shelling, as well as shattered rims in wheels. Models for this type of failure exist, but are sensitive to the magnitude of the actual defects and residual stresses in either wheel or rail for accurate prediction of initiating loads or critical defect size.

RCF MODELS

Surface crack initiation in rolling contact generally occurs under high contact stress and traction conditions. The surface material deforms plastically in a dominant traction direction. A combination of strain hardening and residual stress, if sufficiently high, leads to surface crack formation as the fracture strain of the wheel or rail material is exceeded. This mode of failure is termed ratcheting.

If tractions are bidirectional, the material in the contacting bodies will not ratchet, as plastic flow will occur in both directions with zero net accumulated strain.

There are two surface crack initiation models currently accepted and available.

- Shakedown theory approach, i.e., mapping material flow and crack initiation in relation to Hertzian stresses, the shear yield limit of the materials of the contacting bodies, and the tractions across the contact patch

- Surface energy approach (T-gamma), an empirically based model relating frictional energy dissipated across the contact patch

Shakedown Theory Approach Model

K. L. Johnson developed the shakedown theory approach model, which relates material behavior on and beneath the contact patch to the normalized vertical contact pressure, P_0/K and normalized surface tractions (Figure 1).[3]

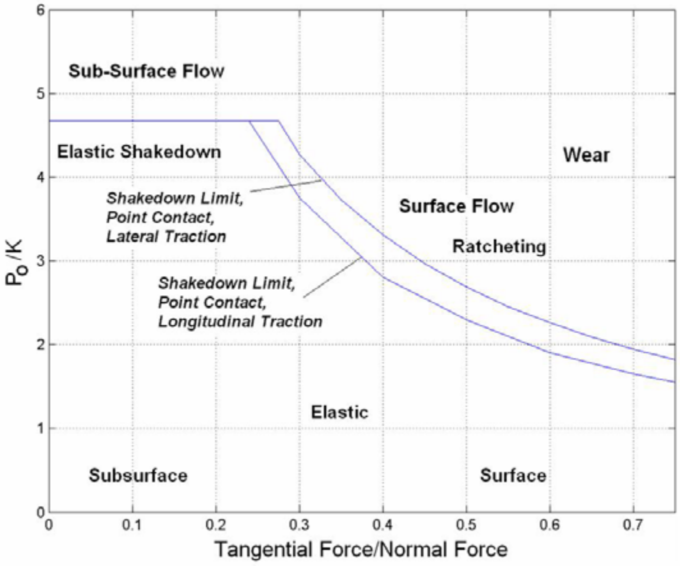

Figure 1. Shakedown Diagram

Shakedown is based on the Hertz theory. In the shakedown map, two boundaries between elastic and plastic behavior are defined based on the assumption of point contact, and whether the tractions are longitudinal or lateral, a map for line contact is also available. The upper bound of the map suggests a limit for P_0/K, above which subsurface fatigue will occur. This bound is sensitive to subsurface defect position, size, and orientation.

To obtain a better prediction of contact stresses, exact or approximate elastic modeling can be employed.[4] Then, a fatigue criterion can be used to quantify the fatigue impact from evaluated stresses and strains. These criteria tend to be cumbersome under the varieties of dynamic loading conditions encountered on railroads.

A combination of multiaxial, low-cycle fatigue and ratcheting criteria has proven to be successful in predicting fatigue initiation in rails.[3]

Shakedown has been successfully used to suggest the root cause for thermal mechanical shelling in wheels.[1]

Although the shakedown map has been successfully used to suggest limits for the onset of surface cracking, it is not amenable to the determination of fatigue life. It does not quantify the cycles to failure or quantify the effect of surface wear on fatigue life.

It has been shown under experimental and practical applications that wear above a certain rate can remove the fatigued material faster than fatigue cracks can be formed. In addition, shakedown cannot quantify the rate of plastic flow in contact.

In an effort to quantify the severity of shakedown, a surface fatigue index has been proposed.[5] This index is expressed as:

$$FI_{surf} = \mu - 2\pi abk / (3F_z)$$

Where, μ is the applied traction, a and b the semi-axes of the contact patch, k the yield limit in shear, and F_z the vertical load.

In his review of RCF, Ekberg comments that means of preventing surface fatigue can be identified from the index.[4] Nevertheless, the fatigue index cannot predict cycles to failure or the effect of wear.

In summary, the shakedown approach model advantages are that it provides a theoretically sound model relating Hertzian stresses and tractions across the contact patch and material properties to failure modes. It has been successfully used to indicate the initiation of crack bands on wheels under heavy haul conditions,[1] which may be because the loading conditions under low rail contact are relatively simple and consistent. This approach was not able, however, to predict the number of cycles to failure.

The disadvantages of the shakedown approach are:

- It can become complex to analyze under the many load conditions imposed on wheel and rail in practice.
- It does not simulate the effect of wear or material flow, which can substantially alter load conditions during the life of wheel and rail.
- It does not readily provide a fatigue life.

Surface Energy Approach Model

The surface energy approach model (commonly termed T-gamma) is empirically based and relates the frictional energy dissipated across the contact patch to the observed wear, deformation, and cracking of the contacting surfaces.

It originates in work done in the laboratory, typically using twin-disk rolling contact machines to study the wear of materials in rolling contact[6,7,8] and the onset of RCF.[9]

This model was used as a basis for the development of a so-called "RCF Damage Parameter" by researchers working under the direction of the UK Rail Safety and Standards Board to predict head check formation on Network Rail.[10] This damage function relates wear number ($T\gamma$) with crack initiation fatigue damage (Figure 2). $T\gamma$ is the product of the net tractions and the creepages across the contact patch for a particular contact condition. The damage index is a nondimensional number that is the proportion of the fatigue life of the material exhausted by that contact condition.

The reciprocal of the damage function gives the cycles to failure at each level of Tγ. The damage function can be summed for each load cycle and level of Tγ, and this sum is made for each portion of material in contact. When the sum reaches unity for a particular portion of contacting material, that material has said to have failed.

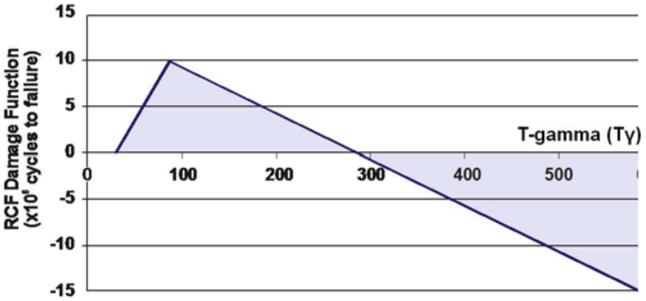

Figure 2. Damage Function

The damage function comprises four regions:

- A threshold of Tγ below which damage does not occur and relates to loadings below the shakedown limit
- A region where damage increases linearly with Tγ to a particular level; it should be noted that cycles to failure decrease inversely with respect to the damage function
- A region where damage decreases linearly with Tγ; in this region wear removes damaged material, but at a rate insufficient to completely counter the effect of fatigue
- A region where material damaged through fatigue is completely removed through wear

Figure 2 shows the function developed for Network Rail conditions.

Interestingly, observable fatigue cracks developed only when tractions acted in a sense to open the cracks, which is thought to permit fluid entrapment to progress crack propagation.[10] It is stated that crack initiation (ratcheting) will take place with shear forces in any direction, but observable RCF will only occur with fluid entrapment. Consequently, tractions were positive and negative according to traction condition, and only positive (crack-opening) tractions were considered. This phenomenon will require more investigation. The action of traction forces in the opposite direction may inhibit plastic shakedown. Could the reason for crack development thus be that tractions and material flows occur in a dominant direction?

In summary, the surface energy approach appears attractive in that it has been used successfully in other railroad applications and can account for the complex load and wear conditions arising between wheel and rail. The damage function will, however, need to be tested and possibly tuned for heavy haul conditions in North America.

CONCLUSIONS

A literature review reveals that there are currently only two analytical models to predict RCF initiation:

- The so-called shakedown theory approach model
- The surface energy approach model (energy-related damage model commonly termed T-gamma)

Each model has its merits. The shakedown approach is complex to apply, particularly under the complex loading conditions of wheel/rail contact. The surface energy approach is more pragmatic and can be tested and tuned for prevailing conditions in heavy haul operations.

RECOMMENDATIONS

It is recommended that means and tools be developed, either in the laboratory or in service, to test the efficacy of each model. Particular attention should be paid to the influence of traction direction and the influence of reversed tractions on material flow and crack initiation.

The development of means to test each model and tune the T-gamma model will be reported in subsequent TDs.

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