Computational Model for Predicting Fracture in Rails Subjected to Long-Term Cyclic Fatigue Loading

David H. Allen, Ph.D., P.E.
Professor
Department of Ocean Engineering,
Texas A&M University, College Station, College Station, USA.
Email: dhallen@tamu.edu

Yong-Rak Kim, Ph.D., P.E.
Professor
Zachry Department of Civil & Env. Engineering,
Texas A&M University, College Station, College Station, USA.
Email: yong-rak.kim@tamu.edu

Hesam Mortazavi, M.S.
Ph.D. Student
Zachry Department of Civil & Env. Engineering,
Texas A&M University, College Station, College Station, USA.
Email: hesamm93@tamu.edu

Santosh R. Kommidi, Ph.D.
Post-doctoral Research Associate
Zachry Department of Civil & Env. Engineering,
Texas A&M University, College Station, College Station, USA.
Email: santosh.kommidi@tamu.edu

A Report on Research Sponsored by

University Transportation Center for Railway Safety (UTCRS)

Texas A&M University

September 30, 2025

Technical Report Documentation Page

<table>
<tr><td>1. Report No.
UTCRS-TAMU-I2CY24</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Computational Model for Predicting Fracture in Rails Subjected to Long-Term Cyclic Fatigue Loading</td><td>5. Report Date
September 30, 2025</td></tr>
<tr><td>6. Performing Organization Code
UTCRS-TAMU</td></tr>
<tr><td colspan="2">7. Author(s)
D.H. Allen, Y-R. Kim, H. Mortazavi, and S. R. Kommidi</td><td>8. Performing Organization Report No.
CRR-2025-01</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
University Transportation Center for Railway Safety (UTCRS)
Center for Railway Research (CRR)
Texas A&M University (TAMU)
College Station, TX 77843</td><td>10. Work Unit No. (TRAIS)</td></tr>
<tr><td>11. Contract or Grant No.
69A3552348340</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
U.S. Department of Transportation (USDOT)
University Transportation Centers Program
1200 New Jersey Ave. SE
Washington, DC, 20590</td><td>13. Type of Report and Period Covered
Project Report
June 1, 2024 – August 31, 2025</td></tr>
<tr><td>14. Sponsoring Agency Code
USDOT UTC Program</td></tr>
<tr><td colspan="3">15. Supplementary Notes
This work is a collaboration with MxV Rail (Rail Industry Research Testing Facility)</td></tr>
</table>

16. Abstract

Subsurface fatigue crack growth within railheads can lead to catastrophic failures in rails and is currently one of the major concerns of the rail industry, as they pose a significant safety concern accompanied by critical rail maintenance costs. It is necessary to better assess and predict crack growth within rails, especially when an internal defect is detected, to establish timelier and more cost-effective railway operation protocols. The method most commonly used for predicting the fatigue life of railheads is based on the Paris-Erdogan law, which has limitations in addressing diverse, realistic situations affected by geometric characteristics (e.g. size, orientation, location) of internal flaws (or cracks). This study proposes a nonlinear cohesive zone (NCZ) model capable of accounting for the geometric characteristics of internal defects and inelastic nonlinear fatigue fracture growth in railheads. This study shows that the model effectively simulates fatigue crack growth in rails. The parametric analysis conducted within this study indicates that key NCZ parameters are effective indicators of rail fatigue life. Application of this model would enable appropriate fracture characterization that can be used for predicting fatigue crack growth rate and fatigue life of railheads that contain pre-existing flaws. Simulations of sub-surface crack growth, leveraged by experimental observations from fatigue testing of railheads, demonstrate the potential for the NCZ model to properly characterize fatigue fracture growth in railheads. This fatigue characterization serves as an effective tool for predicting the remaining life of rail sections, which can facilitate proactive maintenance.

<table>
<tr><td colspan="2">17. Key Words
Cracking, Fatigue cracking, Computer models, Nonlinear programming</td><td colspan="2">18. Distribution Statement
This report is available for download from https://www.utrgv.edu/railwaysafety/research/infrastructure/index.htm</td></tr>
<tr><td>19. Security Classification (of this report)
None</td><td>20. Security Classification (of this page)
None</td><td>21. No. of Pages
15</td><td>22. Price</td></tr>
</table>

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Acknowledgments

The authors want to acknowledge the University Transportation Center for Railway Safety (UTCRS) for the financial support provided to perform this study through the USDOT UTC Program under Grant No. 69A3552348340.

Research Overview

The American railway system is a critical component of the national infrastructure, serving as a backbone for promoting economic growth, interconnectivity of the states, and transport of required commodities and individuals. The United States owns the biggest rail network in the world, containing approximately 260,000 kilometers of total route, with over 80% (220,000 kilometers) of it being freight lines. This freight network carries nearly 40% of the nation's intercity freight, which reflects the enormous dependence on proper working rail operations for commerce (*1*). Due to such strategic importance, the structural integrity and safety of rail infrastructure is critical.

Fatigue cracking in railheads, which receive the most cyclic loading from rolling stock, is one of the most common threats to the physical strength of railroads. Even with improvements in rail maintenance and inspection technologies, the U.S. still experiences around 1,100 train derailments each year, with approximately 7% of those caused by rail fractures (*2*). Although modern technological improvements have decreased the number of derailments, certain areas have yet to be fully addressed. This is especially so in the context of increasing rail traffic, increased axle loads, and expansion in high-speed rail networks.

There has been a critical need to design safer railroads to support the increasing demand for heavy haul tonnage and high-speed rails. One of the major problems that communities currently face is that continuous heavy haul can lead to fatigue failure of railheads. Repeated loads continuously stress railheads where sub-surface flaws exist and propagate. Most railheads contain flaws that are introduced during fabrication as demonstrated in **Figure 1**. The nature of these flaws leads to either stable or unstable growth dependent on the loading and environmental operating conditions. Subsequent loading will cause such cracks to enlarge, slowly at first, but increasing in rate as the crack propagates, eventually reaching a critical size. Critical sized cracks fracture the railhead, which may lead to train derailment. Alternatively, cracks smaller than the critical size may remain in operation as periodic inspections are conducted using nondestructive ultrasonic evaluation methods.

Figure 1. Railheads with internal flaws.

Nondestructive ultrasonic testing is capable of detecting subsurface defects, however cracks outside of the focal distance within the railhead tend to escape detection. Therefore, accurately quantifying the geometry of subsurface flaws and predicting their progression over repeated loading cycles is essential for strategic maintenance planning and effective risk mitigation. Conservative maintenance methods are generally utilized by rail operators due to the lack of effective performance predictions, and result in unnecessary costs that could be avoided with more accurate failure forecasting. The development of robust models for accurately predicting crack growth is a pressing priority but is complicated by the variability in contributing factors. These factors include material microstructure, rail residual stresses, rail geometry, substructure support, and traffic loading frequency.

An approach based on linear elastic fracture mechanics (LEFM) has been used to model the fatigue behavior in railheads, specifically targeting sub-surface fatigue cracking. The critical flaw size is a function of applied and residual stress acting on the structure, as well as the toughness of the materials. The principles of LEFM can be used to describe the functional relationships for unstable (brittle, rapid) fracture that occurs even though the stresses are low or below the general yield strength (i.e., before full plasticity has occurred in the rail). The most widely used approach for predicting crack growth within railheads is based on the Paris-Erdogan law (*3*). Paris-Erdogan equations have often been employed using different parameters acting as the driving force, such as stress intensity factor (SIF) (*4*), cyclic J-integral (*5*), and strain energy density (*6*). The limitations of these models are that they fail to address nonlinear behavior, rate-dependent effects, and crack path evolution under mixed-mode loading. Moreover, they fail to portray geometric complexities like railhead curvature, and subsurface flaw orientation, size, and depth (*7*).

This study proposes a nonlinear cohesive zone (NCZ) model to predict subsurface defect growth in railheads. The NCZ model is a nonlinear mechanistic model that can capture the initiation and propagation of cracks via a traction–separation law. The model is well-suited to address issues involving complex stress distributions and primary fracture zones, and can be combined with residual stress, thermal, and load history conditions to provide a more complete, realistic prediction of crack growth behavior. With the simulation of the fracture phenomenon in front of a crack tip and combination with finite element methods, the NCZ approach not only enhances predictive capability but also facilitates calibration from experimental observations. In particular, this study attempts to explore the validity and effectiveness of the NCZ model in capturing fatigue crack growth in railheads. This was accomplished by investigating core material parameters that control crack growth, which enable effective risk-based rail maintenance strategies.

Modeling Approach

This project investigates fatigue crack growth in railheads using the NCZ modeling framework. The fracture process zone ahead preceding a crack tip is described by the NCZ, where cohesive elements have been pre-inserted. , This approach is well-suited forwith integration ngwith finite element methods, .as Iit models damage evolution through theby introduction of inginternal boundaries governed by key fracture-induced material parameters. In contrast to LEFM, the NCZ approach models fracture as a continuous process defined by a traction–separation law.

The version of the NCZ model applied here was originally developed by Yoon and Allen (*8*) and further extended by Allen and Searcy (*9*) via the inclusion of rate/time-dependent and mixed-mode fracture phenomena. When implemented in a finite element framework, it can provide an efficient and physically grounded method for predicting crack growth in railheads. The model effectively addresses a variety of crack configurations and accounts for the size, orientation, and location of subsurface flaws. A schematic of the traction–separation behavior defined by the NCZ model is shown in **Figure 2**.

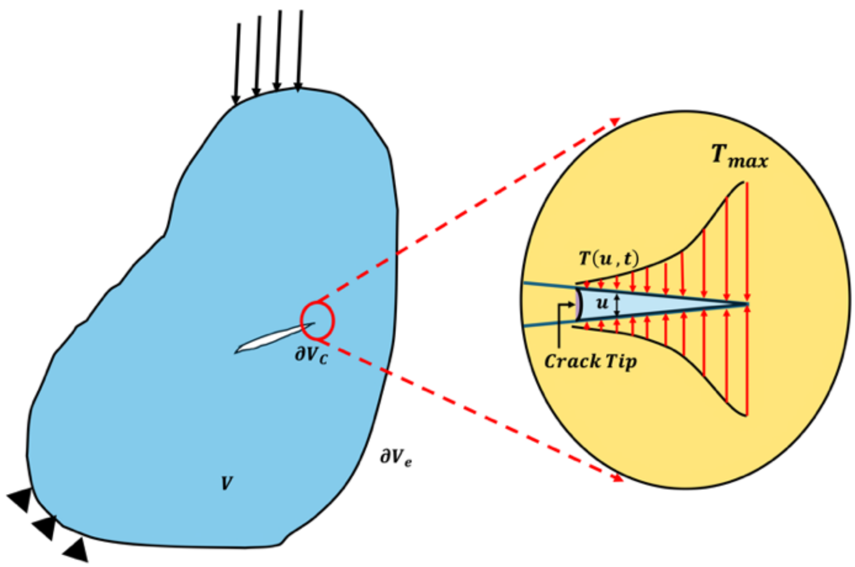

Figure 2. A schematic of the NCZ model depicting the fracture behavior of a crack tip in a general body.

The NCZ model defines the inelastic damage zone near the crack tip through a traction–separation relationship detailed in Equations (1) to (3).

$$T_i(t) = \frac{1}{\lambda(t)} \frac{u_i(t)}{\delta_i} \big(1 - \alpha(t)\big) \int_0^t E(t-\tau) \frac{\partial \lambda(\tau)}{\partial \tau} d\tau \tag{1}$$

$$\lambda(t) = \sqrt{\left(\frac{u_1(t)}{\delta_1}\right)^2 + \left(\frac{u_2(t)}{\delta_2}\right)^2} \tag{2}$$

$$\dot{\alpha}(\lambda) = \begin{cases} A\lambda^m & when\ \dot{\lambda}(t) > 0 \text{ and } \alpha(t) < 1 \\ 0 & when\ \dot{\lambda}(t) \le 0 \text{ or } \alpha(t) = 1 \end{cases} \tag{3}$$

Where, $T_i(t)$ is the cohesive zone traction vector functioning over the boundary of CZ elements, $u_i(t)$ is the displacement of the CZ elements, $\lambda(t)$ is the Euclidean norm of the displacement vector, δ_i is the cohesive zone material length parameter, $\alpha(t)$ is the internal damage evolution variable, and $E(t)$ is the relaxation modulus. As indicated by Equation (1), once the damage parameter $\alpha(t)$ approaches one, the cohesive traction $T_i(t)$ approaches zero. This state denotes the full separation of the cohesive zone element and the creation of a new surface as it implies a total loss of resistance due to displacements. A key component of the NCZ model is the damage evolution law. In this study, a power-law relationship is adopted (*10*), where damage growth is defined as a function of λ(t) and two material constants, named *A* and *m* in the equation (3). However, the form of α(t) can be modified to reflect corresponding material behavior based on experimental or observational data, such as with the general power-law model (*8*), the probabilistic damage model (*11*), and the new power-law-damage model (*12*).

Results to Date

The principal test results were obtained by a uniaxial fatigue test of a specimen that was extracted from a rail section provided by MxV Rail. Prior to testing, a phased array ultrasonic transducer was used to detect internal flaws (i.e., pre-existing crack). A rail specimen approximately 19 mm × 60 mm × 400 mm with a 2.7 mm internal flaw was then cut out for uniaxial testing as illustrated in **Figure 3**.

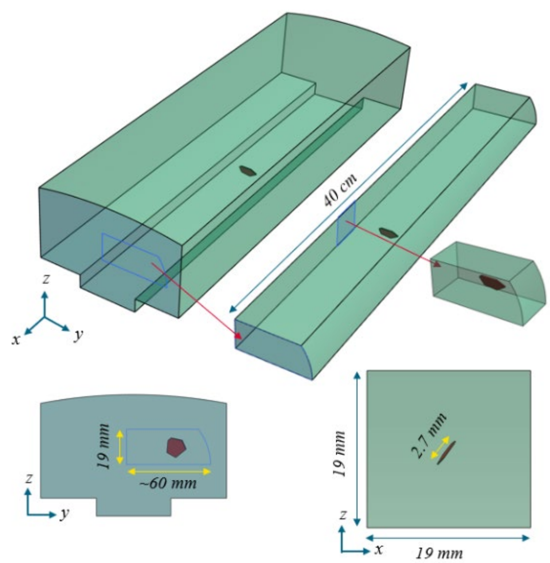

Figure 3. 3D rail section and its simplified 2D model.

The uniaxial fatigue testing apparatus installed at the Center for Infrastructure Renewal (CIR) located at Texas A&M University, was used for testing the cut rail specimen as depicted in **Figure 4(a)**. **Figure 4(b)** illustrates the phased array ultrasonic test (PAUT) conducted on the specimen, **Figure 4(c)** shows the raw result of the PAUT, and **Figure 4(d)** shows a typical geometry of an internal flaw (or pre-existing crack). Crack geometries were monitored every 100,000 loading cycles by the phased array with target measurements extending to several million cycles. It should be noted that even though the PAUT was effective in detecting internal flaws, it was surface sensitive and susceptible to human error. In conjunction with the ongoing uniaxial testing, model simulations were used to explore fracture properties of the rail. These model simulations were based on a combination of early experimental observations and insights from previous studies conducted by researchers at the CIR (*12, 13*). The goal of this initial modeling phase was to establish a reasonable starting point for characterizing crack propagation under cyclic load. Based on empirical data, an estimated crack growth rate of approximately 1 mm per 100,000 loading cycles was adopted as the initial starting point for the simulations. This assumption is subject to refinement as additional test results become available, however this provided a practical basis for evaluating the fracture response and guided subsequent simulation efforts.

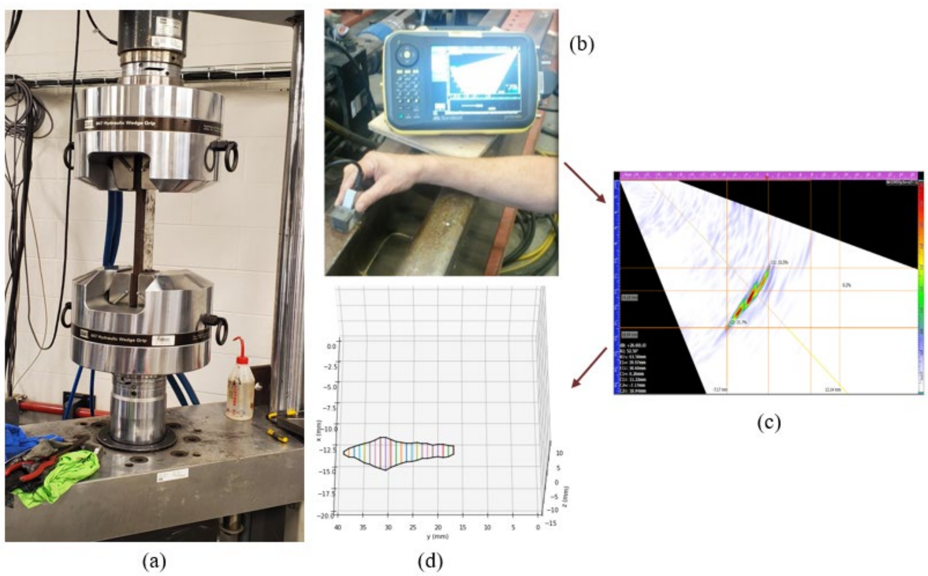

Figure 4. (a) Uniaxial fatigue testing of the rail specimen performed at TAMU-CIR (b) PAUT scan on the rail section, (c) raw results, (d) converted results showing a typical 3D geometry of the pre-existing crack.

As illustrated in **Figure 3**, the rail specimen consisted of a 3D flaw (crack) small enough along the x-axis to be simplified to a 2D model for computational efficiency. This simplification still preserves key physical characteristics through approximations. The resultant 2D finite element (FE) model is depicted in **Figure 5**. A fine mesh size was utilized near the crack tip, and a coarse one was used at the far field, which resulted in 486 linear triangular elements (CST). Based on experimental observations from PAUT measurements, the internal defect (crack) was modeled as a 2.7 mm-long flaw located at the center of the 2D domain, oriented at an angle of 60° to the x–z plane. Boundary conditions were applied to mimic the uniaxial test shown earlier in **Figure 4**. A solely horizontal cyclic load in the form of a haversine wave was imposed on the right boundary, with a peak amplitude of 68.5 MPa and a frequency of 4 Hz. The left boundary nodes were fixed in the horizontal direction, and the bottom boundary was fixed in the vertical direction. The simulation was conducted under 2D plane stress conditions.

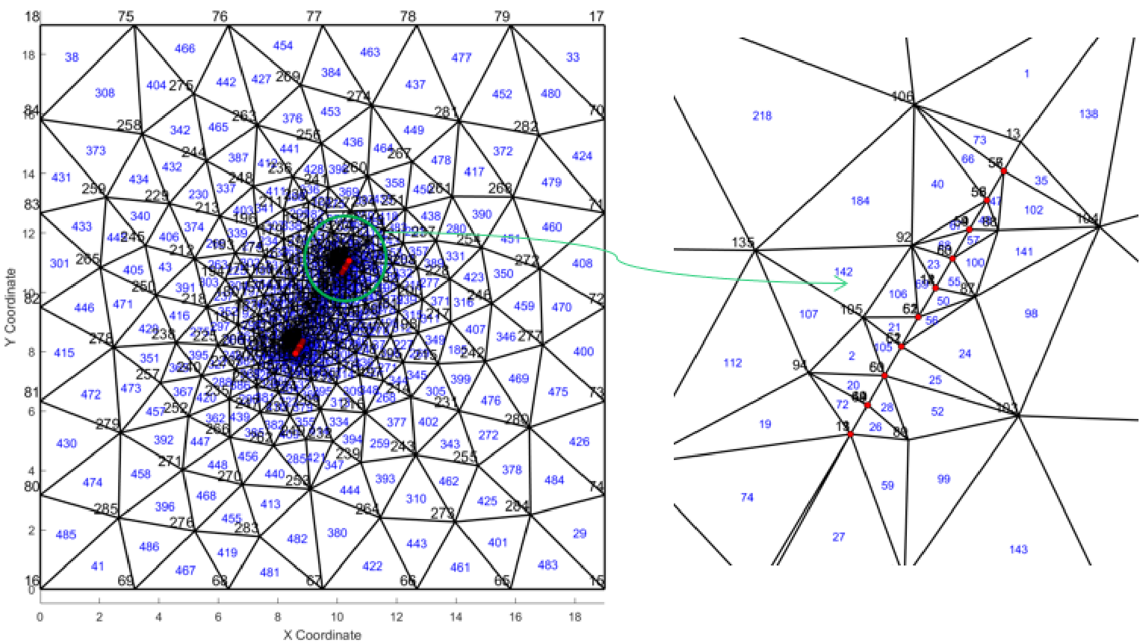

Figure 5. 2D FE model of a railhead section with an internal flaw which grows as a fatigue crack with the use of NCZ elements.

The primary target of this project is to demonstrate the feasibility of the NCZ modeling approach for predicting large-cycle fatigue crack growth and to calibrate NCZ material properties of the 2D FE model to mimic realistic fatigue cracking. Calibration of the NCZ model focuses on determining the parameters A and m in Equation (3), which govern damage evolution. As noted earlier, a crack growth of approximately 1 mm over 100,000 loading cycles was adopted for preliminary simulations. To represent this growth, 20 cohesive elements (≈ 0.05 mm per cohesive zone element) were placed along the original flaw corresponding to a total extension of 1 mm when fully opened. The emphasis at this stage was on estimating the material parameters A and m to achieve the target crack growth, rather than on the precise validation of test results. Under the condition that full damage (i.e., $\alpha(t) = 1$) occurs in all cohesive elements at 100,000 cycles, multiple combinations of *A* and *m* can satisfy the requirement. As an initial approximation, *m* was fixed at 1.0, 1.5, and 2.0, and for each case the parameter *A* was calibrated to achieve a full 1-mm separation at approximately 100,000 cycles. This process was then repeated by fixing *A* value as 1.0 and calibrating the parameter *m*. Through the calibration processes, the model fitted very well to the proper values of the parameters *A* and *m*. With *m* as 1.0, 1.5, and 2.0, the corresponding values of *A* are approximately 0.15, 5.5, and 90, respectively. Subsequently, with *A* fixed at 1.0, the value of *m* was approximately 1.255. **Figure 6** shows the crack length changes over loading cycles when different *A*-*m* pairs were used. It should be noted that as the calibration here is simply to meet the first approximate criterion (i.e., 1 mm crack growth over 100,000 loading cycles), other *A*–*m* pairs exist, while the more appropriate parameters can be better identified by comparing experimental data.

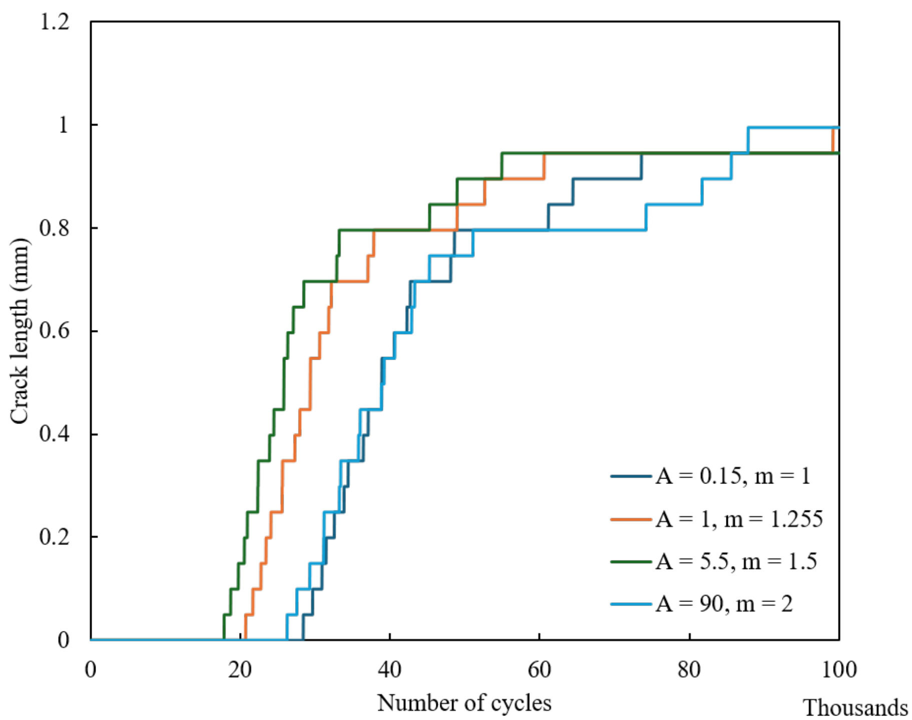

Figure 6. FE model simulation results (crack growth vs. number of loading cycles) when varying NCZ damage parameters: *A* and *m*.

We also conducted additional model simulations using finer meshes that included 80 CZ elements (each of them is approximately 0.0125 mm) and a total of 1,084 and 1,510 CST elements, compared to the initial mesh that used 20 CZ elements and 486 CST elements. The simulation was conducted only for the case where *A* is 0.145 and *m* is 1.0 to demonstrate as an example for mesh convergence. As shown in **Figure 7**, all three cases present a good agreement, indicating that the original mesh with 486 CST and 20 CZ elements was a reasonable choice, while it can be noted that using a greater number of CZ elements enabled smoother curves as expected.

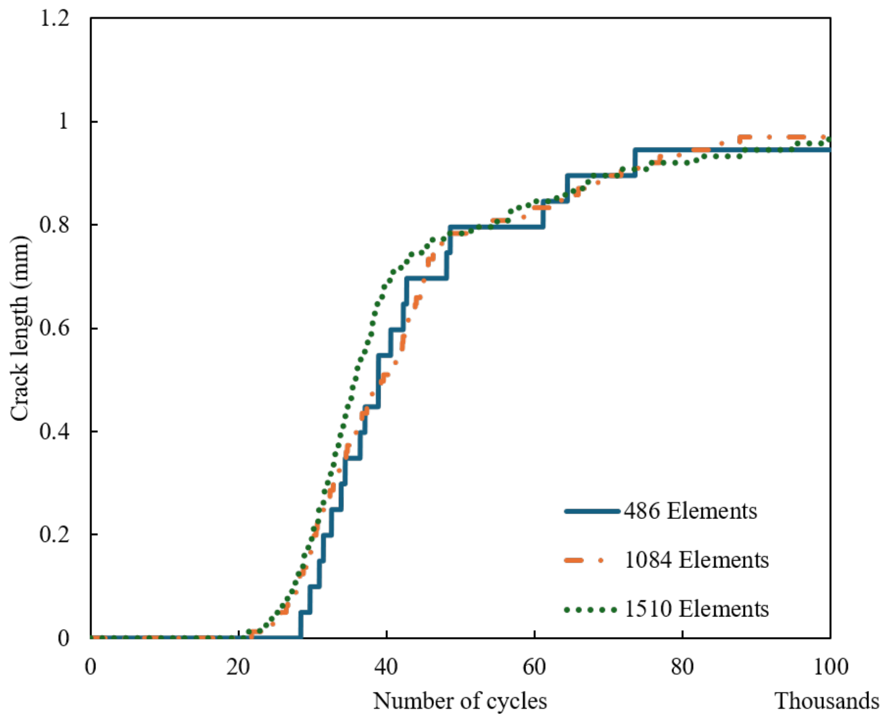

Figure 7. FE model simulation results (crack growth vs. number of loading cycles) when varying FE mesh structure with a fixed *A*-*m* pair.

Figure 8 presents model simulation results in terms of stress development and crack progression at three different fatigue stages (i.e., 20,000, 40,000, and 80,000) for one of the parametric model simulations (with A = 0.15 and m = 1.0). Horizontal stress (s_{xx}) distribution within the model, especially at the tips of internal flaw at the stage before cracking (i.e., 20,000 loading cycles) is quite different from the later two stages with the crack growth. As the modeling allows the crack growth up to a total of 1 mm with the CZ elements embedded, the stress contour plot at 80,000 cycles is a final stage of the model simulation, while crack growth can be continued to a larger size with an increasing number of fatigue loading cycles by embedding more CZ elements in the domain. This is currently in progress by comparing the FE model simulation with the uniaxial fatigue testing of the rail specimens.

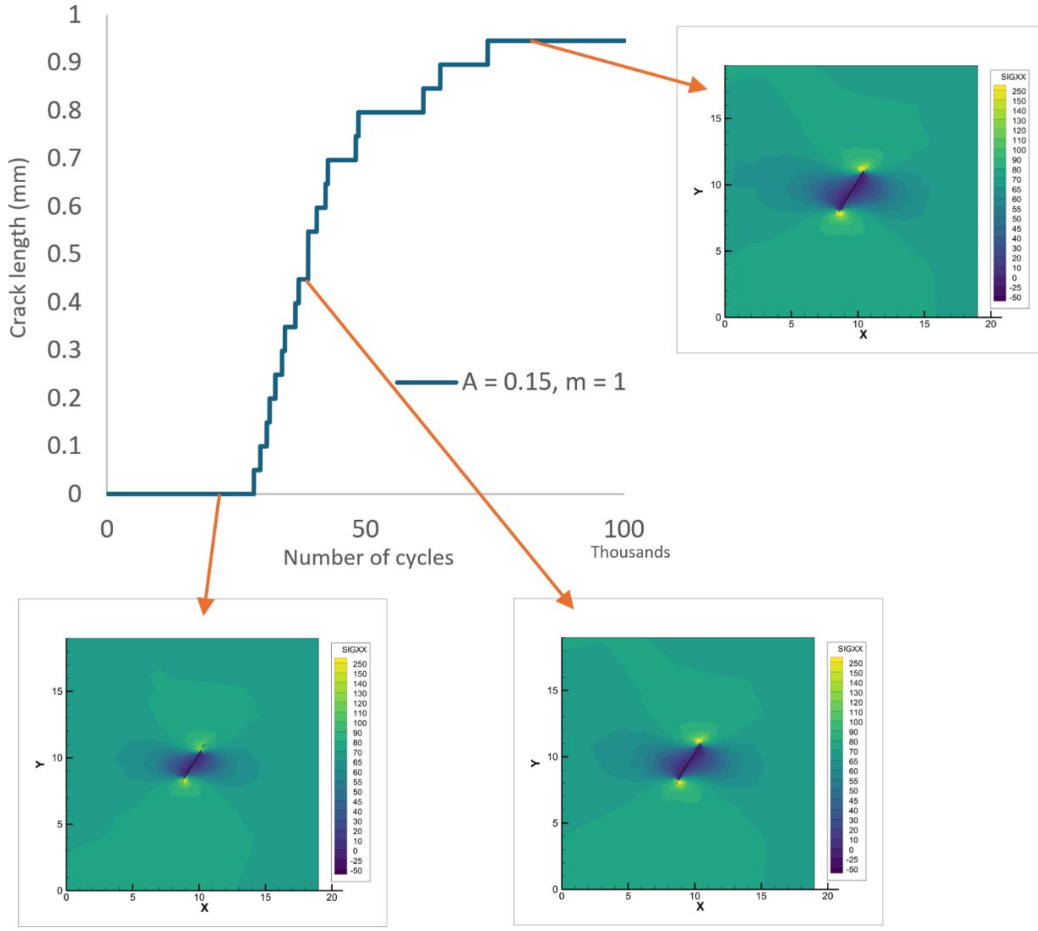

Figure 8. FE model simulation results: horizontal stress contour plots at different fatigue loading cycles.

This project demonstrated the feasibility of using the NCZ modeling approach to simulate subsurface fatigue crack growth in railheads through a 2D finite element model. These initial results indicate that our novel approach to modeling rail head fractures caused by long-term cyclic fatigue holds strong promise as a powerful tool for assessing structural integrity and ensuring the safety of rails with internal imperfections.

References

1. Association of American Railroads, "Overview of America's Freight Railroads." March 2020. https://www.aar.org/wp-content/uploads/2018/08/Overview-of-Americas-Freight-RRs.pdf.
2. Federal Railroad Administration, "Freight Rail Overview." United States Department of Transportation FRA, February 2025, Access date May 9, 2025. https://railroads.dot.gov/rail-network-development/freight-rail-overview.
3. Paris, P., A. Director, and F. Erdogan. A Critical Analysis of Crack Propagation Laws. 1963.
4. Tanaka, K. Fatigue Crack Propagation from a Crack Inclined to the Cyclic Tensile Axis. Engineering Fracture Mechanics, Vol. 6, No. 3, 1974, pp. 493–507.
5. Dowling, N. E., J. A. Begleyl, R. : Dowling, and N. E. And Begley. Fatigue Crack Growth During Gross Plasticity and the J-Integral. American Society for Testing and Materials, 1976.
6. Patel, A. B., and R. K. Pandey. Fatigue Crack Growth under Mixed Mode Loading. Fatigue & Fracture of Engineering Materials & Structures, Vol. 4, No. 1, 1981, pp. 65–77.
7. Saberi, S., P. Memarzadeh, and T. Zirakian. Study of Buckling Stability of Cracked Plates under Uniaxial Compression Using Singular FEM. Structural Engineering and Mechanics, An Int'l Journal, Vol. 69, No. 4, 2019, pp. 417–426.
8. Yoon, C., and D. H. Allen. Damage Dependent Constitutive Behavior and Energy Release Rate for a Cohesive Zone in a Thermoviscoelastic Solid. 1999.
9. Allen, D. H., and C. R. Searcy. A Micromechanical Model for a Viscoelastic Cohesive Zone. 2001.
10. Kim, Y. R., and F. T. S. Aragão. Microstructure Modeling of Rate-Dependent Fracture Behavior in Bituminous Paving Mixtures. Finite Elements in Analysis and Design, Vol. 63, 2013, pp. 23–32. https://doi.org/10.1016/j.finel.2012.08.004.
11. Allen, D. H., and C. R. Searcy. A Micromechanically-Based Model for Predicting Dynamic Damage Evolution in Ductile Polymers. 2001.
12. Saberi, S., G. Whetstone, and D. H. Allen. Multiscale Computational Modeling of Subsurface Cracking in Railhead: Insights Into Fatigue Life. No. 87776, 2024, pp. V001T05A002.
13. Whetstone, G., T. Liu, P. Fudlailah, C. V. Droddy, and D. H. Allen. Experimental Evaluation of Crack Evolution in Rails Using a Phased Array. Journal of Nondestructive Evaluation, Vol. 42, No. 4, 2023. https://doi.org/10.1007/s10921-023-00997-z.