U.S. Department of Transportation

Federal Railroad Administration

RESEARCH RESULTS

FRA OFFICE OF RESEARCH, DEVELOPMENT & TECHNOLOGY

RR 20-09 | **May** 2020

INVESTIGATING THE PROMINENT FAILURE MODE OF CUT SPIKES USED IN ELASTIC FASTENING SYSTEMS

SUMMARY

Under the sponsorship of the Federal Railroad Administration, researchers conducted finite element (FE) analyses at the Volpe National Transportation Systems Center from April 2018 to July 2019 to understand the underlying mechanisms contributing to the main observed failure modes of cut spikes used with elastic fastening systems for wood ties. One prominent failure mode featured fatigue crack development across internal spike/screw surfaces located approximately 1.5 inches below the top surface of a tie.

Researchers developed continuum FE models using commercial FE software Abaqus for a single cut spike embedded in a wood tie. The steel spike was assumed to yield plastically upon reaching a yield strength limit. A user material subroutine documented by Abaqus was adopted to simulate the 3D orthotropic failure of the wood tie. The elasticity, strength, and post-elasticity properties of the wood material model were significantly lower in the transverse direction than in the fiber direction. Different combinations of vertical, lateral, and longitudinal forces were applied directly to the spike in the FE analyses. The forces were monotonically increased in magnitude until the steel reached its yield strength (i.e., developed permanent plastic deformations) from bending. The corresponding forces were recorded as damage initiation forces. The corresponding yielding locations were recorded as damage initiation locations and compared with the field-observed fatigue fracture locations of the spikes.

The FE analyses indicated that wood damage initiation always preceded spike damage initiation and occurred at much lower force levels. Further, the combination of the longitudinal force applied on the spike and the weaker wood properties and support in the longitudinal direction was a main factor contributing to spike failure cracking at approximately 1.5 inches below the top tie surface. Research is ongoing to examine the loading cycle or fatigue loading effect and the longitudinal rail force distribution to individual ties at the track level.

BACKGROUND

Traditional track construction employs cut spikes to hold rails directly to wood ties, thereby providing lateral restraint to the rails and maintaining rail gage. Recently, elastic fasteners have replaced cut spikes for rail securement in curved, high tonnage wood tie tracks. These elastic fastening systems use cut spikes or lag screws to secure the tie plate to the crosstie. The elastic fastening systems are considered to provide superior fastening performance.

Several recent derailments have been attributed to the failure of significant numbers of spikes or screws used with the elastic fastening systems. A commonly observed failure mode is fatigue cracking across internal spike/screw surfaces, located as deep as 1.5 inches below the top surface of a tie. Such failures have been difficult for inspectors to detect and can grow into failed clusters of spikes, leading to wide gage problems. These failures occur predominantly on curved tracks with large lateral rail forces, but longitudinal forces are also believed to play a significant role (Kerchof, 2017).

To understand the root causes and to develop preventive measures for the spike failures, research is being conducted to understand the force distribution, force transmission, and damage development mechanisms at track, tie, and individual spike levels. The work presented here characterizes the damage force and damage location predictions at the individual spike scale using the FE method with appropriate material failure models.

OBJECTIVES

By modeling the system of a single steel spike embedded in a wood tie, the main objectives of this project were to determine (1) lateral and longitudinal force levels needed to initiate damage in the tie or the spike and (2) damage initiation locations in the spike. The effects of load configuration and wood material properties on these measures were evaluated.

METHODS

Figure 1 illustrates a single spike model with a spike embedded in a piece of wood representing the subset of a wood tie. Small tie plate pieces were modeled surrounding the upper shaft of the spike. Vertical, lateral, and longitudinal forces (V_p, L_p and F_p) were applied on the tie plate pieces. The vertical force was applied as pressure or downward traction on the plate surfaces with a resultant force of V_p. The lateral (L_p) and longitudinal forces (F_p) were applied as concentrated forces. The portions of L_p and F_p transmitted to the spike were denoted as L_s and F_s, respectively, and calculated based on the plate-spike contact forces in the respective directions from the FE analysis results. The resultant force (R_s) applied on the spike was further calculated as:

$$R_s = \sqrt{L_s^2 + F_s^2}$$

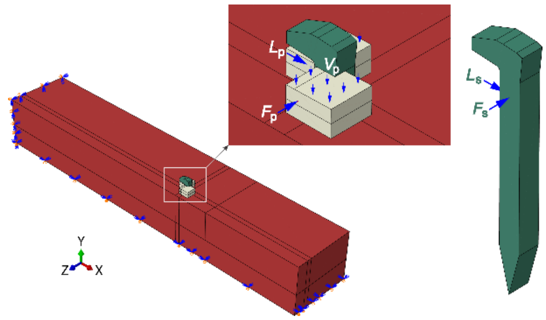

Figure 1. FE model of a single spike embedded in wood

Five different combinations of V_p, L_p and F_p were applied in the FE analyses: (A) V_p=2L_p, F_p=0; (B) V_p=2F_p=2L_p; (C) V_p=2F_p=4L_p; (D) V_p=2F_p, L_p=0; and (E) V_p=L_p=0, F_p>0. Of the first four cases, Case A had vertical and lateral forces only; Case B had equal lateral and longitudinal forces; Case C had twice as much longitudinal as lateral force; and Case D had vertical and longitudinal forces only. From A to D, there were decreased lateral and increased longitudinal force proportions (Yu and Liu, 2019).

Case E corresponded to an uplifted case identified as a likely loading condition leading to spike failure (i.e., the absence of vertical pressure and consequent lack of frictional forces meant all plate forces were transmitted to the spike) (Gao et al., 2018; FRA, 2019). Figure 2 shows an observed uplifted spike in track.

Figure 2. Uplifted spike observed in track

The steel material properties shown in Table 1 were applied. Once the von Mises stress reached the yield strength, there were irreversible permanent plastic deformations (measured by the equivalent plastic strain parameter PEEQ in Abaqus) in the material. The onset of nonzero PEEQ was used as an indication of damage initiation in the spikes.

Table 1. Steel spike material properties

Young's modulus	29,900 ksi
Poisson's ratio	0.3
Ultimate tensile strength	70 ksi
Yield strength	40 ksi

The orthotropic elasticity and strength properties of the white oak and Engelmann spruce wood species, based on the Wood Handbook (Bergman et al., 2010), were applied in the FE analyses (Table 2, where Direction 1 is the longitudinal or fiber direction; Directions 2 and 3 are radial (or transverse) and tangential directions; *E* and *G* are elastic and shear moduli; $X_{\text{-t}}$ are tensile strengths; $X_{\text{-c}}$ are compressive strengths; and S_{12} is the shear strength). White oak consistently had stronger properties than Engelmann spruce. The lateral and longitudinal load directions were aligned with wood material Directions 1 and 2, respectively. As such, lateral forces were resisted in the stronger fiber direction, while longitudinal forces were resisted in the weaker transverse direction of the wood.

A user material (UMAT) subroutine previously developed for fiber-reinforced composites (Linde et al., 2004) was adopted to simulate the 3D orthotropic elasticity and failure for wood. The damage variables calculated by this UMAT model were used to assess the wood damage in the analyses.

The coefficient of friction between the steel spike and the wood tie was assumed to be 0.3. A coefficient of friction of 0.25 was assigned for the plate-wood interfaces.

Table 2. Elasticity and strength properties of white oak and Engelmann spruce

Properties	Wood Species	
	White Oak	Engelmann Spruce
E_1 (psi)	1,958,000	1,300,000
E_2, E_3 (psi)	230,065	121,550
G_{12} (psi)	163,493	158,600
G_{23} (psi)	41,118	13,000
X_{1t} (psi)	15,200	9,300
X_{2t} (psi)	800	350
X_{1c} (psi)	7,440	4,480
X_{2c} (psi)	1,070	410
S_{12} (psi)	2,000	1,200

RESULTS

Figure 3 and Figure 4 show the resultant force (R_s) to initiate wood and spike damage, respectively, by loading case and wood species. With the increased proportion of longitudinal force in the force combination, the resultant force needed to initiate either wood or spike damage decreased consistently. The stronger wood species increased the forces needed to initiate damage. Further, wood damage initiation always preceded spike damage initiation, and much lower forces were needed to initiate wood damage than to initiate spike damage. The uplifted Case E corresponded to the lowest force levels needed to initiate wood or spike damage.

Figure 5 shows the location of spike damage initiation measured from the top tie surface. The damage locations are sensitive to the load configuration. Higher proportions of longitudinal force in the load configuration corresponded to deeper damage initiation locations in the spike. For a damage location as deep as 1.5 inches, there had to be a substantial longitudinal force in the load combination (Cases C, D, and E). Figure 6 shows two field observed spike failure modes approximately matching the calculated Cases A and C.

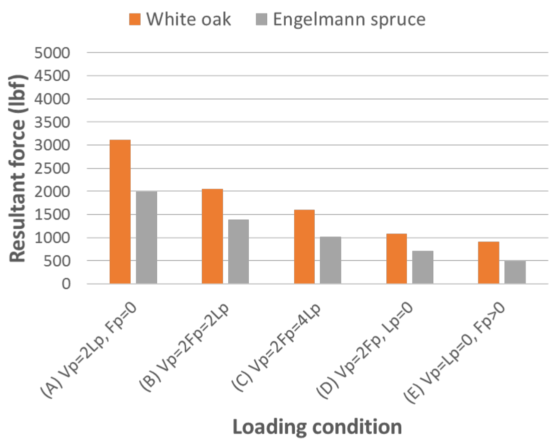

Figure 3. Resultant force (R_s) to initiate wood damage by loading case and wood species

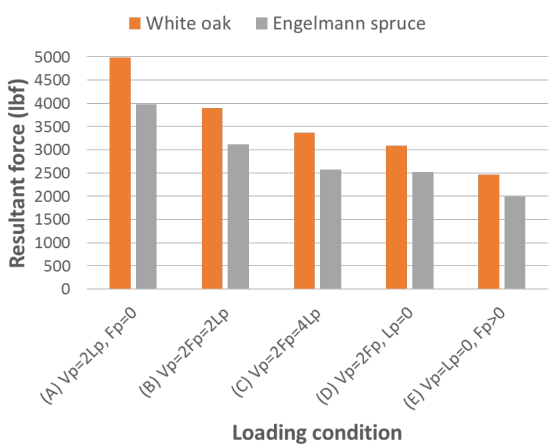

Figure 4. Resultant force (R_s) to initiate spike damage by loading case and wood species

CONCLUSIONS

FE modeling and analyses of a single spike embedded in a wood tie indicate that wood damage initiation always precedes spike damage and occurs at much lower force levels (as low as several hundred pounds). The uplifted loading case resulted in the lowest force levels needed to initiate wood or spike damage. Different force combinations produced different spike damage initiation locations. Spike failure at 1.5 inches below the top tie surface requires a load condition with a significant proportion of longitudinal force.

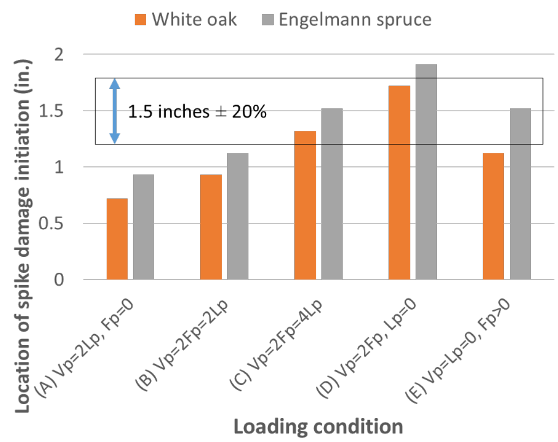

Figure 5. Location of spike damage initiation by loading case and wood species

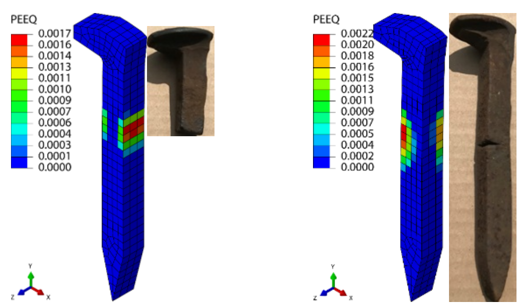

Figure 6. Field-observed spike failure modes matching FE Case A (left) and C (right)

FUTURE ACTION

The analyses presented here monotonically increased the applied forces until damage initiated in the spike. Under cyclic loading conditions, the force levels needed to initiate damage in the spike can decrease. Researchers are conducting cyclic loading simulations to obtain the spike damage S-N curves under different loading combinations. Researchers postulate that once damage initiates in the wood tie, it takes a limited number of cycles to initiate damage in the spike.

The single spike model results clearly showed that the longitudinal force contributed significantly to the observed deep location failure mode of the spikes. Research is currently being conducted to study the longitudinal rail force distribution to individual ties at the track level to further understand the significance of the longitudinal rail force distribution.

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ACKNOWLEDGMENTS

This work was sponsored by the Track Research Division, Office of Research, Development and Technology, Federal Railroad Administration.

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KEYWORDS
Elastic fastener, broken spike, spike failure mode, vertical rail force, lateral rail force, longitudinal rail force, wood tie, wood species, wood tie damage, finite element analysis

CONTRACT NUMBER
DTFR5315X00044