



Investigation into the effect of lateral and longitudinal loads on railroad spike stress magnitude and location using finite element analysis



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ABSTRACT

Multiple wide-gage derailments have recently been attributed to broken spikes in track constructed with premium elastic fastening systems. Premium fasteners on timber crossties were introduced into heavy axle load (HAL) freight service in North America over the past few decades and have gained popularity given they are thought to reduce maintenance costs, reduce rail-rollover risk, and they do not generally require rail anchors. However, given recent derailments and identification of failed spikes during field testing at higher rates than traditional fasteners, the University of Illinois at Urbana-Champaign is investigating the stress state of cut spikes in premium fasteners. This paper provides background on the broken spike problem and initial results from a validated finite element model that was developed to quantify the magnitude and location of spike stress concentrations as load magnitude, load direction, and crosstie species are varied. Results from this study indicate that the longitudinal loading, which is not generally present in traditional cut spike fasteners, is more detrimental to the performance of the spike than lateral loading. Further, the depth to the maximum stress concentration increases as the ratio of longitudinal to lateral load increases. Finally, as crosstie species is varied, the magnitude and depth of spike stress changes; these changes are more likely driven by changes in compressive and shear strengths, and then by modulus. Results from this work are presented in an effort to provide information which can be used to mitigate field failures by reducing the spike stresses in an effort to increase the overall safety of HAL freight rail networks and increase the life cycle of premium spike fastening systems.

1. Introduction

The function of railroad track fastening systems is to transfer vertical, lateral, and longitudinal loads from the rails to the crossties while controlling rail movements. Over the past few decades, North American Class I railroads have been installing premium fastening systems on timber crossties in some of their most demanding locations: those with high curvature and high tonnage [1].

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Fig. 1. (a) A premium fastening system found to have two broken spikes. Broken spikes were found and removed from the crosstie during a walking inspection. (b) Example fracture surface of a broken spike. (c) Examples of broken spikes with varying depths of failure location found during walking inspections. Measurements in inches.

Premium fastening systems use an elastic clip to clamp the rail to the crosstie plate, and spikes to hold the plate to the crosstie [1]. Spikes are installed by being driven into the timber through the tie plate to hold either the rail (line spikes) or the crosstie plate itself (hold-down spikes) in place. There are many varieties of spikes that include cut spikes, screw spikes, lag/coach screws, and lock spikes (“hairpins”), etc. Some of the advantages of premium systems are that they provide rail-rollover resistance and typically do not require the use of rail anchors for longitudinal restraint. Additionally, in some premium systems, no spikes need be removed during rail replacement, reducing the likelihood of spike-kill of timber crossties and reducing the time and cost of rail replacements [1]. Taken as a whole, these advantages of premium fastening systems should result in lower track maintenance costs for demanding territories.

However, several recent derailments [3–6] have occurred due to wide gauge in track constructed with premium fastening systems, and investigations of these derailments found that the wide gauge was caused by broken spikes. The derailments occurred on three different railroads and in each case the track met the applicable track class geometric standards and had no visually-detectable problem with broken spikes. Each derailment also occurred in track with different designs of premium fastening system, using both screw and cut spikes. Post-derailment investigations found the depth at which the spike failure occurred ranged from 25 to 50 mm (1–2 in.) with a typical depth to failure at approximately 38 mm (1.5 in.) below the top of the crosstie surface (Fig. 1). Further detailed investigations also found that the spike fracture surfaces were consistent with fatigue in the lateral and longitudinal directions.

Though spikes broken within the crosstie in premium systems were noted as a problem as early as 1982 [2] there has been limited research focusing on causes of these failures. The two most relevant pieces of literature to date are from Dick et al. [7] and Gao et al. [8]. In 2007, [7] conducted both finite element modeling (FEM) and field experimentation for Union Pacific to learn more about lag screw failures. It was found that stress is unevenly distributed across the spikes in a given plate, likely leading some to break before others. Additionally, it was also found that both rail temperature and timber stiffness affected the stress in spikes.

Previous testing at the Transportation Technology Center (TTC) [9] has identified numerous broken spikes in the premium fastening systems installed at the Facility for Accelerated Service Testing (FAST). In collaboration with Norfolk Southern Railroad, [8] used a finite element model to identify plate uplift and contact position of spikes within a plate as potential drivers of spike breakage. Additionally, it was found that the longitudinal load was transferred into the spike with these premium fasteners, a loading scenario that is not associated with traditional cut spike fasteners [8].

Because of this lack of understanding in the cause of the spike breakage failure mechanism, and the direct relationship with safety, the Federal Railroad Administration (FRA) has funded research at the University of Illinois at Urbana–Champaign (UIUC) to investigate the broken spike problem on premium fastening systems and methods to mitigate it. UIUC is currently conducting an industry-wide survey and a program of field visits to heavy axle load (HAL) railroads to observe and learn more about the performance of spikes (cut and screw) in revenue service [10].

The results from this work will generate mechanistic hypotheses explaining possible causes of spike breakage and what can be done to mitigate and/or prevent them. Preliminary results from the survey and field visits show that railroads are manually

inspecting curves susceptible to broken spikes, tapping each spike as they walk to see if it is broken. This is a time and labor intensive process, and involves an element of subjectivity. Geometry car reports may in some cases be used to identify broken spike locations, though curves must still be walked to find and remediate the actual broken spikes. Further, thus far, findings are in agreement with previous railroad experience in that broken spikes are primarily found in curves, and may be found in combination with steep grades or in special trackwork (e.g. the locations with highest lateral and longitudinal forces). Further, broken spikes typically exhibit a fracture surface with beech marks radiating from the spike corner, suggesting a fatigue failure due to both lateral and longitudinal loads. Chief among the concerns of the rail engineering practitioners facing these issues are the rapid gage deterioration observed in some broken-spike curves and lack of a better method for locating them.

Aside from simply learning more about the problem, researchers at UIUC want to further the work started by [7] and [8] by investigating the stress state within the rail spike fasteners. Through the use of a FEM the mechanics of these failures can be better understood. Therefore, researchers at UIUC have developed a 3D FEM to quantify the cut spike stress state when subjected to lateral and longitudinal loads when installed in various crosstie types. The spike stresses were compared to fatigue thresholds to understand how they would survive when installed in track when subjected to cyclic loading applications.

2. Objective and scope

Given the primary motivation to install and use premium fasteners is to improve safety and reduce maintenance, the recent derailments and need for walking inspections indicates these systems are not meeting the desired performance and thus represent a strong need to understand the failure mechanism of the spikes and develop a solution to mitigate this challenge.

Therefore, the objective of the research described further in this paper is to investigate the relationship between the location and magnitude of maximum stress and the consequent performance (e.g. fatigue life) of a cut spike fastener as loading and material parameters are realistically varied. Specifically, stresses within the cut spike shaft, approximately 13–50 mm (0.5–2.0 in.) below the top surface of the crosstie will be investigated, with the objective of evaluating the implications of subjecting spikes to lateral and longitudinal forces. To achieve this objective, a 3D FEM was developed.

3. Methodology

FEM is a common numerical simulation method for solving complicated structural and mechanical problems and thus was adopted in this study [11]. Abaqus/CAE, a commercially available software was selected to perform the simulations for this study given its recent use in studying other rail infrastructure components [11–14].

The spike fastener modeled for this study was the standard 152 mm (6 in.) long by 15.9 mm (0.625 in.) square shaft cut spikes. The design and other relative information are provided in Fig. 5-2-1 in Chapter 5 of the AREMA Manual on Railway Engineering [15]. This type of cut spike is used for both HAL and rail transit systems in North America. Fig. 2 presents the numerical model in this study, which consists of two primary components: a simplified cut spike and timber crosstie block. Both components were modeled as 3D deformable solids. Further, the cut spike was meshed using linear brick, type C3D8R for both the spike shaft, where the stress was of most interest, and spike tip with a total of 9936 elements. The simplified timber crosstie block was also modeled using 33,584 linear brick, type C3D8R elements and incorporated reduced integration and hourglass control. The static coefficient of friction (CoF) between the cut spike and timber block was set at 0.7 and the interaction between the spike and timber were modeled as two contact surfaces, and did not consider perfect bonding [16].

4. Simplifications and assumptions

In order to reduce the computational cost for the parametric study, yet maintain representative conditions, multiple simplifications and assumptions were made to spike and crosstie block models.

First, only a single cut spike and block of the crosstie were modeled. Given the scope of the project was investigating the effect of load magnitude and direction on spike stress, investigating the distribution and transfer of the forces from the rail to various cut spikes in multiple crossties was not considered to be necessary. Further, [7] had already shown the magnitude of load imparted into spikes varied significantly [7]. This choice also provided computational efficiencies and increased accuracy through the use of more refined meshes at key locations. Additionally, only a section of crosstie was modeled given a complete crosstie was not necessary to accurately represent the transfer of forces from the spike. The spike location modeled was designed to represent the field-side plate hold-down spike and thus the size of the crosstie block and amount of timber material for reaction was set accordingly as can be seen above in Fig. 2. Additionally, the cut spike head geometry was simplified given it was not the specific area of interest and does not play a role in stress distribution.

An additional simplification to the timber crosstie block was the placement of a 15.9 mm (0.625 in.) square hole into the timber block at the location where the spike would be installed. This provided clearance for the spike without having to spend computational time to insert the spike into the crosstie and calculate the resulting stresses. This assumption was further justified given this study was focused on simulating the working condition of the spike, thus making the process of driving the spike into the timber beyond the scope. Therefore, the model sets the spike at a predefined position and defines interaction between the spike and the timber crosstie accordingly.

Given the authors' knowledge that failed spikes can occur at various stages of spike life, the detailed spike-crosstie reaction was also simplified. That is, given spikes are known to lift out of the crosstie as well as skew, the stresses directly after installing a spike

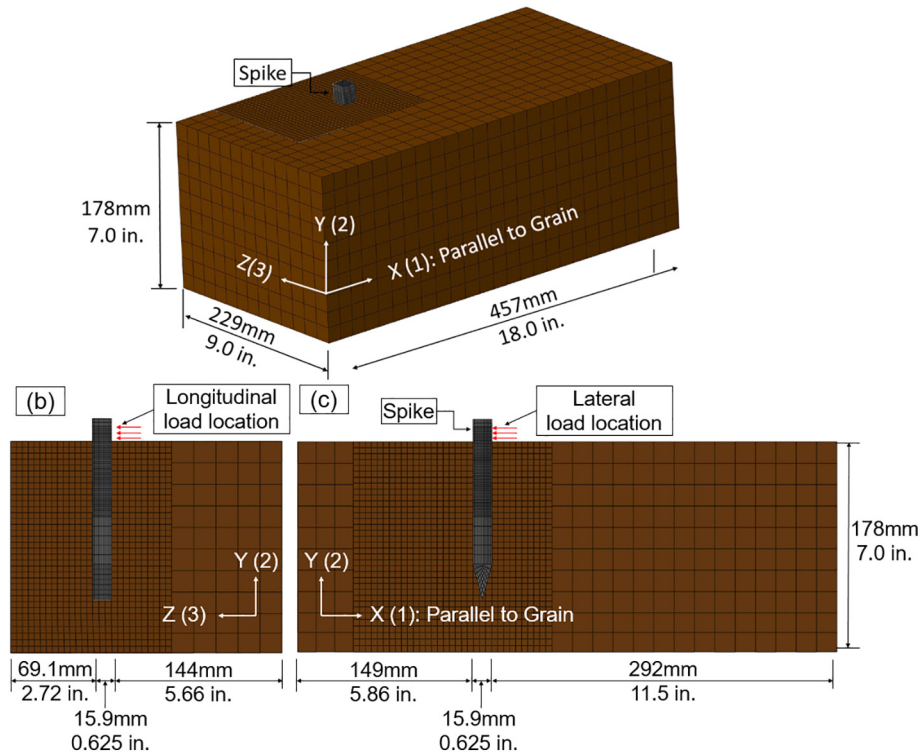


Fig. 2. (a) isometric view of 3D block and spike model; (b) view x-y cut section of cut spike in timber crosstie block; (c) view z-y cut section of cut spike in timber crosstie block.

are not as relevant as a spike which has been in track and settled.

Finally, unlike previous studies which have modeled and investigated the spike performance, the timber crosstie block was modeled as an orthotropic material given timber's unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal (parallel to the direction of the timber fibers), tangential (perpendicular to the direction of the timber fibers and tangent to growth rings), and radial (perpendicular to the direction of the timber fibers and growth rings) [16]. To account for this behavior, a timber user-defined material model (UMAT) was incorporated that had been developed and validated previously to investigate the mechanical behavior of timber joints with slotted-in steel plates [17,18].

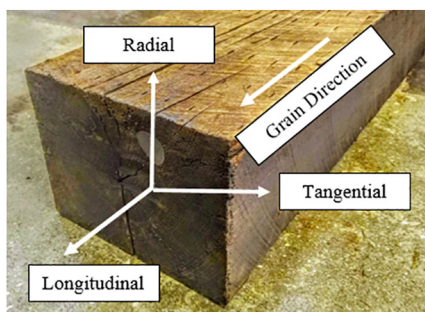
4.1. Materials, loads, and outputs for parametric studies

The first study investigated the effect of the orthotropic nature of the timber on the resulting cut spike stresses given an applied lateral and/or longitudinal load. Additionally, three (3) species of timber were investigated to understand how this change in species effected the magnitude and location of maximum stress within the spike. The magnitude of stress was compared to the fatigue and plastic limit of the spike to better understand how the spike would perform over time. Additional details into the materials and loads considered during the study as well as the outputs monitored will be introduced in detail in the following sub-sections.

4.2. Timber crosstie materials

As mentioned, timber is an orthotropic material [16,19], that must be accurately represented in the model [17,18,20]. Fig. 3 below illustrates the nomenclature used within this paper for the principal axes of timber with respect to grain direction. The longitudinal direction, runs parallel to the timber grains, aligns with the length of the crosstie, and will be the primary reaction direction of any lateral loads. The tangential and radial directions primarily run perpendicular to the timber grain, would align with the width and depth of the crosstie and will be the primary reaction direction of any longitudinal loads.

To quantify the effect of load magnitude and direction, a laboratory-calibrated model was used; the timber properties used for this model are presented in Table 1. The material properties all fall within the expected ranges found within the literature when accounting for expected variability and/or strength reductions [19,21]. To quantify the effect of timber species, three timber species were considered in addition to the laboratory-calibrated model. Two of three additional species were hardwoods, given these are the primary type of timber used in curves and demanding areas while one of the species was a softwood, to better understand the effect of timber mechanical properties on the spike stress state. All species selected are regularly treated according to the Railway Tie Association (RTA) [22] and used by North American Class I HAL railroads. The three types were White Oak, Silver Maple, and Northern



Timber Definition	Grain Direction	Loading Definition	Model Direction
Longitudinal	Parallel	Lateral	1
Tangential	Perpendicular	Longitudinal	3
Radial	Radial		2

Fig. 3. Principal axes of timber with respect to grain direction, growth rings, and train loadings.

Table 1
Engineering properties of select hardwood timber.

Timber	Modulus of elasticity (MPa; psi)		Shear modulus (MPa; psi)		Compression (MPa; psi)	Tension (MPa; psi)	Compression (MPa; psi)	Tension (MPa; psi)	Longitudinal Shear (MPa; psi)	Rolling Shear (MPa; psi)
	E1	E2 = E3	G12 = G13	G23	Perpendicular to grain	Parallel to grain	Parallel to grain	Parallel to grain		
Calibrated model	11,376	1338	1127	283	1.6	1.9	20.7	49.4	6.9	5.5
White oak	1,650,000	194,000	163,493	41,118	235	270	3000	7161	1000	800
	12,273	1442	1055	644	7.4	5.5	51.3	82.7	13.8	5.5
	1,780,000	209,150	153,080	93,450	1070	800	7440	12,000	2000	800
Silver maple	7860	798	951	350	5.1	3.4	36.0	61.4	10.2	3.1
	1,140,000	115,710	137,940	50,730	740	500	5220	8900	1480	444
Northern white cedar	5516	375	1158	557	2.1	1.7	27.3	44.8	5.9	1.8
	800,000	54,400	168,000	80,800	310	240	3960	6500	850	255

Per Sandhass (2012), the chosen Poisson's ratios have the values incorporating damage at the beginning of the model and thus some improvement could be made in future models incorporating linear degradation.

Given the limited values within the literature, and the limited affect they have on the current model, the Fracture Energy values were treated as constants as 0.53 (3), 6.30 (36), 10.50 (60), & 10.50 (60) ((N/mm; lb./in.)) for the tension perpendicular to grain, tension parallel to grain, longitudinal shear, and rolling shear respectively.

White Cedar and their various material properties, which were found within the literature, are listed in Table 1 [18,19,21,23,24].

4.3. Cut spike materials

As mentioned above, the cut spike specifications can be found in Chapter 5 of AREMA [15]. Per AREMA as well as multiple North American Class I railroad specifications, the tensile and yield strength of the cut spikes must be at a minimum of 483 MPa (70,000 psi) and 317 MPa (46,000 psi) respectively [15]. However, to improve the accuracy of the model within this paper the steel from three spikes were subjected to a standard ASTM tensile test [26] to quantify the actual mechanical properties that could be used as inputs into the model. The steel was found, on average, to exhibit a Young's Modulus of 212,700 MPa (30,850,000 psi), a yield strength of 390 MPa (56,265 psi), and a tensile strength of 585 MPa (85,000 psi). It was assumed that the spike had a Poisson's ratio of 0.3, and density of 8050 kg/m³ (0.029 lb./in.³). Finally, the endurance limit was set at 233 MPa (33,800 psi) given it was assumed to be approximately 60% of the yield strength, which falls at the high end of the expected 35–60% range found within the literature [25].

4.4. Lateral and longitudinal load magnitudes

Lateral and longitudinal loads were applied to the spike shaft over a representative area as a crosstie plate contact patch. Five load cases were considered in which the loading magnitude of both lateral and longitudinal load ranged from 0 to 22.2 kN (0 to 5000 lb) (Table 2). Though the authors believe the maximum load levels to be aggressive, the ranges are feasible given the findings in the available literature, as confirmed below.

AREMA Chapter 30 recommends applying a lateral load of 75.2 kN (16,900 lb) to a single rail seat fastening system for the Tie and Fastener System Wear/Deterioration Test [27]. If this lateral load were evenly distributed among four (4) spikes, the load in each

Table 2

Five load cases in which the loading magnitudes of lateral and longitudinal load varied between 0 and 22.2 kN (0 and 5000 lb).

Timber definition	Grain direction	Loading definition	Model direction
Longitudinal	Parallel	Lateral	1
Tangential	Perpendicular	Longitudinal	3
Radial	Radial		2

spike would be 18.8 kN (4225 lb). Further, [7] measured a 22.2 kN (5000 lb) lateral spike load from temperature changes alone, and measured a maximum lateral spike load of 65.8 kN (14,800 lb). Though this load magnitude was indeed measured in the field, it was not considered in the model given it would yield the spike. Additionally, [7] also found the load was not evenly distributed among spikes in a plate, and in the field setup, a single spike among four took 63% of the total load.

Regarding the longitudinal load, which would typically be applied to the fasteners through the expansion of the rail via thermal forces or braking/traction forces from the train wheels, AREMA C30 specifies that a fastening system withstand at least a 10.7 kN (2400 lb) longitudinal load before rail slip for a single fastening system (or rail seat) [27]. Premium fastening systems tested by [2] took more force than this before rail slip; the strongest system tested was the German K-Type system which took 28.1 kN (6310 lb) of longitudinal load per rail seat before rail slip occurred. In 1977, the South-African Railways used then-new e-clips to increase their rail seat longitudinal restraint to 28 kN (6300 lb) to combat rail creep problems on concrete crossties in HAL service [28]. Therefore, considering a situation where one spike is taking a large share of the load in a crosstie plate, as was found by [7], it seems reasonable that this high loading could translate into 22.2 kN (5000 lb) or more load into a single spike, though a lower value like the one specified by AREMA (or less) is more likely.

4.5. Model validation

In an effort to validate the modeling approach and the parameters selected for the calibrated model as listed in Table 1, data were collected in the laboratory when loading was applied to an instrumented spike perpendicular to the grain (simulating a longitudinal load). A strain gauge was attached to a spike at approximately 62 mm (2.44 in.) from the top of the spike (as measured in the model); this would result in the strain gauge being approximately 43 mm (1.69 in.) from the top of the crosstie. Additionally, the longitudinal displacement of the spike head was measured approximately 13 mm (0.50 in.) from the top of the spike. These strains and displacements were measured for the duration of the test in which load was applied up to approximately 10.2 kN (2300 lb). Corresponding data from the lab and the model are presented in Fig. 4.

The model appears to accurately represent the spike response at approximately 43 mm (1.69 in.) below the top of crosstie, which is considered to be the critical location given this is approximately the depth spikes break in the field. Further, the model accurately represents the displacement behavior of the spike as recorded in the laboratory. Therefore, based on these data, the model is considered to be validated and can be used to quantify the effect of load magnitude and direction on spike stress.

4.6. Outputs

The key output parameters monitored within the FEM are as follows, (A) the largest von Mises stress observed within the spike shaft, which is directly related to fatigue failures regularly found in the field and (B) the depth of the largest von Mises stress below

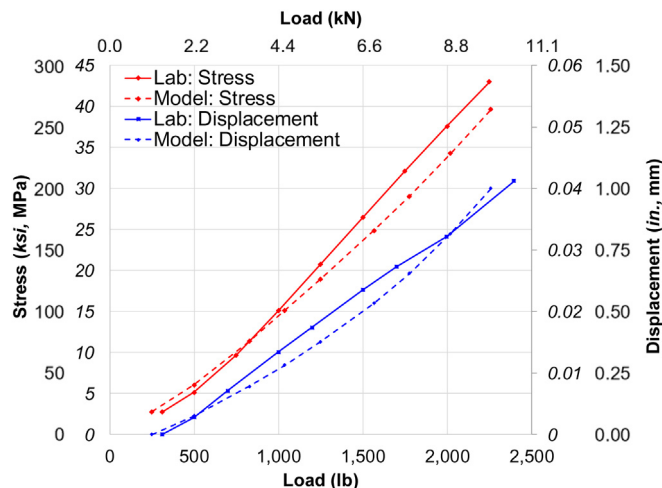


Fig. 4. Comparison of laboratory measured and model output stress and displacement at critical locations.

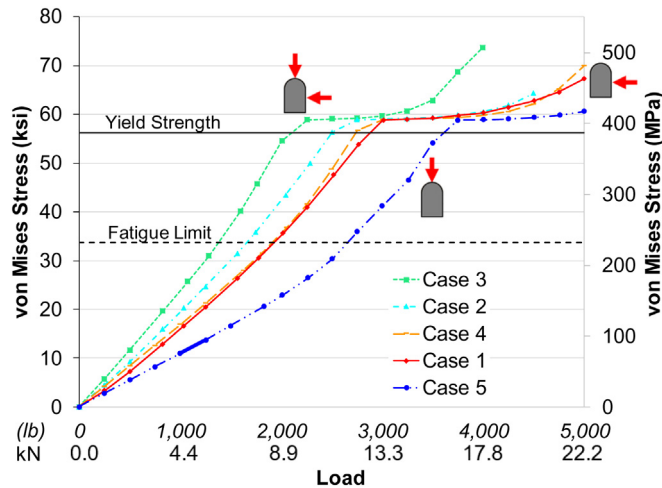


Fig. 5. Effect of various lateral and longitudinal loads on maximum spike stress.

the top surface of the crosstie.

5. Results and discussion

As stated previously, the magnitude of lateral and longitudinal load were varied between 0 and 22.2 kN (0 and 5000 lb) in five (5) different load cases to quantify the effects of load magnitude, load direction, and timber species on the maximum von Mises stress as well as the location (depth) of the maximum von Mises stress. As would be expected, load magnitude plays a significant role on maximum stress, with maximum stress increasing as load magnitude increases (Fig. 5). Fig. 5 demonstrates that longitudinal load is more detrimental to spikes than lateral load. This can be attributed to the orthotropic characteristics of the timber. More specifically, not only is the modulus of the timber perpendicular to the grain approximately only 10% of the modulus parallel to the grain, the compressive, tensile, and shear strengths are also significantly weaker in that direction. These lower values allow for timber damage at lower load magnitudes that in turn lead to greater spike stresses and deflections when longitudinal loads are applied. This then means that the stress exceeded the endurance limit at a lower applied load magnitude when only longitudinal loads were applied when compared to only lateral loads (i.e. Case 1 vs. Case 5). This is further confirmed when comparing Case 2 and Case 4; once again when more longitudinal load is applied (ratio of longitudinal to lateral load increases), the total load required to exceed the fatigue stress is reduced.

To quantify this, when a lateral load is applied, with zero longitudinal load (Case 5), a cyclic load of approximately 12.2 kN (2750 lb) would be required to result in a fatigue failure of the spike. However, a longitudinal load of only 8.9 kN (2000 lb) would be required to produce the same failure, or approximately a 30% reduction in magnitude when considering Case 1. Again, this aligns with what should be expected given timber's weakest direction is perpendicular to the grain. Furthermore, fatigue failure would be expected when longitudinal and lateral loads are applied simultaneously and at the same magnitude (Case 3) of 6.7 kN (1500 lb). This provides one reason why there are little to no broken spikes failing in fatigue for standard fastening systems given the need for a quantifiably higher magnitude of lateral load and the sensitivity of the spike to longitudinal load which is not typically present in traditional fasteners.

Qualitative assessments of the stress distribution within the spike as longitudinal and lateral loads are varied are shown in Fig. 6. When longitudinal or lateral loads are applied individually (Case 1 and Case 5; (a) and (b)), the stress is distributed uniformly across the same face as load is applied. However, as loads are applied together (Case 3; (c)), the stress is no longer uniformly distributed along the face, but is concentrated on a corner of the spike. When comparing Case 1 to Case 5, one can also see that the stress is distributed over a larger area of spike when longitudinal loading is applied to the spike compared to the lateral load. This is logical given there would be greater deflection in the weak direction of the timber. Furthermore, the damage of the timber near the surface of the tie leads to increased deflection, which in turn, leads to a greater depth in the maximum stress location, which will be discussed in greater detail below.

To ensure these findings were typical for what would be expected with various timber species, three different species of timber were modeled: White Oak, Silver Maple, and Northern White Cedar. As is evident in Fig. 7, the species of timber significantly affects the maximum stress in the spike. It should be noted that the model was unable to converge in more cases when the timber was weaker due to significant timber damage and excessive spike displacements. With that said, though Northern White Cedar was not able to run as long, it was evident that the spike in the soft wood experienced higher stresses at lower loads due to the fact that the timber experienced more damage. Further, and as expected based upon the literature [16] even though they were both hardwoods, the von Mises stress data from the White Oak and Silver Maple indicate that different hardwood species will behave differently. With that said, both hardwoods modeled clearly outperformed the softwood. Finally, as could be expected, the White Oak, the hardest and strongest timber modeled, resulted in the lowest spike stresses.

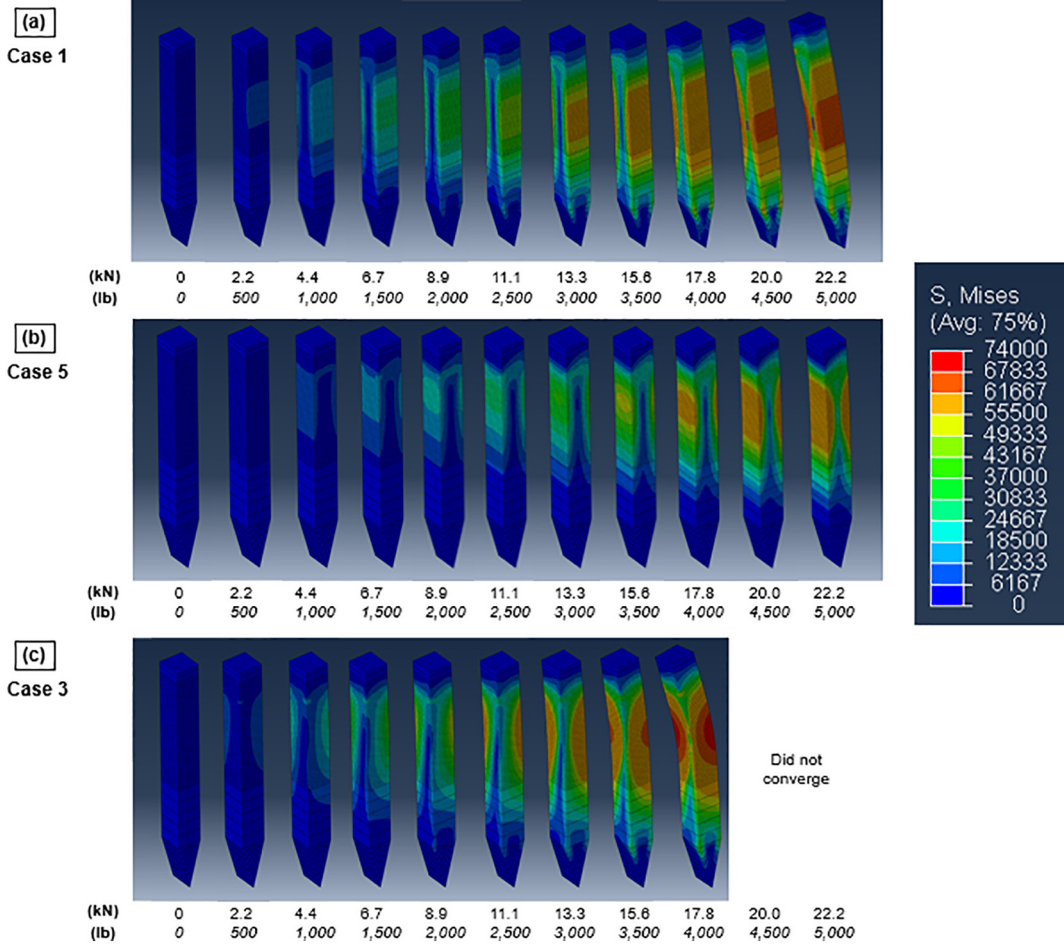


Fig. 6. Effect of lateral and longitudinal loading on cut spike stress distribution for Load Case 1 – Longitudinal Only (a), Load Case 5 – Lateral Only (b), and Load Case 3 – Lateral and Longitudinal Load (c).

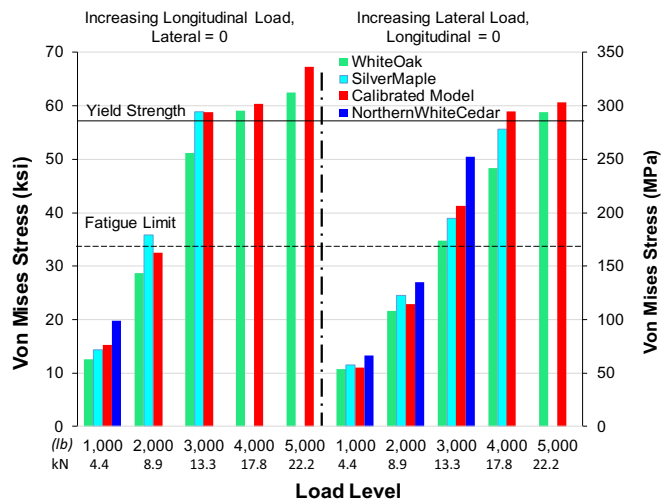


Fig. 7. Effect of load level and timber type on maximum Von Mises stress.

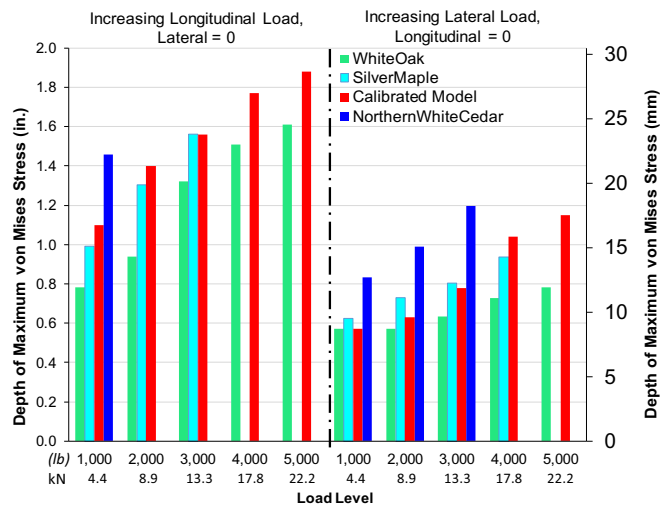


Fig. 8. Effect of load level and timber type on the depth of the maximum Von Mises stress.

Beyond quantifying the effect of load magnitude and direction on maximum stress, researchers quantified the depth of maximum spike stress. Given the field failure has typically been found to range between 25 and 50 mm (1–2 in.) it is critical to understand what factors could affect the depth of the maximum stress. Regardless of timber species, the depth of maximum stress was greater when longitudinal loads were applied compared to lateral loads (Fig. 8). The maximum depth quantified with this model was 48 mm (1.9 in.) at 22.2 kN (5000 lb) applied with the calibrated model. Additionally, one can see that as the timber mechanical properties were reduced (modulus, compressive, tensile, and shear strengths) the depth to maximum stress became greater for a given load application. Further confidence in the model was gained when seeing that the depths to maximum stress fell within the typical ranges found within the field (Fig. 1). Further, the shallowest depth recorded was 15.3 mm (0.6 in.) below the top of cross-tie and occurred when lateral load only was applied at 1000 lb.; a load which would produce stresses that would not lead to failure. Finally, as was seen in Fig. 5 and in Fig. 7, in all cases when longitudinal load was applied, the magnitude of maximum stress was always greater than when lateral load was applied. Further, this data demonstrates that there is a quantifiable range of depths that the maximum stress could be found depending on the load magnitude, load direction, and timber species. Taken as a whole, all this data suggests that the longitudinal load is driving the failures in the field given the failures are regularly found deeper in the cross-tie.

The results from the study confirm that the timber species significantly affects the maximum stress magnitude and location (Figs. 5, 7, and 8). Given this, the selection of timber used in conjunction with premium fastening systems should be considered critical. Additionally, as has been indicated within the industry, not all hardwoods are created equally, and therefore, simply specifying a hardwood will not ensure repeatable or acceptable results. The data clearly indicates that as the value of critical mechanical properties of the timber are increased, the spike stress will decrease and the depth to maximum stress will become shallower. Therefore, as a recommendation from this work, one should at a minimum ensure the timber used in conjunction with a premium fastening system is a hardwood, but if possible, also ensure the compressive, tensile, and shear strength properties are as high as the locally sourced timber could allow. These improvements will help delay premature failure of the timber which in turn leads to excessive deflections and spike stresses; additional work would be needed to quantify recommended values.

Additionally, as has been demonstrated in the data, the load magnitude and direction have quantifiable effects on the spike stress state. Therefore, to lower the stress state within the spike, one should eliminate or mitigate longitudinal loads transferred to the spike. Further, where possible, reduce lateral loads imparted into the track structure through properly selecting track geometry (cant, gauge, etc.), using rail lubrication, and strategically deploying truck performance detectors (TPDs). This would lead to lower stress magnitudes, reductions in failure rates, and increased safety.

6. Conclusions and future work

Recent derailments caused by broken spikes within premium fasteners on timber cross-ties as well as walking inspections of track to find broken spikes motivated this work given the primary motivation to install and use premium fasteners is to improve safety and reduce maintenance. Therefore, these systems are not currently meeting the desired performance and thus present a need for additional research.

This paper investigated the relationship between the magnitude and depth of maximum stress and the consequent performance (i.e. fatigue life) of a cut spike fastener as load and material parameters were varied within reasonable ranges. A 3D FEM consisting of a single cut spike fastener and timber cross-tie block were developed for this study. A calibrated model was validated using laboratory data and the model outputs were representative of field performance, with the depth to maximum stress location being what was typically found in the field. The primary takeaways from this study related to cut spike stress state are:

- When longitudinal and lateral loads are applied equally (Case 3), the fatigue strength of the spike can regularly be exceeded with a load of only 6.7 kN (1500 lb) in each direction
- Longitudinal load had a more detrimental effect on spike stress state than lateral load. To exceed the fatigue strength of the cut spike, a longitudinal load approximately 30% lower than a lateral load (8.9 kN (2000 lb) vs. 12.2 kN (2750 lb)) could be applied.
- Loading direction had a significant effect on maximum stress depth. When only longitudinal load was applied, the depth of maximum stress could be up to 2 times deeper than when lateral load only was applied.
- Timber species significantly affected the magnitude and depth of maximum stress. It is believed that the timber mechanical properties driving this are compressive, tensile, shear, and rolling shear strengths.

Findings from this study help to quantify the sensitivity of spike stress to the addition of longitudinal loading. The results identify the addition of longitudinal load as a key driver of recent cut spike failures which have recently led to multiple derailments. Additionally, the findings indicate that hardwoods should be used exclusively with these premium fastening systems and specifications should recommend as high of strengths as locally sourced timber could provide.

Future work will continue this research to investigate other potential drivers as well as methods to mitigate the fatigue failure. Based on the findings from this and future studies, improved design recommendations for spikes used in premium fasteners, and/or premium fasteners themselves, can be made.

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