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Effect of pre-drilling, loading rate and temperature variation on the behavior of railroad spikes used for high-density-polyethylene crossties

Ibrahim Lotfy, Maen Farhat and Mohsen A Issa

Abstract

Railroad spikes represent a vital component of the rail track system, as they fasten the rail to the supporting crossties. Thus, it is important to understand its behavior and effect on the fastening assembly to mitigate any local failure, which, in turn, could lead to system deterioration or damage. Currently, alternative solutions to the traditional hardwood timber crossties are increasing being adopted by the railroad industry in the USA, with recycled plastic composite crossties being among the available alternatives. Their sustainably, environmental benefits, durability and ease of installation render them an attractive and competitive solution. Several research programs have studied this material and its fastening system in the past; however, additional research is required to fully understand the behavior of these materials and their interactions with the fastening system components. This paper presents an investigation that aims to understand and assess the performance of typical railroad spikes used for recycled high-density-polyethylene crossties. The study encompassed a comprehensive experimental investigation and analytical finite element modeling. The testing program evaluated railroad spikes using static testing methods recommended by the American Railway Engineering and Maintenance-of-Way Association (AREMA) manual. These tests addressed the rail spike pullout and lateral restraint for both screw and cut spikes. Finite element models were constructed and calibrated using the data obtained from the experimental program in order to extrapolate on the experimental results and predict the behavior of full-scale systems beyond the scale of the laboratory. The results observed in this study showed great promise, surpassing all the AREMA recommendations, which highlights the potential of these materials if properly optimized and engineered. Screw spikes exhibited a very good performance, surpassing the minimum recommendations by a significant margin (up to more than 200%) and are thus are highly recommended for future implementation.

Keywords

Railroad crossties, high-density polyethylene, fastening system assembly, experimental testing, finite element modeling

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Introduction

In the USA, railroad crossties are traditionally manufactured using hardwood timber. However, concerns regarding the sustainability and efficiency of wooden crossties have recently threatened the status quo. The main issues facing timber crossties are their susceptibility to rot and organic decay, which render the use of toxic wood-treating chemicals a necessity; in addition to sparsity and deforestation.[1–5] Currently, alternative solutions to the traditional hardwood timber crossties are increasing being adopted by the railroad industry.

Engineered composite plastic and pre-stressed concrete are among these alternative materials for railroad crosstie applications. Recycled composite plastic is well-suited for both new and replacement operations of railroad crossties. It can be designed and engineered to meet the required performance criteria. It is manufactured with the same geometry and weight as its timber counterpart, thus allowing one-to-one replacement strategies.[6] It can offer high strength and durability when properly designed and

Department of Civil and Material Engineering, University of Illinois at Chicago, IL, USA

Corresponding author:
Mohsen A Issa, Department of Civil and Material Engineering, University of Illinois at Chicago, 2095 Engineering Research Facility, 842W. Taylor Street, Chicago, IL, 60607, USA.
Email: missa@uic.edu

manufactured. In addition, its inherent damping capability can result in a prolonged service life with enhanced rideability and passenger comfort. Moreover, recycling plastic waste to manufacture crossties is a green process, which makes it very appealing in today's society, where the emphasis is directed towards environmental issues, greenhouse gas emission reduction and limiting climate change.

Recycled plastic composite crossties have numerous apparent environmental and structural advantages, ranging from pollution and waste reduction to life cycle cost-efficiency.[6–9] These advantages have resulted in several manufacturers offering commercial solutions using different recycled plastic composite crossties. Moreover, thousands of plastic crossties are currently in service in a wide variety of railroad applications in the USA and other countries.[10]

Past Research

Several researchers have performed studies that considered plastic composite crossties and fastening system assemblies based on these crossties using experimental laboratory or field testing. Jimenez[11] conducted an experimental study that addressed the vertical track modulus for both plastic and wooden crossties in two different types of fastening systems. Lampo et al.[12] investigated the performance of composite crossties using both laboratory and field testing. Roybal[13] conducted a study that addressed the cyclic loading response of composite crossties. The test was performed using cut spikes to fasten the rail and steel bearing plate to the crosstie. Reiff and Trevizo[14] studied the effect of several factors, including the type of spike, on the performance of plastic composite crossties.

As evident from past studies, only a small literature is available that considers composite plastic crossties and their fastening spikes. The behavior of a railroad spike and its interactions with a composite plastic crosstie when subjected to rail loading is not yet fully understood. Moreover, the prevalent USA rail design manual; the American Railway Engineering and Maintenance-of-Way Association (AREMA) manual, does not have fully developed criteria for composite crossties and their fastening system.[15] Therefore, additional research is necessary to properly characterize, describe and model the behavior of railroad spikes when used with composite plastic crossties, as well as to assess the feasibility of implementing them in railroad applications.

Research Objective

Sponsored by the New University Rail Center research program "U.S. DOT-RITA", the University of Illinois at Chicago conducted a series of studies to assess the feasibility of implementing high-density polyethylene (HDPE) crossties in both conventional and high-speed rail applications. Previous papers by the present authors have explored the flexural performance of HDPE composite railroad crossties, reinforced with discontinuous randomly distributed glass fibers, as well as its sensitivity to temperature variations.[16,17] In this paper, the results of an investigation aimed at understanding and assessing the performance of typical railroad spikes used with recycled HDPE crossties are presented. The study encompassed comprehensive experimental investigations and analytical finite element modeling. The testing program evaluated the railroad spikes using static testing methods recommended in the AREMA manual. These tests addressed the railroad spike pullout and lateral restraint for both screw and cut spikes. Then, an analytical finite element model was constructed, using the existing and obtained testing results to accurately portray the railroad spike behavior and interactions with the HDPE crosstie. This model will be used for future, full-scale, investigations beyond the scale of laboratory experiments. The objectives of this paper are as follows.

1. Understand the behavior of rail spikes under pure pullout forces and their interactions with the HDPE crosstie.
2. Assess the effect of temperature, rate of loading and type of spike on the spike's pullout behavior.
3. Investigate the behavior of rail spikes when subjected to lateral forces.
4. Develop an accurate finite element modeling technique that accurately portrays the behavior of the fastening system using the experimental data.

Experimental program

Description of the crosstie and fastening components

The HDPE crossties used in this study were manufactured using an extrusion process and recycled plastic milk and detergent bottles; of which 7.2 billion pounds (3.27 billion kilograms) are land-filled each year in the USA.[7] The crossties were reinforced with randomly distributed discontinuous glass fibers to achieve the desired stiffness. Foam-inducing agents were used to control the density and cost of the final product. Finally, UV inhibitors and anti-oxidants were also added to a thin skin layer to protect the surface of the crossties. This process creates an efficient cross-section with an optimum distribution of the reinforcing fibers and minimal weight. It also produces a difference in the properties between the core and exterior regions of the cross-section.[16] The final products had sectional dimensions of 9×7 in. (22.86×17.78 cm), length of 8 to 9 ft (2.44 to 2.74 m) and an average density of 56.8 pcf (910 kg/m^3).

The railroad spikes used in this study were provided by the Chicago Transit Authority (CTA).

They correspond to the spikes used for actual plastic composite crossties applications within the state of Illinois. Figure 1 shows the HDPE composite crosstie and the railroad spikes used in this study. The fastening system is composed of the following: the steel base plate is fixed to the crossties using the rail spikes and then the rail is fixed to the steel base plate using the fastening clips. Railroad cut spikes/screw spikes were used to fix the steel bearing plate to the HDPE crosstie. They were manufactured from A36 steel with yield stress of 36,000 psi (248 MPa), yield strain of 0.00124 in./in. (0.00124 cm/cm) modulus of elasticity of 29,000,000 psi (200,000 MPa).

Spike Pullout

The spike pullout test was performed as per the AREMA manual recommendations; AREMA Part 2- Section 2.4.1 – Test 3 A.[15] This test was used to measure the ability of an embedded railroad spike to resist withdrawal from the plastic composite crosstie. It was conducted by driving a rail spike into a sample of the HDPE crosstie and then applying a withdrawal force on the head of the spike using a pullout device. The minimum AREMA recommendations for withdrawal capacities are 5000 lbs (22.2 kN) for screw spike pullout and 1900 lbs (8.5 kN) for cut spike pullout.[15] The total rail and fastening system resistance to pullout is a combination of the pullout resistances of both the spikes and fastening clips; this test investigated the spike's pullout resistance; fastening clips will be investigated in future research. For this test, the crosstie specimens were cut into 12 in. (30.5 cm) long segments. A spike pilot hole was predrilled in the center of each specimen to enable spike installation. In order to fix the specimens to the testing bed, four through holes were drilled near each corner of the specimens and two 1 in. (2.54 cm) thick, steel plates were used to restraint the specimen from each side. A spike pullout device was specially designed with the same thickness as the rail bearing plate; it was used to apply the pullout force. All the spikes were installed manually using an adjustable wrench for the screw spikes and a sledgehammer for the cut spikes. A total of 55 pullout tests were performed to investigate several parameters that potentially affect the interactions between the spike and the HDPE composite crosstie; they include: size and shape of the pre-drilled pilot holes, type of spikes used, rate of loading and temperature variation. It is worth noting that all the tested specimens surpassed the minimum AREMA recommendations by a significant margin in all the tested conditions. Figure 2 illustrates the test configuration, the mode of failure/spike pullout and the specially designed steel pullout device.

Size and shape of the pre-drilled pilot holes. Four different pre-drilled pilot hole configurations; A to D, were investigated. Five specimens were tested for each pre-drilling configuration. Screw spikes were used in this investigation, as the pre-drilled hole profiles affect screw spikes more noticeably compared with cut spikes. A stroke-controlled, rate of loading of 0.5 in./min (1.27 cm/min) was used. The rate of loading was kept constant to properly determine the effect of the different pre-drilling configurations. All the tests were conducted at room temperature of 70°F (21.11 °C). The best-performing configuration was determined in terms of allowing the screw spikes to be installed in the specimens without creating excessive stress and material deformation around the spike while still providing enough bond and friction to resist pullout. Figure 3 presents the different pre-drilled pilot hole configurations investigated. Figure 4 presents a sample of the results obtained; i.e. the five specimens tested using setup B. Figure 5 presents a summary of all the tests comparing the different pre-drilling configurations.

The same trend was observed in all the tested specimens, as illustrated in Figure 4. Three phases were

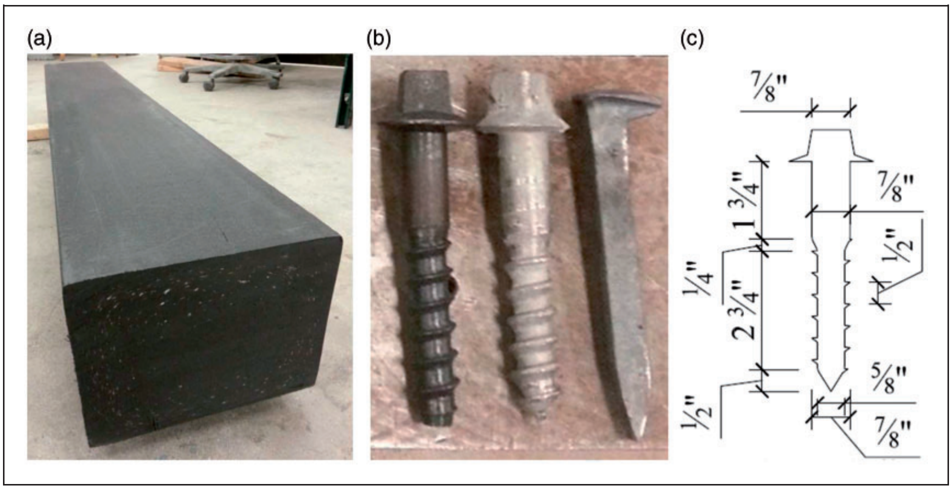

Figure 1. HDPE composite crosstie specimens and typical railroad spikes. (Units are in inches; 1″ = 2.54 cm).

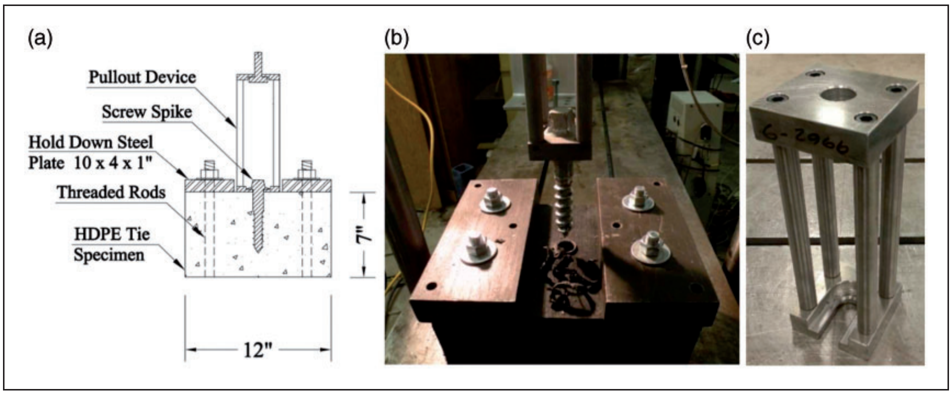

Figure 2. Pullout test configuration, mode of failure and pullout device. (Units are in inches; 1″ = 2.54 cm).

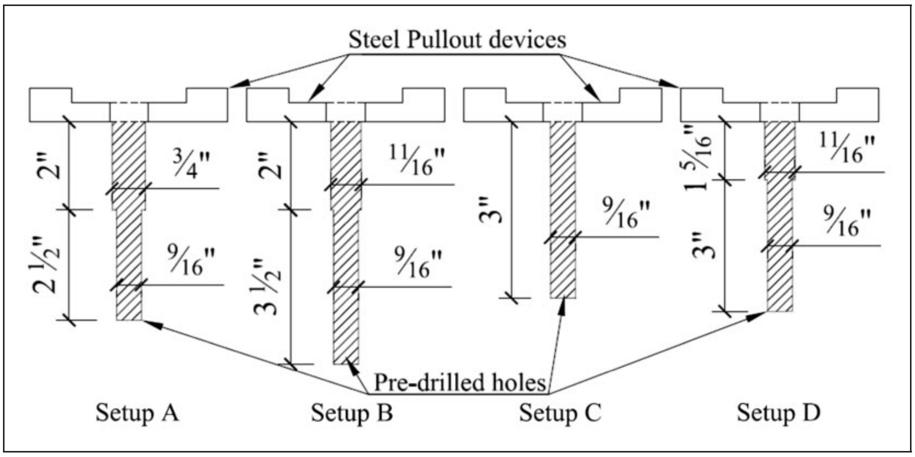

Figure 3. The configurations of the pre-drilled pilot holes. (Units are in inches; 1″ = 2.54 cm).

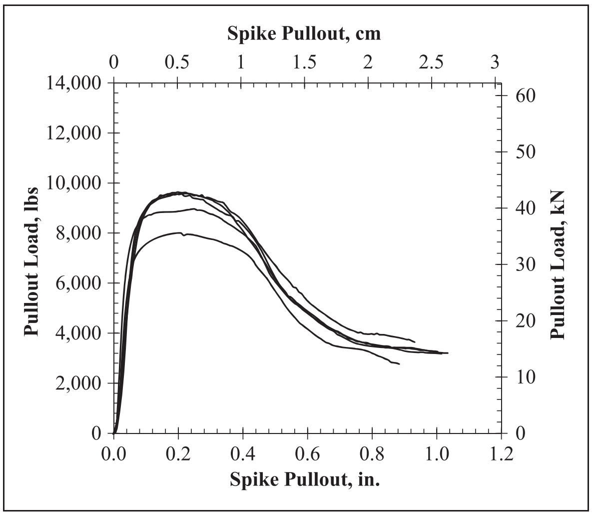

Figure 4. Sample result: load–pullout curve for the five specimen using setup B.

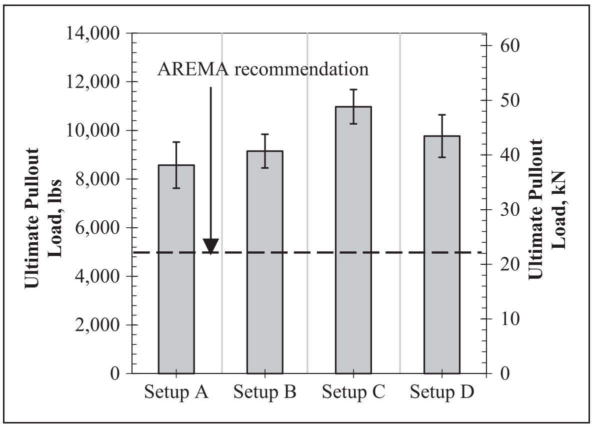

Figure 5. Ultimate pullout load comparison between the four pre-drilling configurations.

observed; the first begins with the application of the load where the load substantially increases with little deflection until the specimen reaches its ultimate pull-out load. The second phase begins after bond failure, where the load remains almost constant with an increase in deflection; in this phase the resistance to pullout is provided by HDPE material yielding and friction with the spike. In the third, and final phase, the load significantly decreases with an increase in deflection; this represents the failure state; i.e. with-drawal of the spike from the HDPE specimen.

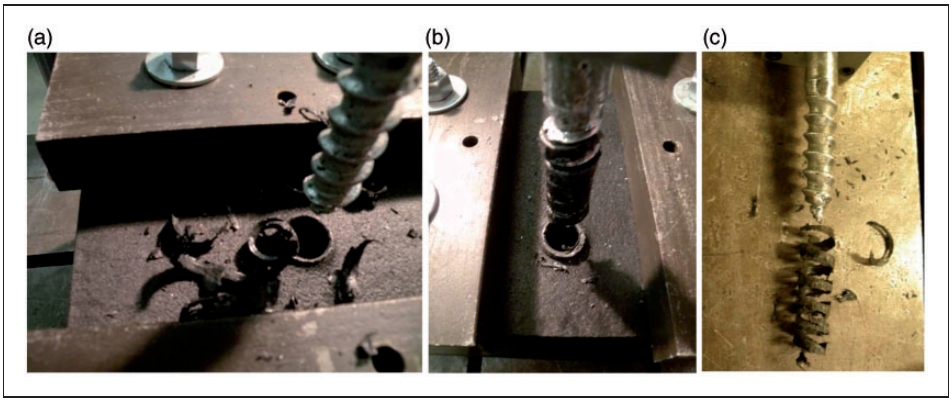

Figure 6. Material between the threads extracted after pullout (setup A and B- loose material (left); setup C – very tight material (center); setup D – tight material (right)).

The pullout resistance of the screw spike is largely dependent on the size, shape and depth of the pre-drilled hole. The pullout resistance is provided by the bearing of the spike threads on the HDPE material between the spike threads. A direct indication of the volume and density of the material between the spike threads can be acquired by the material between the threads, extracted after spike pullout as shown in Figure 6.

Setups A and B both had relatively large pre-drilled holes and did not provide enough material for the spike threads to bear on, as shown by the loose material extracted after pullout in Figure 6, which is reflected in their relatively low pullout resistance. Setup C produced the most (tightly compacted) extracted material between the spike threads (see Figure 6) and the highest pullout resistance out of all the setups as demonstrated by Figure 5. However, overdriving screw spikes in undersized holes introduced local stress concentrations around the spike. Moreover, the installation of the spikes using this configuration required a lot of effort and often caused material bulging/build-up under the steel plate/pullout device. This build-up often introduced a small gap between the steel plate/pullout device and the HDPE crosstie, which could cause problems in actual application. Therefore, setup C is not recommended. Setup D is the configuration recommended by the authors, as it provides a good bond without causing material bulging/build-up in the vicinity of the spike. Setup D tailors the actual profile of the screw spike while being slightly undersized, refer to Figure 3. Even though setup C exhibited better pullout resistance, excessive material bulging occurred due to its significantly undersized pilot hole, which prevented proper contact between the crosstie and the bearing plate and thus was not recommended.

Type of rail spike. The two most commonly used rail spikes were investigated; cut and screw spikes. Five specimens were tested using each spike type. A loading rate of 0.5 in./min (1.27 cm/min) was used and the tests were conducted at room temperature of 70 °F (21.11 °C). As previously recommended, all the specimens were pre-drilled using the profile of setup D for the pilot hole for the screw spikes. When testing the cut spikes, all the pre-drilling configurations were evaluated; A to D, as well as no pre-drilling at all. The pullout resistance of the cut spikes did not vary significantly due to the pre-drilling configuration, or lack thereof. However, material build-up/bulging occurred when driving spikes in undersized holes, as well as the case with no pre-drilling at all. In addition, driving cut spikes in undersized holes was very challenging. Therefore, the authors recommended using pre-drilling pilot holes to enable proper installation/contact of the rail bearing plate and the HDPE crossties and not to optimize the pullout resistance of cut spikes. Figure 7 presents the applied load–spike pullout relationship for all the tested cut spikes. Figure 8 presents a summary of all the tests, comparing the pullout resistances of both the screw spikes and the cut spikes.

The investigated cut spikes exhibited significantly less holding power than screw spikes as expected, however, they still surpassed the AREMA minimum recommendations for a cut spike, which is 1900 lbs (8.5 kN).[15] Inspection of Figure 7 reveals that, unlike the three stages observed in screw spikes, the behavior observed for cut spikes is similar to pure friction behavior with only two stages. The first begins with the application of the load, where the load increases substantially with little deflection until the specimen reaches its ultimate pullout load. The second phase begins immediately after the ultimate pullout force was surpassed; a slightly reduced, steady, approximately constant, relationship was observed until the spike is completely withdrawn from the HDPE specimen. The behavior of cut spikes is mainly controlled by friction, as the spikes are smooth. After the initial bond was overcome, the friction force remained almost constant until failure; i.e. complete withdrawal from the HDPE specimen. Since the behavior is governed mainly by friction forces, the results obtained for cut spikes are very consistent when compared with the results of the screw spikes, as shown in Figure 8.

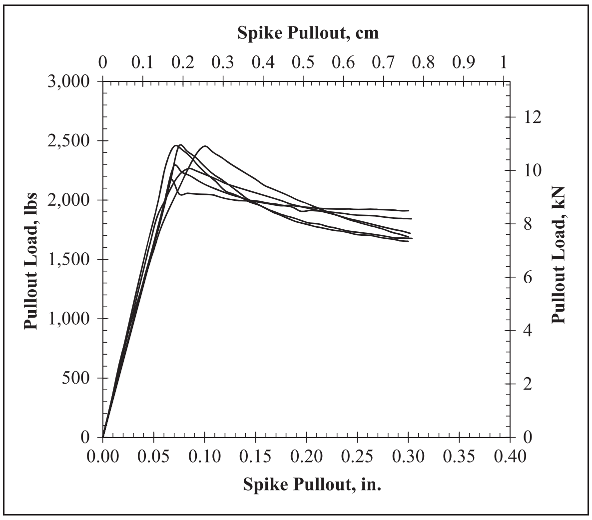

Figure 7. Load–pullout curve for the five specimens using cut spikes.

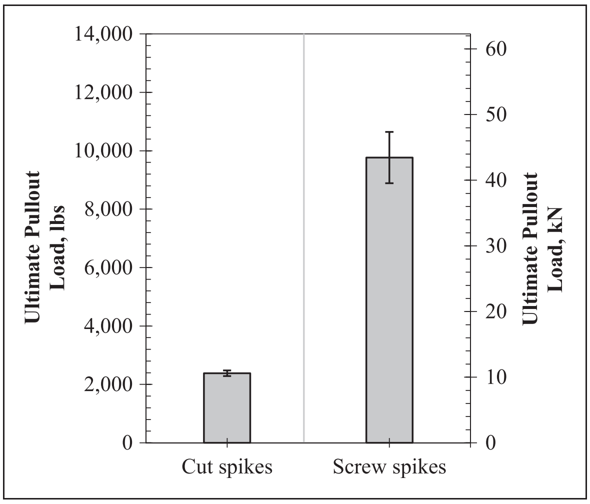

Figure 8. Ultimate pullout load comparison between the three loading rates.

Even though cut spikes fulfilled the AREMA minimum recommendations, it is clear that the screw spikes performed significantly better when combined with HDPE composite plastic crossties, as they surpassed the minimum AREMA recommendations by a significant margin.

Loading rate. Three different stroke-controlled loading rates within the AREMA recommended range were investigated; 0.5, 1 and 2 in./min (1.27, 2.54 and 5.08 cm/min). Five specimens were tested using each loading rate. Screw spikes were used in this investigation and the tests were conducted at room temperature of 70°F (21.11 °C). All the specimens were pre-drilled using setup D pilot hole profiles as previously recommended. Figure 9 presents a summary of all the tests comparing the three different loading rates investigated.

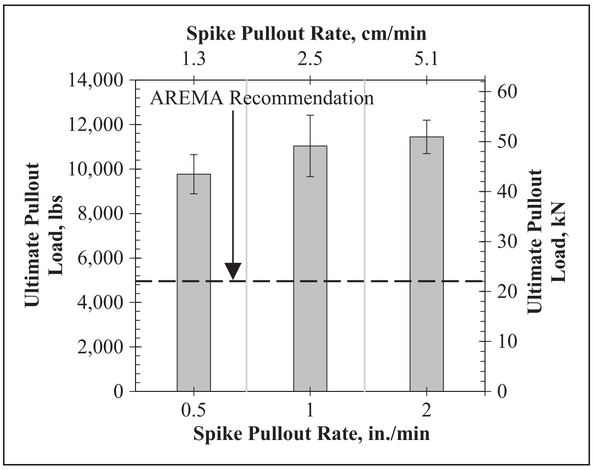

Figure 9. Ultimate pullout load comparison between the three loading rates.

Inspection of Figure 9 reveals that the ultimate pullout resistance displayed at faster loading rates was higher than slower loading rates. This result was expected as the HDPE crossties have high inherent damping and energy absorption. Moreover, the HDPE material will experience more creep strain at slower loading rates, which results in relaxation and, ultimately, lower pullout resistance. Therefore, it is recommended to use the slowest and most conservative loading rate for evaluation or characterization of pullout resistance in future applications. It is worth noting that actual train wheel loading is significantly faster than the loading rates investigated, which will further increase a spike's efficiency when resisting withdrawal from the HDPE crossties.

Temperature variation. The pullout resistance of the railroad spikes was investigated at different temperatures; 10, 40, 70, 100 and 125 °F (-12.22, 4.44, 21.11, 37.78 and 51.67 °C). Five specimens were tested at each investigated temperature. A loading rate of 0.5 in./min (1.27 cm/min) was used and the tests were conducted using screw spikes and pre-drilling setup D. To achieve the desired temperature, the HDPE crosstie specimens were placed in a sophisticated "Hotpack" controlled environmental chamber. The temperature of the chamber was rechecked using a digital "Weiss" thermometer to create additional redundancy. The temperature of the specimens was also monitored using another infrared "Omega" thermometer. The test was conducted when the three temperature-monitoring thermometers displayed the desired testing temperature. After the test was concluded, the temperature of the specimens was again recorded to ensure that it did not significantly vary. In all cases, the temperature of the specimens after failure was within ±5 °F (±2.78 °C) of the desired testing temperature. Figure 10 presents the test results for the five different temperatures investigated.

The expected outcome of this test was that, at lower temperatures, the pullout resistance would increase due to the hardening of the HDPE material, and vice versa at higher temperatures. Inspection of Figure 10 reveals that at lower temperatures the pullout resistance increased, which was expected, however, at higher temperature, the pullout resistance remained almost constant, which is very interesting. More to the point, the ultimate pullout capacity increased between 70 and 100 °F (21.11 to 37.78 °C), which was not expected, as the material softens at higher temperatures. This difference could be considered as insignificant and that the observed behavior is normal for HDPE, i.e. higher creep rates for higher temperatures. However, the authors believe that this was a result of the additional stresses/confinement introduced as a result of thermal expansion/squeezing of the HDPE specimen and the steel spike. These additional stresses enhanced the bond and friction between the HDPE specimen and the steel spike, and they were able to overcome the softening of the HDPE material. However, these additional thermal stresses were not sufficient to overcome the softening of the HDPE material at the temperature of 125 °F (51.67 °C), as the pullout capacity slightly decreased. Considering the authors previous experience when investigating the temperature effect on the behavior of HDPE crossties,[17] it is apparent that the properties of this material have a strong correlation with temperature variation. However, a more detailed investigation on the creep behavior of this material is required before reaching a definite conclusion. In any case, as evident from the test results, the pullout capacity of the specimens was not negatively affected, to any significant extent, by the variation in temperature, which is a notable, previously unexpected, outcome.

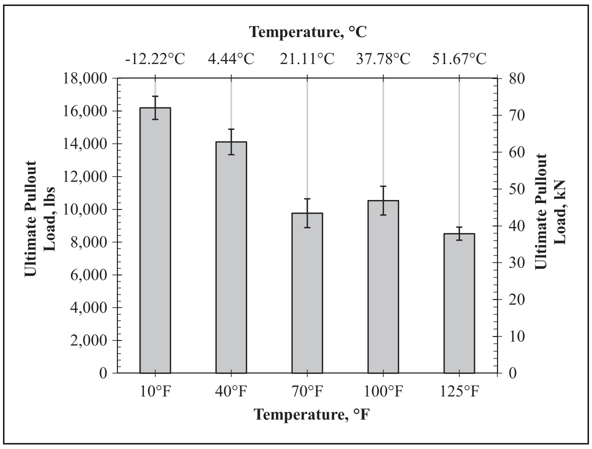

Figure 10. Ultimate spike pullout resistance at different temperatures.

Spike Lateral Restraint

The railroad spike lateral restraint test is used to identify the ability of an embedded screw spike to withstand lateral forces, thus, in turn, giving an indication of the total resistance to lateral movement of the system. The test was performed as per AREMA recommendation: AREMA Part 2- Section 2.4.2 – Test 3B.[15] It is conducted by driving a rail spike into a sample of the HDPE crosstie and then applying a lateral force on the head of the spike using a loading device. The AREMA manual recommends limiting lateral movement to less than 0.2 in. (0.51 cm).[15] The crosstie specimens were cut into 10 in. (25.4 cm)-long segments for this test. A spike pilot hole was pre-drilled in the center of each segment using the setup D profile. Four holes were drilled through the side of the specimens, near the corners, to properly fix the specimens to the testing bed during load application. Another specially made steel device, with a thickness of 0.5 in. (1.27 cm), was used to properly apply the lateral load. Figure 11 illustrates the test configuration and the lateral loading device. As per AREMA recommendations, a stroke-controlled loading rate of 0.2 in./min (0.51 cm/min) was used, a 0.2 in. (0.51 cm) lateral deflection was recorded as well as the ultimate load. A total of five specimens were investigated.

As presented in Figure 12, the trend observed in the tested specimens displayed two distinct phases. The first begins with the application of the load, where the load increases substantially with little deflection. During this phase the load–deflection relationship is linear and the spike and the HDPE specimen are working together to resist lateral movement. The second phase begins with a change in the slope of the load–deflection curve; i.e. after the end of the proportionality limit. The specimen continues to resist lateral forces with significant lateral deformation and yielding. The lateral load– deflection relationship continues almost linearly until failure. During this phase the spike starts to bend and thus bears on the HDPE material underneath, and both the steel spike and the HDPE material experience significant yielding and permanent deformations. After the ultimate lateral resistance is reached, the specimen is badly damaged and cannot resist an increased load. The mode of failure observed was the bending/yielding of the steel spike and deformation/yielding of the HDPE material under the spike as illustrated in Figure 13. It is important to note that no cracking was observed in any stage of the test for all the tested specimens.

As noticed from Figure 13, the HDPE specimen and the spike experienced composite action; i.e. they were working together to resist the lateral force in all stages of the test. It should be noted that the spike was bent at the section where the threads started, as shown in Figure 13, which is the weakest section of the spike under the applied bending stresses. It should also be noted that the lower portion of the spike, i.e. the threaded part, did not experience any bending, rather it was straight and upright when it was extracted from the specimen. Moreover, it was very

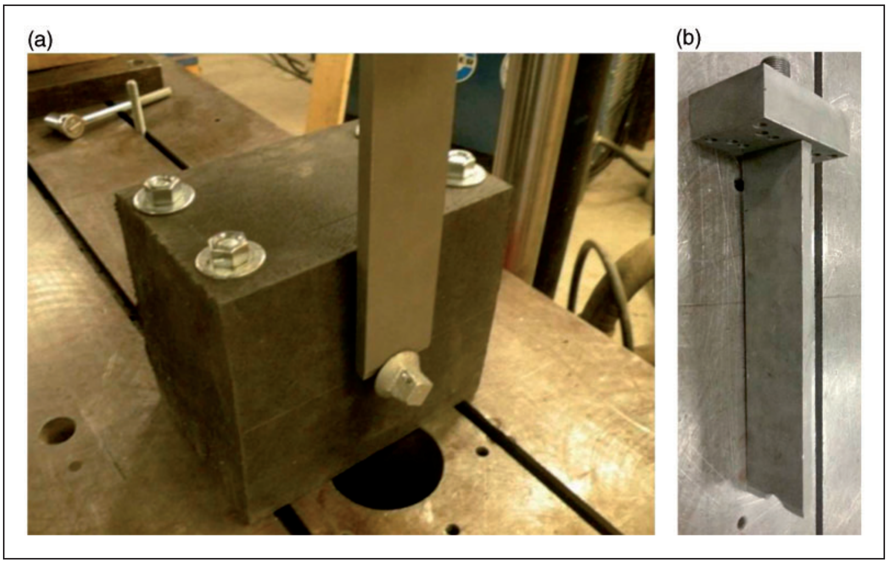

Figure 11. Spike lateral restraint test setup and loading device.

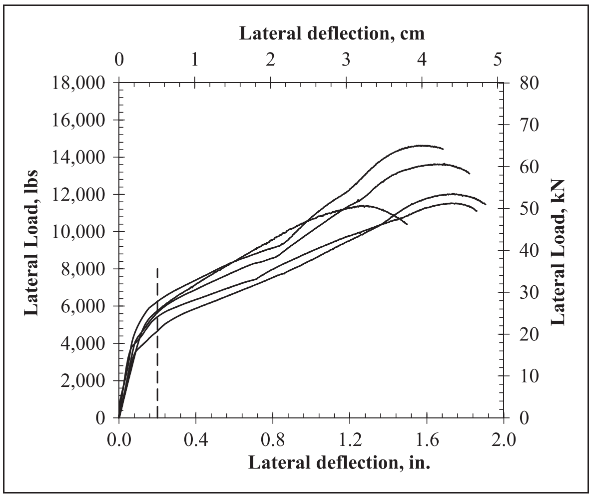

Figure 12. Lateral load and deflection for the spike lateral restraint specimens.

challenging to extract a bent spike from the specimen, as the plastic material has to be further deformed to release the spike. Therefore, the spike was completely fixed in the specimen, further validating the composite behavior between the spike and the crosstie. It can be inferred that the first linear phase is elastic and can be fully recovered whereas the second phase causes yielding and permanent deformation. Figure 14 shows a summary of all the tested specimens.

The maximum lateral displacement recommended by the AREMA manual is 0.2 in. (0.51 cm) to limit gauge widening. In all the tested specimens, the yielding point (proportionality limit) occurred before 0.2 in. (0.51 cm), which is ideal as, when properly designed, the system should not reach yielding under normal conditions. However, it should be noted that the specimens have a lot of reserve capacity/ductility and did not crack at any time during testing, which eliminates the possibility of sudden brittle failure.

Finite element analysis

Several previous studies, in medical fields such as surgery and dentistry, have used finite element analyses to model threaded bolts. It has been used to simulate the behavior of screw bolts in applications where experimental evaluation was infeasible, for example, where it involves human organs or tissue. Zhang et al.[18] investigated the pullout strength of a fixation screw in the human spine using finite element analysis; the threads were modeled in detail based on given geometry and dimensions. Similarly, Hsu et al.[19] used finite element analysis to assess the stripping torque and pullout strength of three types of pedicle screws embedded in polyurethane foam. Their model showed promising indications as the results mimicked the experimental data.

In engineering and railroad applications, the use of finite element analysis to study the performance of different system components is growing. It provides the means to examine the structural behavior of a given system and extrapolate/predict the behavior of applications beyond that observed at laboratory scale. In this study, it was used to simulate the pullout and lateral resistance of the screw spikes embedded in HDPE crossties. After its construction, the finite element model was calibrated/validated using the experimental data presented earlier in this paper.

The finite element analyses were performed using the general-purpose finite element software ANSYS Version 14.[20] For the three-dimensional modeling, the geometry of the system was separately created using the ANSYS Workbench Design Modeler software and then imported to ANSYS APDL.

Two models were created to study the pullout and lateral restraint behavior of a fixation screw in a HDPE crosstie. The models were built with the maximum possible detail, to simulate the actual behavior

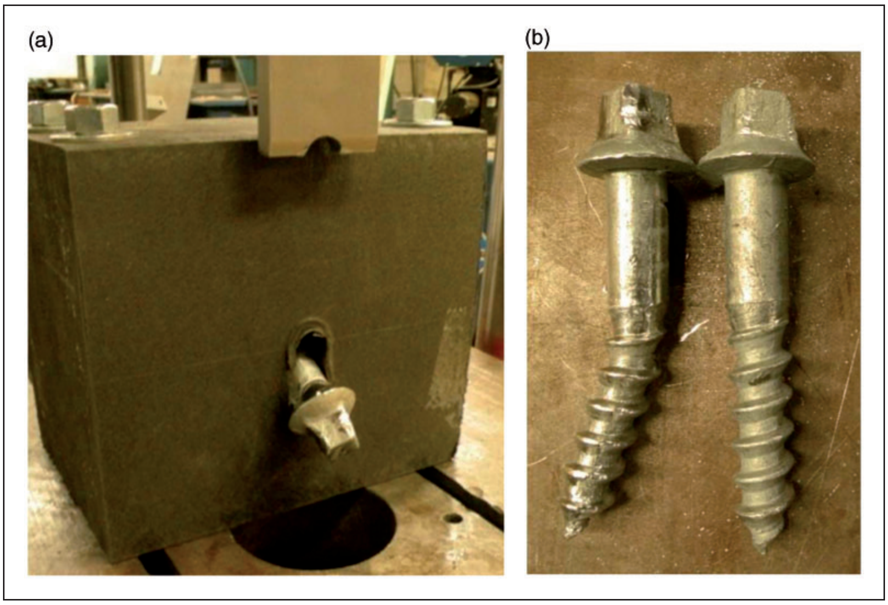

Figure 13. Spike lateral restraint mode of failure.

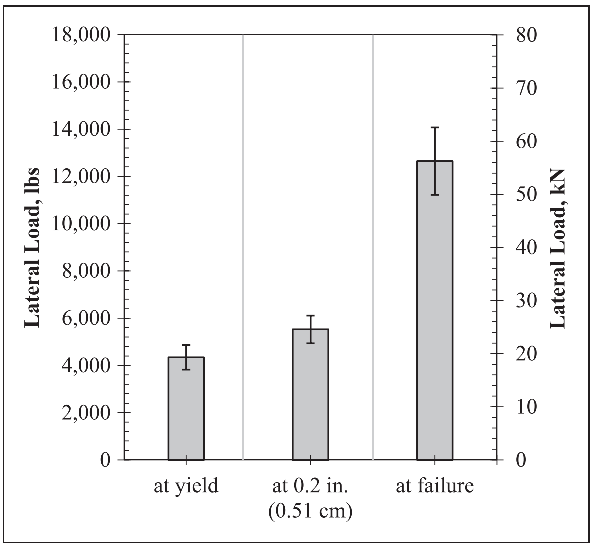

Figure 14. Lateral capacity at yield, 0.2 in. (0.51 cm) and at failure.

of the spikes, and were optimized to maintain computational and time efficiency. The spike pullout model consisted of a screw spike, with exact dimensions (refer to Figure 3), HDPE crosstie specimen, bottom steel plate for support, and upper steel plate for fixation. The model was assumed to display quarter symmetry in order to minimize the computational cost. Similarly, the lateral restraint model consisted of the same screw spike, HDPE crosstie specimen, bottom steel plate for support, and though steel rods with upper knots for fixation. The difference between the pullout and lateral restraint models lies in the boundary/symmetry conditions. In the pullout model, the fixation plate is placed in the same plane as the screw spike. The load is applied as a vertical displacement parallel to the vertical axis of the screw spike. In the lateral restraint model, the fixation knots are placed in a plane that is perpendicular to the screw spike and the load is applied as a vertical displacement perpendicular to the vertical axis of the screw spike. The geometry of the finite element model for spike pullout and lateral restraint are shown in Figure 15.

As mentioned earlier, the manufacturing procedure of the HDPE crossties, investigated in this study, creates a difference in the properties between the core and exterior regions of the cross-section. The properties and dimensions of both regions were investigated in detail by the authors in a previous work;[16] and those findings were implemented in this study; i.e. core region dimensions of 4×6 in. (10.2×15.2 cm) and the material properties presented in Figure 16 were used.

In the finite element models, eight-node isoparametric brick solid 185 elements were used to model all the solid geometries. They are defined by three translational degrees of freedom at each node. The element has the capability to undergo plasticity, stress stiffening and large deformations.[21] To optimize the calculation time, a fine mesh was used in regions of high stress gradient and a coarser mesh was used in other areas. Additional mesh refinement was applied to the areas close to the vicinity of the screw spike threads, based on the findings of Grewal and Sabbaghian,[22] in order to accurately represent the stress distribution around the thread. Moreover, the screw spike thread tips were slightly modified with small fillets to produce a circular contact at the tip of the threads. This technique was used to eliminate stress concentrations due to sharp contact edges

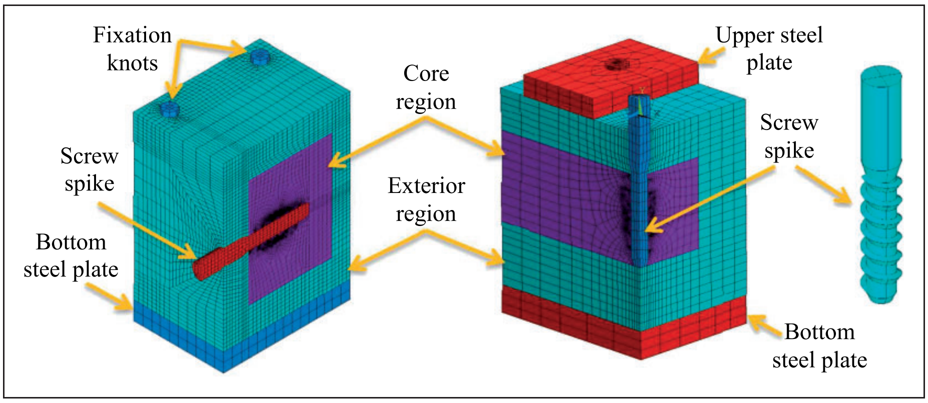

Figure 15. Description of the two finite element models; spike lateral restraint (left-half symmetry), and spike pullout (right-quarter symmetry).

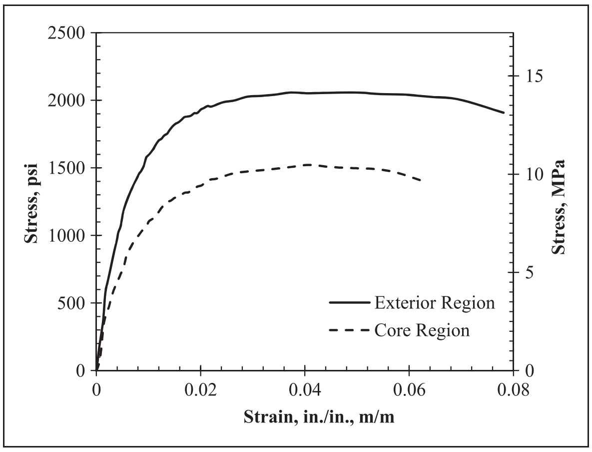

Figure 16. Stress–strain curves for both exterior and core regions of the HDPE crossties.

between the threads and the HDPE crosstie as shown in Figure 17.

To simulate contact between the steel spike, the HDPE crosstie and the steel plates; surface-to-surface, flexible-to-flexible contact elements were used in the model. The surface of the screw spike/steel plates were meshed with the elements of TARGE 170, and the surfaces of the HDPE crosstie were meshed with CONTA 174 elements. The boundary conditions and loading were identical to those applied in the experimental tests. The bottom steel plate was fixed at the bottom surface. For the spike pullout model, the loading condition was a vertical displacement of 0.2 in. (0.51 cm) applied to the top of the spike. Symmetric boundary conditions were applied to two inner planes, in order to account for quarter symmetry. The total number of elements in the models was approximately 32,200 elements. For the lateral restraint model, the loading condition was a vertical displacement of 0.3 in. (0.76 cm). It was applied at the top surface of the spike over an area of 0.2 $in.^2$ (1.29 cm^2) to account for the contact area of the loading device as shown in Figure 17. Similarly, a symmetric boundary condition was applied to the inner plane to account for the half-symmetry. The total number of elements in the models was 64,493.

Results of the Finite Element modeling

Figure 18 presents a sample of the results obtained in the modeling studies; the stress distribution at failure for the spike pullout model and deformation for the lateral restraint model at 0.25 in. (0.64 cm) deflection at the point of load application. For the spike screw pullout, it is apparent that the HDPE plastic in the vicinity of the threads experienced yielding due to the threads bearing on the plastic material. Failure occurred in the HDPE material at the top thread where the stresses exceeded the material's resistance; which was 2050 psi (14.1 MPa). Only the elements close to the threads reached the ultimate capacity, followed by large plastic strain before failure; i.e. pullout from the plastic. At failure, the shear stresses in the HDPE material near the threads reached 1170 psi (8.06 MPa), which is also significant. The stress value of the outer circumference surface of the spike can be much smaller than that at the inner diameter. In this condition, it can be deduced that the pullout failure occurred along a surface around the inner diameter of the spike, where the screw threads cut a cylinder formed by those failed areas.

For the lateral restraint model, the bearing of the spike on the HDPE material led to a complicated combined stress state of tension, compression and bending stresses. The bearing area below the spike was subjected to direct compression stresses whereas the HDPE around the sides was subjected to tensile stresses. The spike exhibited a bending behavior that occurred at the section with the smallest cross-sectional area; i.e. the start of the threads. The stress analysis showed yielding in the steel accompanied by significant deformation in the HDPE material around the spike, as shown in Figure 18. As observed in the experimental tests, the threaded section of the spike (the lower section) was straight through all the test phases and experienced negligible deformations. Figure 19 presents a comparison between the finite

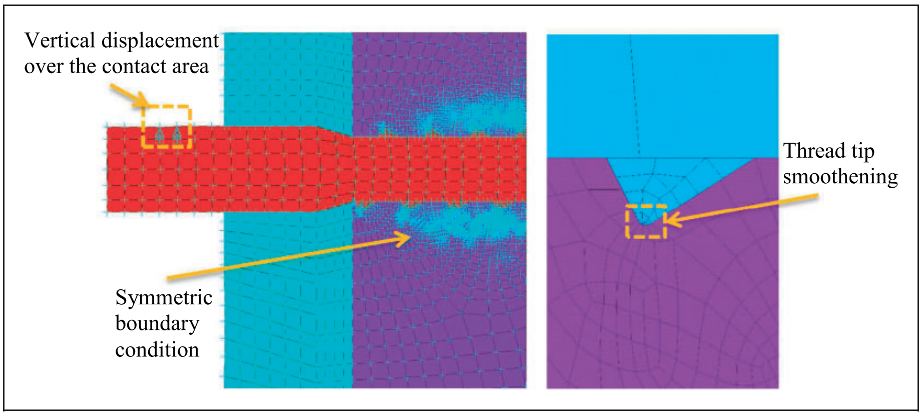

Figure 17. Load application for lateral restraint model (left); thread circular contact (right).

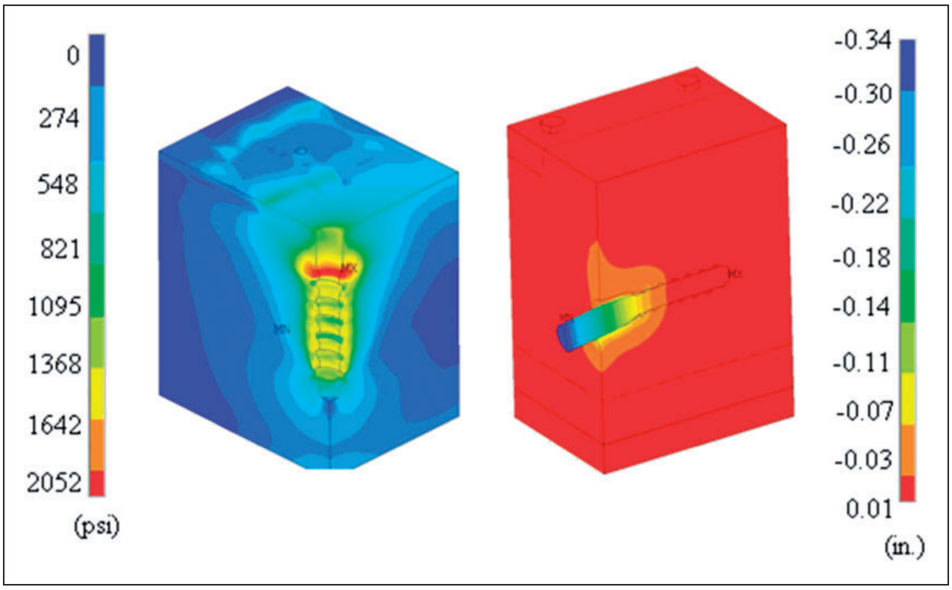

Figure 18. Stress distribution for the spike pullout model (left) and deformation for the lateral restraint model (right) (1″ = 2.54 cm & 1 psi = 6.9 kPa).

element models and the experimental testing, which was used to validate the finite element models.

Inspection of Figure 19 reveals a good correlation between the finite element models and the experimental data obtained from the testing program. The pullout model shows a major escalation of the curve at the initial stages of loading. When the system reaches the ultimate load, the curve exhibits a plateau. From the lateral restraint model, the model shows a consistent behavior with that of the average of the experimental test data. The load versus deflection curve shows a linear increase followed by a hardening behavior. The hardening behavior is due to the yielding of the screw spike and the HDPE material, which had a slightly increasing hardening behavior rather than a steady plateau. It was also found that the spike experienced zero displacement at the bottom and acted as a cantilever restrained at its base and bearing on the side of the plastic.

Summary and Conclusions

In this study, an experimental testing program that aimed to assess the behavior of railroad spikes typically used with HDPE composite railroad crossties was presented. It used static test methods recommended by the AREMA manual to address rail spike pullout and lateral restraint for both screw and cut. Finally, the development and calibration of a finite element model capable of simulating the behavior of the screw spikes and their interaction with the HDPE crossties was presented. Highlighted below are the findings and conclusions of this paper.

1. All the tested specimens surpassed the AREMA recommendations for screw and cut spike in polymer composite crossties. Moreover, the screw spikes exhibited a greater than expected performance, surpassing the minimum recommendations

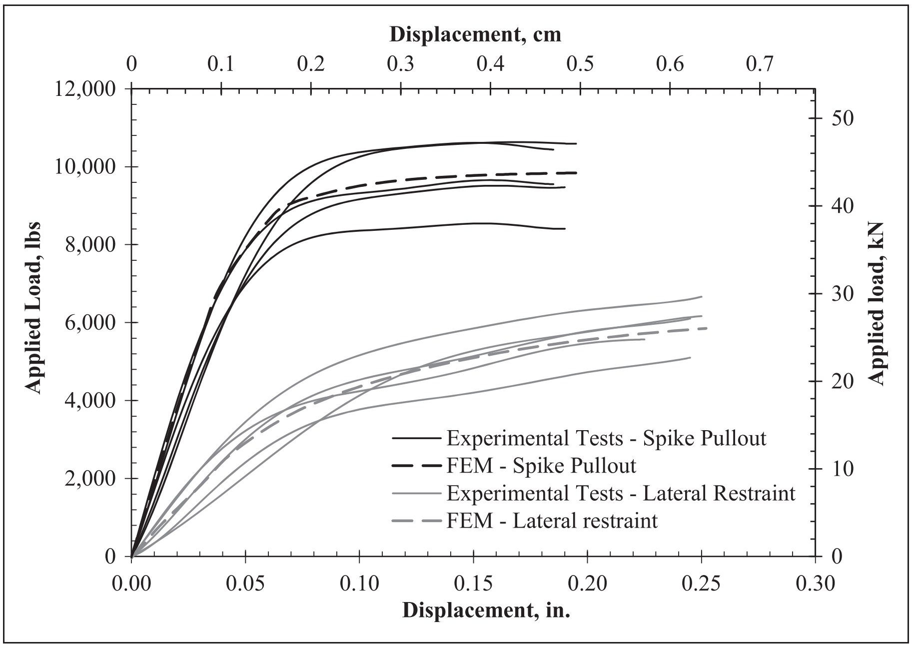

Figure 19. Finite element model (FEM) validation.

by a significant margin (up to more than 200%) and thusly are highly recommended for future implementation.

2. An optimal pre-drilling configuration was proposed for screw spikes; setup "D" (refer to Figure 3). This configuration exhibited the best holding power without either introducing stress concentrations or causing material build-up and bulging in the vicinity of the spikes. Pre-drilling did not affect the pullout capacity of cut spikes and is only recommended to achieve proper installation.
3. The slowest loading rate produced the most conservative spike pullout resistances. Therefore, it is recommended for use in the evaluation or characterization of spike pullout resistance in future applications.
4. At low temperatures, the pullout capacity significantly increased due to material hardening. Most intriguing, the pullout capacity of the specimens was not negatively affected, in a significant way, by elevated temperatures as material softening was compensated by confinement due to thermal expansion/squeezing.
5. Both the crosstie and the spike acted together as a composite section when resisting lateral forces. Moreover, the observed failure was ductile, as evident by the absence of cracks and the prolonged phase of yielding/strain hardening that the specimens experienced. Additionally, there is a significant reserve capacity in the system after yielding.
6. The constructed finite element model showed good accuracy and correlation with the experimental results. The model was optimized and refined to have an optimal computational time and cost while maintaining accuracy. This model will be implemented in future studies in this research program.
7. It should be noted that the creep behavior for this HDPE material is still under investigation, and that a detailed understating of this behavior is required in order to achieve a safe implementation in real applications with long loading and exposure periods.

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Declaration of Conflicting Interests

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