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EFFECT OF LONGITUDINAL FASTENER STIFFNESS AND FASTENING SYSTEM LOADING

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ABSTRACT

Over the past 20 years, there have been at least 10 derailments due to spike fatigue failures in North America. Researchers believe that fatigue failure is caused by overloading of the spike through a combination of lateral and longitudinal loads. The literature also indicates that vertical load fastener friction must also be considered when estimating failure locations. Further, though there has been research to quantify the vertical, lateral, and longitudinal fastener forces in track that has experienced spike failures, there is a need to account for additional fasteners and track locations. Additionally, because the fastening system can affect the track stiffness, laboratory experimentation was performed to quantify stiffness of multiple fastening systems. This data was input into an analytical model to quantify the effect of stiffness on fastener loading. The laboratory data indicates that there is significant variance in fastening system stiffness within, and between, systems. However, this variation in fastener stiffness has minimal effect on the load transferred to the fastening system. More work is needed to validate this in the lab or field given variability within a system could lead to stress concentrations that are not fully captured using the current idealized analytical method. The characterization of longitudinal stiffness of multiple fastening systems as presented within this paper can be used to advance track mechanistic-empirical design and improve rail neutral temperature prediction and track buckling models.

Keywords: fastening systems, elastic, anchored, stiffness, laboratory, longitudinal load

NOMENCLATURE

k_a	Longitudinal track modulus
k_p	Rail-tie stiffness
k_b	Tie-substructure stiffness

1. INTRODUCTION

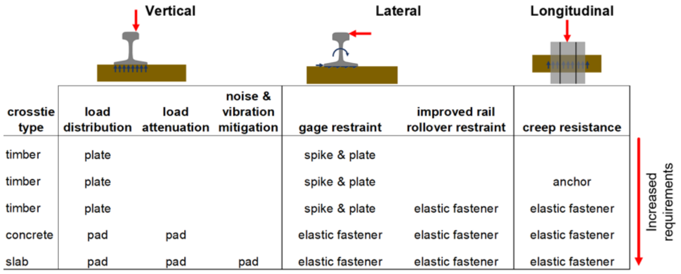
94% of the world's railroad infrastructure is supported by ballast [1]. A ballasted track system is comprised of the rail, fastening systems, crossties, ballast, sub-ballast, and sub-grade [2]. The fastening systems are used to anchor the rail to the crosstie controlling lateral and longitudinal movement. This results in fastening systems having to transfer vertical, lateral and longitudinal loads to the track structure.

Fastening systems have evolved over time to withstand increased loading demands or provide greater track strength as stricter limits are placed on geometrical tolerances. Table 1.1 below provides an overview of the role of fastening system components and how they can change in response to increasing vertical, lateral, and longitudinal forces or the need for increased track strength.

The misapplication of these fastening systems results in track strength deficiencies such as plate cutting, rail seat deterioration, rail roll over, and rail pad movement which then can lead to component failures.

Spike fatigue failure is one example of such a component failure. Over the past 20 years, there have been at least 10 derailments due to spike fatigue failures within timber crossties using elastic fastening systems in North America [4]. These spike fatigue failures reduce the safety and integrity of the track and require manual walking inspections thus increasing risk to employees. Recent studies have shown that spike fatigue failures within elastic fastening systems, unlike anchored systems, transfer additional longitudinal load to the spike [4], thus leading to higher magnitude resultant spike loading. Further, because of the elastic fastener attachment of the rail to the plate, the wave action of the rail as explained through beam on elastic foundation (BOEF) principles, leads to the separation of the tie-plate and the crosstie. This separation eliminates friction at this interface thus leading to most of the longitudinal load being transferred to the spike directly [5]. Fatigue failures are almost exclusively found in environments that are subjected to high lateral loads (curves, special track work, etc.) [6]. Therefore, researchers believe fatigue failure is caused by overloading the spike through a combination of lateral and longitudinal loads transferred to the spikes [5].

Table 1.1: Requirements of track fastening systems as a function of increasing demands



	Vertical			Lateral		Longitudinal
crosstie type	load distribution	load attenuation	noise & vibration mitigation	gage restraint	improved rail rollover restraint	creep resistance
timber	plate			spike & plate		
timber	plate			spike & plate		anchor
timber	plate			spike & plate	elastic fastener	elastic fastener
concrete	pad	pad		elastic fastener	elastic fastener	elastic fastener
slab	pad	pad	pad	elastic fastener	elastic fastener	elastic fastener

Dersch et al. [7] recently noted that quantification of lateral and longitudinal fastener loads is not sufficient in estimating where failure would occur. Rather, the vertical, lateral, and longitudinal loads and an estimate of the friction at the tie-plate and crosstie interface must be quantified. This is because the vertical load and fastener friction has been shown to govern the load required to exceed the threshold for failure.

To this end, Dersch et al. quantified vertical, lateral, and longitudinal fastener loads in the field at a location that had experienced spike fatigue failures[8]. However, this data only represents one location and one type of fastening system. Thus, further quantification is required to account for various fastening systems used within railroad infrastructure.

It is hypothesized that the variability in fastening system can lead to variations in track stiffness and in-turn, load transfer. One example why fastening system variability exists is that to manage rail creep, or longitudinal rail movement [2], anchors or elastic fasteners can be used. Further, these fastening systems installed can use plates of varying size, shoulders, spike quantity and patterns.

Therefore, this paper quantifies the longitudinal stiffness of various fastening systems and quantifies how fastening system stiffness affects load transfer. Quantification of fastener stiffness occurs through the execution of controlled laboratory experiments using a bi-axial load frame.

This data can be used to improve future fastening system designs to mitigate spike fatigue failures and other force transfer deficiency challenges. Further, this data can be used to improve the accuracy of track models that predict distribution of rail stress and track buckling strength.

In addition to quantifying the effect of fastener stiffness on spike loading demand, quantification of fastening system stiffness will also provide an input that could be used within the proposed mechanistic-empirical (M-E) railroad track design procedure which is currently being developed [9]. This M-E concept, which is akin to the methodology currently used in pavement design (i.e. mechanistic empirical pavement design guide (MEPDG)) [10] has been developed and advanced by researchers within the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign (Illinois) since 2013 [11].

2. MATERIALS AND METHODS

2.1 Laboratory Experimentation Overview

The longitudinal fastening system stiffness was quantified for both an elastic fastening system as well as an anchored fastening system. This quantification was conducted following a modified longitudinal load restraint test as recommended by AREMA [12]. Experiments were performed on a single rail seat using a bi-axial load frame as seen in Figure 1.

The modified procedure was executed in the following steps. A longitudinal load was applied to the rail continuously, without shock, until slip of the rail occurred. The load was applied at approximately ¾" above the bottom of the rail base. Throughout the duration of the load application, the rail displacement and longitudinal load were recorded. Each setup was comprised of a timber crosstie, spikes, plate, and either an elastic fastener (eclip) or anchor. This allowed for the quantification of fastener stiffness variance for both eclip only and anchor only fastening systems (Figure 2).

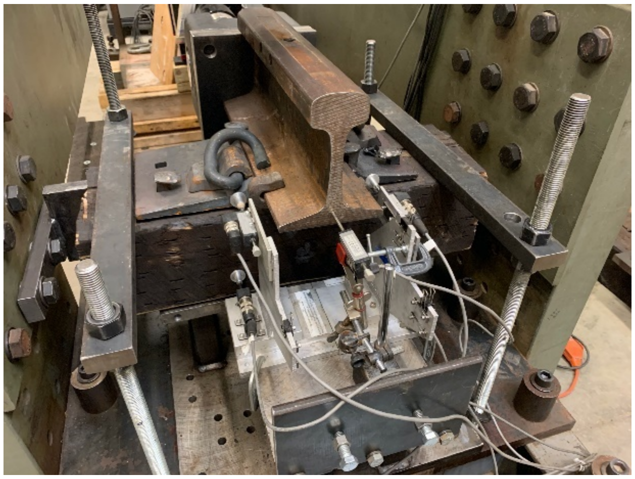


FIGURE 1: LONGITUDINAL STIFFNESS EXPERIMENTATION SETUP

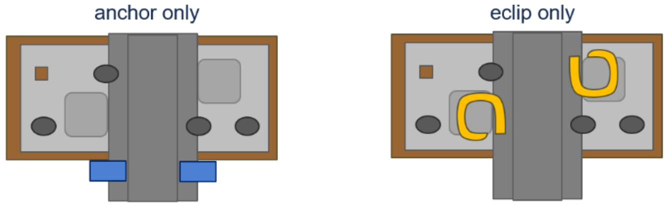


FIGURE 2: EXPERIMENTATION NAMING CONVENTION

2.2 Fastening System Longitudinal Stiffness

As mentioned, the load and displacement were recorded for the duration of the experiment. These values were used to quantify the stiffness of each system. Stiffness was defined as the slope of the load vs displacement data for each fastening system ranging from 500 to 2,500 lb. of applied longitudinal load. This region was used for longitudinal stiffness quantification because it was within the elastic region of each fastening system as pictured in Figure 3.

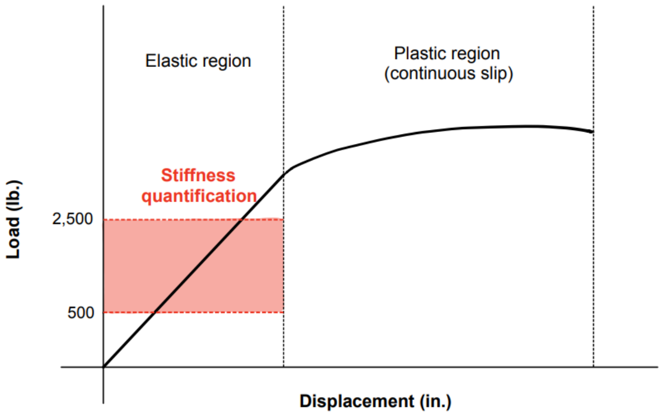


FIGURE 3: SAMPLE LOAD VS DISPLACEMENT PLOT

2.3 Analytical Modeling Overview

To quantify the effect of fastener stiffness on fastener load an analytical model was used. Trizotto et al. [13] was able to develop a linear analytical model that quantifies rail seat response when subjected to a train pass using a quantified number of locomotives, tractive effort and ballast stiffness. This 1D analytical model expanded upon the approach presented by Kerr [14]. This model was inputted with the variances in fastener stiffness recorded from the laboratory data and outputted the load variance that can be distributed to a single rail seat during a three locomotive train pass.

3. RESULTS

3.1 Fastener Stiffness Variance

Three replicates were quantified using the modified longitudinal load restraint test of each fastening system.

The variance of fastener stiffness was quantified and is presented in Figure 4. Anchored fastening systems exhibited stiffness values ranging from 15-20 kips/in. with a mean stiffness of 20.2 kips/in. and variance of 26.8 kips/in. The elastic fastener exhibited stiffness values ranging from 21-134 kips/in. with a mean stiffness of 62.3 kips/in. and variance of 1,976.5 kips/in.

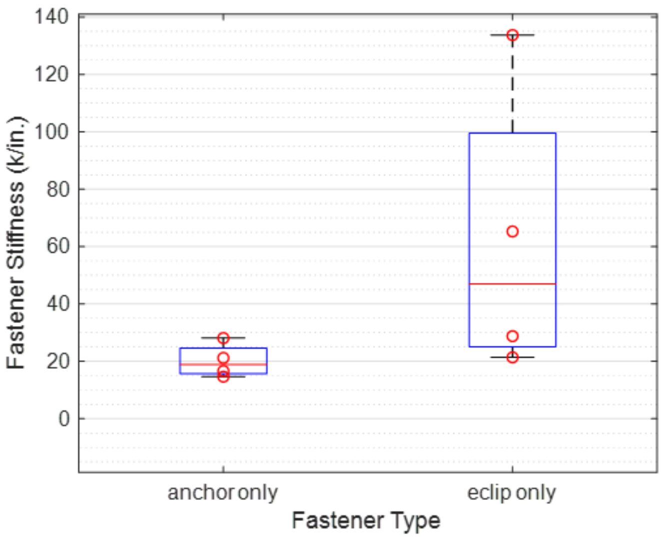


FIGURE 4: FASTENER STIFFNESS VARIANCE

Therefore, the data indicates that the elastic fastening system tested had a three times greater stiffness than the anchor only system. The literature shows that as track stiffness increases the fastener load also increases [13].

3.2 Rail Seat Load Variance

The quantified fastening system stiffness values were input into the analytical model developed by Trizotto [13]. For this exercise, it was assumed that three locomotives with 10 kips/wheel of tractive effort applied the load to track that had a longitudinal ballast modulus of 2 kips/in./in. The longitudinal track modulus was calculated using Equation 1 below [15].

$$\frac{1}{k_p}+\frac{1}{k_b} \qquad (1)$$

The resulting fastener (rail seat) load was quantified and shown in Figure 5. Anchored fastening systems exhibited loads ranging from 1,222 – 1,285 lb. with a mean load of 1250.5 lb. The elastic fastener exhibited loads ranging from 1,261-1,370 lb. with a mean load of 1315 lb.

As can be seen, the variance in fastener stiffness was not translated to a variance in rail seat loads. Even with a greater stiffness variance compared to anchored fastening systems, both elastic and anchored fastening systems experienced minimal rail seat load variance. The difference in average magnitude of rail seat load between anchored and elastic fasteners was only 64.5 lb.

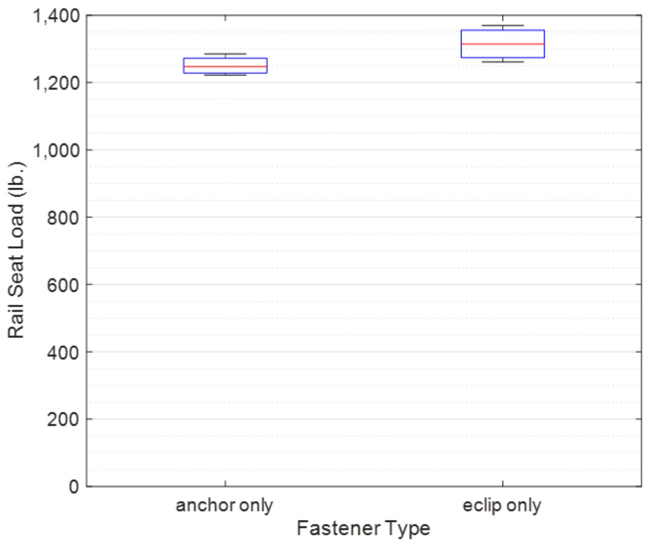


FIGURE 5: RAIL SEAT LOAD VARIANCE

3.3 Discussion

The quantification of fastener longitudinal stiffness led to the findings that elastic components results in both greater magnitudes and variance of fastener stiffness. Anchored fastening systems had smaller stiffness variance but less than half the magnitude of stiffness compared to elastic fasteners. This is likely because the elastic fastener toe load provides higher axial stiffness compared to the anchor bearing on the timber crosstie.

Elastic and anchored fastening system stiffness variance resulted in minimal variance in rail seat loads. This is likely because ballast longitudinal track modulus of 2 kips/in./in. controlled rail seat stiffness. Using Equation 1 above, a sensitivity analysis was performed to quantify the effect of changes in component (e.g. ballast or fastener) stiffness on track stiffness. The data from this analysis (presented in Figure 6) shows that increasing the fastener stiffness by a factor of 7 while maintaining the ballast stiffness led to an increase in track stiffness of 3. Further, when tripling the fastener stiffness from 20 kips/in. (mean of anchored system) to 60 kips/in. (mean of elastic system), there is only an increase of 80%. Trizotto et al. [13] showed that a quadrupling of track stiffness led to ~50% increase in fastener force. Therefore, it can be concluded that track stiffness is less sensitive to the increase in stiffness of a single component and rather controlled by the lowest stiffness value. Further, without a significant increase in track stiffness, the fastener load is not expected to increase significantly.

The results provided should be investigated further given the limitations of the 1D model as described by Trizotto [13]. That is, this model only accounts for the linear approximation of the load-displacement response of the track, is applicable to open track, does not allow for any temperature gradients, and is fixed rail at both ends. Further, the stiffness is not variable throughout the model (i.e. the stiffness is constant for all fasteners). Keeping these limitations and simplifications in mind, the loads under revenue service traffic could be different. Thus, more work in the lab or field is needed to ensure that variance in fastener stiffness results in minimal variance in load distributed to a single rail seat.

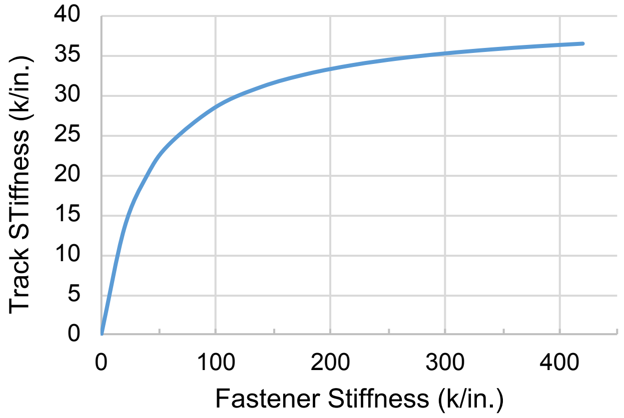


FIGURE 6: EFFECT OF FASTENER STIFFNESS ON TRACK STIFFNESS

4. CONCLUSION

To reduce the risk of fastener failures due to overloading (e.g. spike fatigue failures, etc.) quantification of vertical, lateral, and longitudinal loads is needed to improve current track design methods. Therefore, a laboratory study was undertaken to quantify the longitudinal stiffness of multiple fastening systems and quantify how this change in stiffness affects the fastener loads. The laboratory data indicate that while there is significant variance in fastening system stiffness within, and between, systems, this variation has minimal effect on the load transferred to the fastening system. However, more work is needed to validate this within the lab or field given variability within a system could lead to stress concentrations that are not fully captured using the current idealized analytical method. Though the loading difference is not significant even with the significant stiffness variation quantified, the characterization of longitudinal stiffness of multiple fastening systems as presented within this paper can be used to advance track mechanistic-empirical design principles as well as improve rail neutral temperature prediction and track buckling models.

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