Advancements in Fastening System Design for North American Concrete Crossties in Heavy-Haul Service

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ABSTRACT

As freight car axle loads and cumulative gross tonnage increases, not to mention the development of high-speed passenger rail systems; the need for improved concrete crossties and fastening systems in North America is becoming increasingly important. In addition to increased service demands, poor performance of the fastening system is often correlated to the occurrence of rail seat deterioration (RSD), one of the primary maintenance concerns with concrete crossties on North American heavy-haul railroads. Reducing life cycle costs of concrete crosstie fastening systems is of paramount importance to the railway industry to ensure the continued acceptance of concrete ties as a viable means of rail restraint. Recent advancements in fastening system design for concrete crossties in heavy haul and passenger service in North America stem from research and testing addressing current problems the industry is facing, including RSD and insufficient rail restraint. This paper includes a review of fastening system characteristics and performance criteria, as well as a summary of previous research on fastening systems. Full-scale laboratory testing of concrete crossties and fastening systems is underway at the University of Illinois at Urbana-Champaign (UIUC) to understand the performance of various components and materials in the fastening system: including, surface treatment of the rail seat, crosstie pads, insulators, clips, and shoulders. Preliminary full-scale testing results show that epoxy, which is applied to some rail seats, is worn away more quickly than previously expected. Additionally, tests have been designed to address moisture conditioning of insulators and its affect on the performance of the fastening system.

INTRODUCTION

The purpose of a railway crosstie (hereafter referred to as a "tie") is to support and transmit axle loads from the rail to the next layer of the track structure (typically the ballast) with a reduction in pressure. The tie, which is embedded in the ballast, anchors the track against lateral, longitudinal, and vertical movement (*1*). The loads acting on a concrete tie depend not only on railcar axle loads and tie spacing, but also on the size of the rail, its vertical stiffness, and the properties of the rail fastening system (*2*).

Concrete tie fastening systems are comprised of various components and materials designed to safely transmit forces exerted by the rail to the concrete tie while restraining the rail to the proper gauge and cant as required by the Federal Railroad Administration (FRA) and individual railway engineering maintenance standards. Forces acting on the fastening system are vertical, lateral, rotational (both planes), and longitudinal, and are the result of repeated loading cycles from passing axles, as well as longitudinal stresses in the rail (Figure 1). Fastening system components are constructed from a variety of materials (with variable properties) to securely attach the rail to the tie and properly attenuate and/or transfer loads.

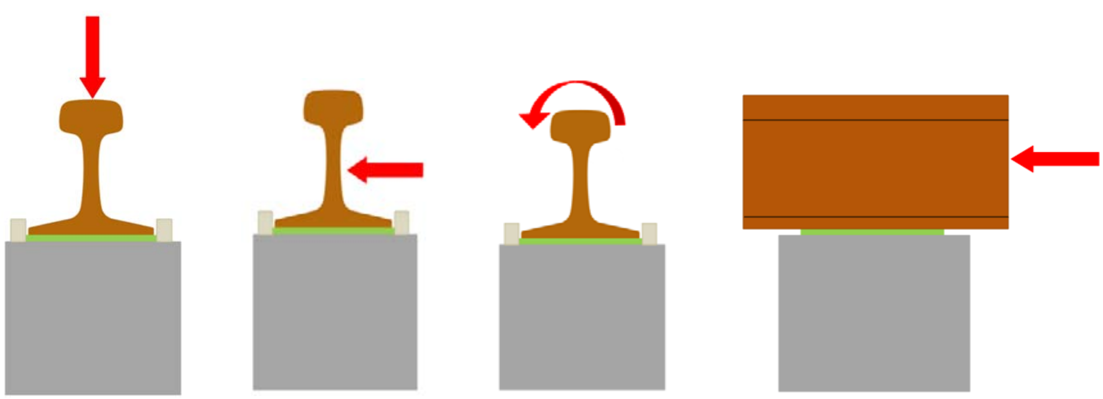


Figure 1: Vertical, lateral, rotational (both planes), and longitudinal forces that the fastening system and rail seat are subjected to under rail vehicle and thermal loading

Modern elastic fastening systems are also designed to operate in conjunction with railway signaling systems. In areas where track circuits are used, the fastening system should provide electrical insulation for the rail (relative to the tie) in order to provide electrical impendence, which is accomplished through the use of insulators. Ties should also facilitate load attenuation to minimize the pressures exerted on the ballast at the bottom of the tie and mitigate impacts from vibration, which may lead to abrasion and crushing damage of fastener components and the rail seat.

Stiffness of Fastening Systems

The stiffness of a fastening system is one of the most important characteristics that directly impacts the fastening system's long-term performance under repeated axle loading. Stiffness closely relates to the degree of wear fastening system components experience, and the resulting life of the system. The dynamic rail / fastening system interaction can be viewed as a complete set of springs and dampers (Figure 2). The stiffness of each component determines how much the rail is allowed to move within the rail seat (*3*). For the purpose of studying fastening system component behavior, it is possible to isolate a force vector and analyze how each fastening system component will perform under a discrete loading event.

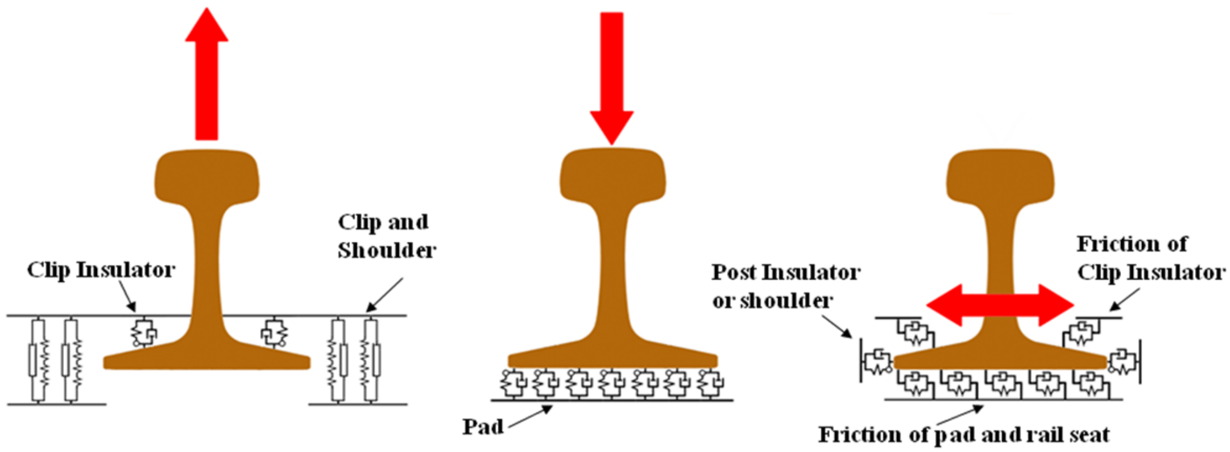


Figure 2: The dynamic interaction of the rail, tie, and fastening system

Types of Fastening Systems

Fasteners are typically classified into two categories: rigid and elastic (*1*). Rigid fasteners refer to systems developed in the early 1900s that rigidly bolted the rail to the tie (*4*). Rigid fasteners were superseded by elastic fasteners, which allow more *resilience* relative to rigid fasteners. *Resilience*, which is also referred to as elasticity, is a proxy for the amount of movement the rail experiences within the rail seat (*5*). By design, most of today's fastening systems allow some resilience to facilitate load attenuation. Within elastic fastening systems, there are large variations in design resilience and the degree of resilience that is tolerated in the field.

Elastic fastening systems have four primary components; an imbedded anchor, a clip or spring, an insulator, and a pad (or pads) between the rail and concrete tie (*2*). Each of these elements is designed to perform a specific function within the fastening system. The clip or spring is designed to apply an appropriate clamping force (toe load) to the base of the rail. The clamping force is one factor that determines the rigidity of the fastening system (*6*). The anchor is designed to hold the clip or spring to the tie, and is cast-in during the tie manufacturing process. The tie pad is designed to properly attenuate the loads exerted by the rail onto the tie, and should be constructed of a material that is averse to wearing the concrete rail seat and the base of the rail. The insulator is designed to properly insulate the fastening system from the rail to facilitate reliable operation of the signal system.

Typical elastic fastening systems designed for heavy-haul service can be classified by how they develop their clamping force at the base of the rail. Clamping forces can be developed by either bolting or screwing an elastic clip into a cast-in shoulder. Alternatively, a clip can be driven into a cast-in shoulder, which forces the clip to hold the base of rail with the prescribed clamping force. We will refer to these two system as “bolt or screwed clip systems” (Figure 3a) and “driven clip systems” (Figure 3b).

(a) (b)

Figure 3: (a) Example of a bolted or screwed clip fastening system

(b) Example of a driven clip fastening system

In bolted or screwed clip systems, the clip is anchored by a bolt or screw which is threaded into an insert that is cast into the concrete. Bolted or screwed clip systems generally have the advantage of allowing field adjustment of clamping forces. Additionally, many designs allow for efficient replacement of components in the field (clips, bolts, and/or screws). With some bolted clip systems, it is possible to vary rail height in order to maintain proper track geometry. A disadvantage for some bolted or screwed clip systems is that their installation tends to be operator-sensitive, thus it is difficult to achieve a consistent clamping force at every rail seat without the use of specialized tools or machinery (*2*). In some bolted or screwed clip systems, it is important to identify whether the movable portion of the clip is fixed onto the bolt or screw. If it is, the movable portion of the clip tends to loosen the bolt or screw and the fastening system will need to be inspected to ensure there is no loss of torque.

Driven clip systems generally include a cast-in steel shoulder (or anchor) and a clip, which is driven into the shoulder to achieve the required clamping force. These systems tend to be less operator-sensitive since their correct installation can be confirmed by visual inspection. Captive driven clip systems (which are fully assembled with the tie at the tie manufacturing plant) are generally less labor-intensive to install and remove. One possible disadvantage of driven clip systems is the inability to make adjustments in the field to vary the clamping force. Table 1 compares the clamping force and provides the year of introduction for common concrete-tie fastening systems used in North American heavy-haul service.

Table 1: Clamping force and year of introduction for common concrete-tie fastening systems used in North American heavy-haul service

Classification	Manufacturer	Model/ System	Nominal Clamping Force per Rail Seat (lbs)	Year of Introduction in North America
Screwed Clip	Vossloh	W with SKL 1	4100	1987
Screwed Clip	Vossloh	W 14 HH with SKL 14R	5400	2006
Screwed Clip	Vossloh	W 30 HH with SKL 30	5400	2009
Driven Clip	Pandrol	PR	4000	1974
Driven Clip	Pandrol	E-Clip	5500	1986
Driven Clip	Pandrol	Safelok I	4800	1988
Driven Clip	Pandrol	Safelok III	5800	2000
Driven Clip	Pandrol	Fast Clip	5500	1992
Driven Clip	Unit Rail	U 2000 with U2100 shoulder	4800	2001

Objective Comparison of Fastening Systems

Given the wide variety of fastening system designs, a standard method for objectively comparing the performance of fastening systems is needed to accurately analyze design variations. Fastening systems may vary in durability, elasticity, ease of installation, ease of maintenance, amount of maintenance required, clamping force, contact area with the rail, cost, design life, and whether or not they provide a vandal-proof design.

One way to objectively compare fastening systems is to analyze the elasticity of each system. The elasticity of a fastening system refers to the amount of rail movement allowed within the rail seat area, or the “working range” of the fastening system. The elasticity of a fastening system provides a measure for how they should perform in the field. In addition to objectively comparing fastening systems on the basis of their elasticity, the durability of fastening system components should also be compared when comparing systems. The durability of a fastening system refers to its ability to resist wear.

Current Problems with Fastening Systems

Previous concrete tie research at the University of Illinois at Urbana-Champaign (UIUC) included a survey of concrete tie experts at major North American freight railroads, regional and shortline railroads, and commuter and transit authorities designed to obtain information about their current problems with concrete ties (*6*). The survey was formulated as a failure mode effect analysis (FMEA), and the results showed that RSD and fastener system wear are the most critical problems experienced by North American freight railroads (Table 2). It is important to note that both of these concrete tie problems occur in the rail seat area and they are often considered to be concurrent failure modes.

Table 2: Rankings of concrete tie problems according to North American freight and passenger railroad operators (6)

Concrete Tie Problems	Rank (Average Value)			
	All Responses	Major Railroads	Regional & Shortline	Commuter & Transit
Shoulder/ fastener wear or fatigue	**1**	**2**	**1**	**3**
Rail seat deterioration (RSD)	**2**	**1**	**--**	**7**
Cracking from center binding	**3**	**4**	**3**	**5**
Derailment damage	**4**	**3**	**3**	**8**
Tamping damage	**5**	**5**	**2**	**2**
Other (ex: manufactured defect, installation damage)	**6**	**7**	**--**	**1**
Cracking from dynamic loads	**7**	**5**	**--**	**4**
Cracking from environmental or chemical degradation	**8**	**8**	**5**	**6**

Many fastening system problems, and consequently concrete tie problems, were traced back to the stiffness of the fastening system. For the purpose of this discussion, the terms *very elastic* and *very rigid* are used to describe the overall behavior of a particular fastening system or fastening system component. Specifically, the terms define whether the component will allow (very elastic) or not allow (very rigid) rail movement within the rail seat. In general terms, a very elastic fastener, used in a system with a very soft pad (e.g. rubber), will result in lower loads on the components and on the concrete rail seat (*7*). Conversely, a more rigid fastening system with a stiffer pad (e.g. hard polyurethane) will cause higher loads on the concrete rail seat.

Accelerated component wear can occur when concrete ties have elastic fasteners that are not designed with properties commensurate with the tie pad. For example, a system with a very elastic fastener but a very rigid pad, or vice versa, may see increased component wear due to the relative motion between the two components. A soft pad (e.g. rubber) is capable of following all movements of the rail within the rail seat under loading cycles, which is typically not observed with stiffer pad materials. If a very elastic fastener is used in conjunction with a stiff pad, the rail will not have continuous support during loading cycles, which can cause unwanted impacts and accelerated component wear. Conversely, if a very rigid fastener is used in conjunction with a very soft pad, the rail will not be significantly displaced within the rail seat, but the softer pad will wear in an accelerated manner. Wear on insulators, clips, shoulders, and pads can lead to loss of clamping force, loss of gauge, loss of cant, and RSD, which ultimately results in increased fastener and rail seat maintenance between rail replacement cycles and a higher life cycle cost for ties and fasteners.

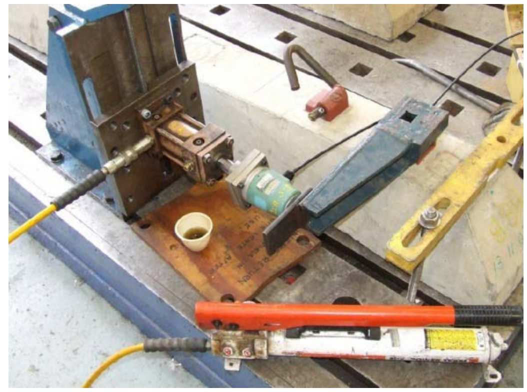
The occurrence of rail seat deterioration (RSD) is related to fastening system elasticity (*7*). With elastic fastening systems that are designed with significant elasticity, energy will be dissipated through rail movement at the rail seat, thus the rail seat will experience lower loads. However, rail movement at the rail seat can allow the intrusion of abrasive fines between components, which tend to accelerate fastener component wear. Rigid fastening systems will dissipate less energy at the rail seat, thus the rail seat will experience higher loads. Higher rail seat loads are not a problem if the concrete tie and rail are designed appropriately, but higher pressures will be transferred to the ballast, which may cause ballast crushing or other problems. In summary, there is a trade-off between fastening systems based on their elasticity. More elastic fastening systems tend to have accelerated component wear (which can cause RSD and other problems) while more rigid fastening systems may cause problems such as rail breakage, pumping, or ballast crushing.

Research by Fastening Systems Manufacturers

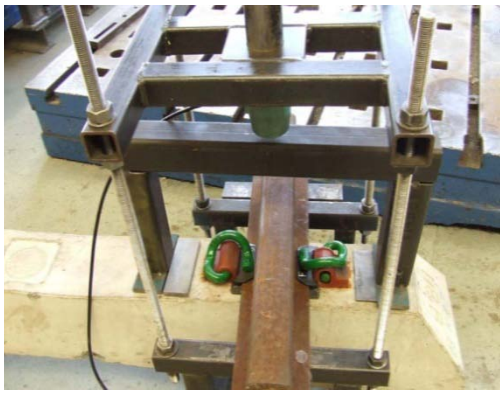
There has been significant research undertaken by fastening system manufacturers to address current heavy-haul concrete tie problems. Among the fastening manufacturers that have developed research and testing programs are Pandrol (headquartered in Britain), Vossloh (headquartered in Germany), and Unit Rail (headquartered in the US).

Pandrol's recent research into fastening system design and performance includes testing on shoulders, clips, pads, insulators, and the complete fastening assembly (*8*). Shoulder extraction (Figure 4a), shoulder torsional resistance (Figure 4b), tie pad attenuation and performance, fastening uplift (Figure 4c), fastening system longitudinal restraint (Figure 4d), repeated load test (Figure 4e), lateral load restraint, and electrical impedance (Figure 4f) are examples of Pandrol's laboratory testing. Pandrol's testing was conducted using protocols contained in either AREMA Chapter 30 (Ties) or European Standard EN-13481-8 (*9, 10*).

(a)



(b)



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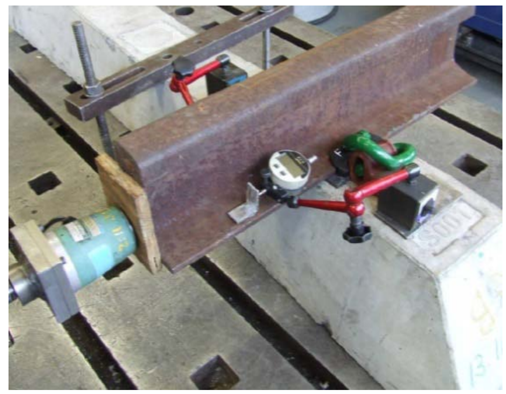


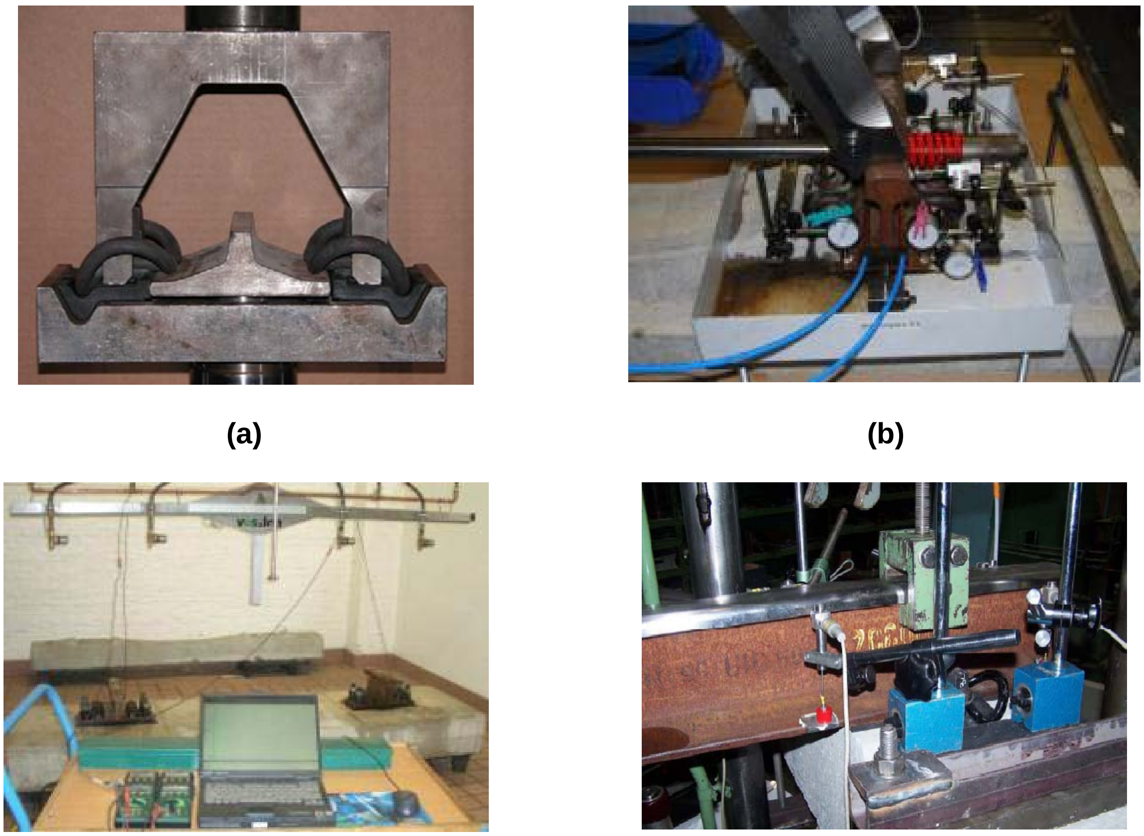
(d)

(e)

(f)

Figure 4: Pandrol concrete tie fastener testing: (a) shoulder extraction, (b) shoulder torsional resistance, (c) fastener uplift, (d) longitudinal rail restraint test, (e) repeated load test, and (f) electrical impedance

Vossloh’s recent fastening system research and testing includes performance and fatigue tests on tension clamps (Figure 5a), repeated load testing aimed at prevention of rail seat deterioration (Figure 5b), longitudinal rail restraint, torsional resistance (twisting of the rail in the fastening system), pad stiffness, electrical resistance (Figure 5c), and determination of clamping force (Figure 5d) (*11*). Vossloh’s aforementioned testing is specified in either AREMA Chapter 30 or European Standard EN-13481-8 (*9*, *10*).



(a) (b) (c) (d)

Figure 5: Vossloh concrete tie fastener testing: (a) fatigue tests on tension clamps, (b) repeated load testing, (c) electrical resistance testing, (d) clamping force measurement

Unit Rail's recent research on improved fastening systems includes testing of full-scale fastening system assemblies and ties, abrasion resistant components, rail seat surface treatments, tie pad durability and attenuation, as well as shoulder, insulator, and spring clip testing. Tie pad durability and attenuation are tested with varying shape factors in an attempt to increase longevity and load attenuation, and lower the cost of assembly manufacture. This research is aimed at understanding the properties and material combinations for varying pad assemblies, which will help determine the specific loading environment that maximizes the life cycle of each pad (Figure 6).

(a) **(b)**

Figure 6: Unit Rail testing of pad stiffness and compressibility testing

Research on insulators has included testing to understand the relationship between insulator moisture content (moisture conditioning) with the insulator's compressive strength and overall performance. Among the insulator materials being tested by Unit Rail are materials with no moisture absorption properties. Unit Rail is currently performing research on alternative methods of insulating the fastening system from the tie. Testing of spring clips with varying working ranges has also been performed in an attempt to understand the relationship between working ranges and overall performance of the fastening system. Unit Rail's fastening system research has been conducted using testing protocols included in AREMA Chapter 30 (Ties) (*9*).

Concrete Tie and Fastening Research at the University of Illinois at Urbana-Champaign

Research aimed at gaining a greater understanding of the mechanisms behind rail seat deterioration (RSD) is currently underway at the University of Illinois at Urbana-Champaign (UIUC). Specifically, research to investigate the moisture-driven mechanisms including hydraulic pressure cracking, cavitation erosion, and hydro-abrasive erosion have been thoroughly investigated using models and experimental testing (*12*, *13*). Future research will be directed at investigating the mechanism of abrasion, thought to be a primary contributor to RSD. Additionally, full scale concrete tie and fastening system research and testing is underway at UIUC's Advanced Transportation Research and Engineering Laboratory (ATREL). Concrete tie and fastener testing equipment at ATREL includes a Pulsating Load Testing Machine (PLTM), which has the capability of objectively comparing the overall performance of the concrete crosstie and fastening system while changing key variables including the fastening system type, pad materials and geometry, rail seat surface treatment, concrete mix design, and the overall crosstie design. This research is sponsored by Unit Rail, Inc., a subsidiary of Amsted Rail Inc., and focuses on continued development of the captive clip insulator assemblies, which are installed at the tie manufacturing plant. In addition, the testing focuses on the post insulator and abrasion resistant tie pad assembly design.

The PLTM consists of three 35,000 pound (lb) actuators with a 10-inch stroke (Figure 7). It is used to simulate severe load conditions on concrete ties using AREMA Test 6 (Wear and Abrasion) to test the performance and durability of different fastening system components and determine an optimal level of load attenuation and pad durability, while reducing rail seat pressures.

(a)

(b)

(c)

Figure 7: (a) Full scale concrete tie and fastening system testing at UIUC,

(b) Vertical and lateral actuators connected to the loading head,

(c) The loading head at rest of the head of the rail

Advancements in Fastening System Design by Manufacturers

Fastening system designs have evolved to accommodate increased loads, speeds, and the overall increased performance requirements expected of the fastening system. Modern fastener designs typically focus on improving the overall performance of the fastening system by increasing the clamping force, increasing component fatigue limit, and by reducing installation costs (e.g. captive systems). Any advancement in fastening system performance must be undertaken to ensure the total life cycle cost of concrete ties is competitive to other tie materials.

Pandrol has performed several design modifications to their heavy-haul fastening systems throughout the years. The “PR” series fastening system, introduced in 1974, was one of the first driven clip systems used in concrete ties and is still in use today. The PR fastening system provides high fatigue limit components with lower clamping force compared to many newer fastening systems. After the PR system, Pandrol introduced in 1986 the “e” series clips. The e clips were the next design advancement as they offered a higher clamping force and a lower cost through the use more efficient clip geometry. “Safelok” I fasteners were acquired by Pandrol in the late 1980’s when Pandrol acquired the railroad division assets of the McKay Company. Pandrol developed the “Fast Clip” in 1992. Pandrol Fastclip is a fully captive system which was developed to reduce installation and maintenance costs. Pandrol’s Fastclip provides a high clamping force and can be used in passenger or heavy-haul freight service. Pandrol’s has also developed a fastener known as the “Safelok III”. The Safelok III system is pre-assembled at the concrete tie manufacturing plant. In this system, the pad, the side post insulators, the spring clip and the clip insulator are all captive. Captive systems allow for more secure transportation to site and either manual or automated track installation. Safelok III provides an increase clamping force compared to all of its predecessors and the same captive capability of the Fastclip, but with the use of a flat bar instead of a round bar.

Vossloh has also been making modifications to their designs. The “W HH” is a captive fastening system assembly for heavy-haul service and the “SKL” is the type of spring clip used for that particular fastening system assembly. The SKL 1 was developed in the 1960’s and was superseded by the SKL 14 in the 1990’s. The SKL 14 has a longer middle bend, which works as an anti-rollover device for the rail and has a higher fatigue limit than the original SKL 1. The SKL 14R is a variation of the SKL 14 with a thicker diameter and allows for a higher clamping force on the base of rail. With the development of the SKL 30 it was possible to further increase the fatigue limit and keep the toe load at a high level.

Unit Rail continues to develop the U2000 spring clip from a piece-meal elastic fastener clip into a fully captive elastic fastening system for all concrete tie applications. This clip is referred to as the “One-Unit” captive fastener. A new spring clip called the U6030, with more metal and a larger clamping force than the U2000, is also being developed. For this type of fastening system, the greatest bending moment occurs at the rear of the clips – away from the base of rail. The new clip U6030 has more metal in this region, and the extra steel reduces the stress level per unit area. In addition, the rear of the clip is the location where the clip fitting forces are applied, thus the likelihood of clip damage during fitting due to excessive forces is greatly reduced.

Preliminary Results from UIUC

Preliminary results from the full-scale concrete tie testing and research at UIUC’s ATREL, using different types of fastening systems and rail seat treatments, have shown that all rail seat surface treatments have failed to resist wear after extended loading cycles. After completion of each three-million-cycle test with epoxy treated rail seats, the epoxy on the field side has entirely worn away from the rail seat (Figure 8). Once the rail seat surface treatment is worn away from a portion of the rail seat, the behavior of the fastening system could be adversely affected due to the relative decrease in rail seat height with respect to the fastening system shoulder. This decrease in height could reduce the clamping force. The worn epoxy within the rail seat may also generate abrasive fines that have the potential to cause increased abrasion on rail seat pads and insulators. Further testing is needed to validate the preliminary results described in this section.

Field Side

Gauge Side

Figure 8: Worn rail seat surface treatment on the field side after 3 million cycles

CONCLUSIONS

As freight railcar axle loads increase in North America, the need for improved performance of concrete crossties and fastening systems is becoming increasingly important. The occurrence of rail seat deterioration (RSD), one of the primary maintenance concerns with concrete crossties on North American heavy-haul railroads, can also be correlated with the performance of the fastening system and concrete crossties. Significant research has been undertaken by universities, testing laboratories, and tie and fastening manufacturers, aimed at increasing fastening system component durability while making installation and maintenance more cost effective. Also, laboratory research has focused on understanding the mechanisms behind RSD and finding practical ways to prevent the occurrence of RSD. To meet the needs of the railway industry, extensive research and advancements are still needed, and they will most likely focus on the areas of fastening system component durability, concrete tie and fastening system cost effectiveness, and prevention of RSD.

FUTURE RESEARCH

Future research in the area of fastening system elasticity will include measurement and modeling of the rail seat pressure distribution with fastening systems of varying elasticity and an investigation of how the loading path is affected by the load distribution at the rail seat. Also, an analysis of how the pressure distribution underneath the concrete crosstie is affected with varying fastening systems elasticity will be conducted. In addition, we propose the development of a stiffness model to classify the fastening systems according to their elasticity and recommend the optimum stiffness for a pad should in order to properly attenuate the load to maximize component durability.

Future research in the area of rail seat deterioration (RSD) in concrete crossties will include the study of the crushing and abrasion mechanisms thought to contribute to RSD. The abrasion mechanism will be addressed through modeling and experimental testing. Research on this mechanism will lead to a better understanding of how concrete mix designs, tie pad materials, and other materials and tie design choices relate to one another and will help to maximize the effectiveness of the overall design of the tie and fastening assembly.

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TABLES

FIGURES