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Dilemma of Direct-Fixation Fastening Systems

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A short, nontechnical discussion of the shortcomings of present direct-fixation fastening systems is presented. The state of the art is reviewed, and some suggestions are made on corrective solutions to existing problems.

The phenomenon of the modern railroad track is a mixture of ingenuity, experience, and long trial and error. From the early years of the rail bolted to the flat stone sleepers to the modern integrated structure, there has always been a delicate balance between the mechanical and track design improvements. The problem, however, has always been the same: how to keep the train on the track and provide a low-maintenance running surface. The balance between the track and the train was radically tipped by the dieselization of the railroads and the economics of the maintenance of way so that the track no longer could support the loading forces or provide longevity of running surfaces.

This problem will ultimately be solved as problems in the railroad industry have always been solved. Fortunately, the industry now recognizes the folly of deferred maintenance and acknowledges the track-train relationship as a total system that must be treated as a whole if all of its parts are to operate successfully.

Today, with aid from the federal government, there are literally hundreds of research programs being undertaken in the academic and scientific community. The interface between rail and wheel is being studied; ballast, subgrade, and tie performance is being analyzed; and rail metallurgy is at the moment extremely important. Research in all of these areas can add dramatically to our fund of knowledge and greatly assist in future development of the railroad system.

One area included in these studies, and in my opinion a most important one, is the interface between the tie and the rail, the rail-fastening system. It is not the intent of this paper to analyze mathematically or theoretically the performance of this area of the structure but merely to point out, in general terms, the effect of the fastening system on the performance of the total track structure.

In the broadest sense, the rail-fastening system can

be defined as a device that can accurately position two rails with respect to each other and with respect to the earth below them. More specifically, rail-fastening systems are generally considered to concern the method used to affix the rails to the ties. Further, this device should have the capability to selectively absorb or transmit the various loads imposed on the track structure by the rail-wheel contact of passing trains. Without this capability, the remainder of the structure may be subjected to damaging forces that will require additional maintenance and perhaps shorten the life of the structure. However, without the input rail-wheel forces, the structure will also remain relatively inert. We may therefore assume that the fastening device will experience only those forces generated statically by thermal changes in the rail and dynamically by the wheel rolling over the rail.

If one conceptualizes in three dimensions a wheel moving along a rail, it can be seen that many forces are working in all three planes, the longitudinal, the vertical, and the lateral. There are three longitudinal forces. One is the static or thermal force, and the other two are dynamic and are caused by the wave action of the track and the drafting and braking forces of the train. The lateral force created by the wheel has now become a major concern in overturning rail and wheel climbing. The vertical forces are created in a downward direction by the wheel load and converted into an uplift force through the wave action of the track. Imposed on this is the vibration effect caused by the wheel on the rail. This effect has been much ignored because most vibration is short lived and of a greatly varying nature in terms of amplitude and frequency. It does, however, occur in the longitudinal, vertical, and lateral planes; in the lateral plane, it occurs more in curves than in tangent track.

Quantifying the various track loads is beyond the scope of this paper. Available data on the magnitude of longitudinal track loadings, for example, are highly variable. Each researcher has made measurements that he or she believes to be correct but that rarely agree with those made by fellow researchers. In a

personal survey, track engineers were asked what was the maximum static longitudinal pull-apart load in their track. The answers received ranged from 445 to 2670 kN [100 000–600 000 lbf (100–600 kip)], which indicates that we really do not know. On the other hand, it also points out that measurements made in one area are not necessarily always valid in other locations. At the present time, therefore, we use state-of-the-art numbers derived from the conventional tie plate, anchor, track spike concept in designing other fastening systems to suit specific needs. By designing to meet a given longitudinal restraint based on experience, without actually knowing the specific longitudinal load involved, we can assume that the system will work.

In present systems, however, there are two areas that are not only critical but are also being overlooked. These are the uplift of the track and the transmission of the intermittent vibrations through the fastener system to the substructure.

As a basis for discussion, I would go back to work done by Talbot (1) at the University of Illinois under the auspices and with the cooperation of the American Railway Engineering Association (AREA). This work is outstanding, since it did not depend entirely on mathematical hypothesis but rather included actual track measurements. By using existing theory, Talbot determined that the rail performed as a continuous beam on elastic supports and that the vertical movement of the crosstie varied with the elasticity of ties, ballast, and subgrade. This he defined as the track modulus. In addition, Talbot's investigators measured rail stresses and found that the passage of a wheel caused compressive stresses in the upper fibers of the rail but also that tensile stresses equal to approximately half of the compressive stresses occurred in the same location before and after the passage of the wheel. This stress reversal indicates that the rail is rising from its neutral position in front and in back of the wheel.

To join these two dissimilar facts, it was further shown that the higher the track modulus is, the greater is the stress reversal or uplift. As the track becomes softer or less rigid and the load is distributed further, the total downward deflection becomes greater and at some point the stress reversal ceases, only to become a variation in the compressive load. Zero, however, is never reached. From a practical standpoint, the worst condition would occur on a continuous surface, such as a rigid slab with a very rigid rail fastener. The initial failure of the fasteners at the Kansas slab test track and in earlier tests at the Pere Marquette track are two good examples of uplift.

How does the conventional railroad track handle this particular problem? The line spike on the tie, even though driven home, in most cases will shortly back off sufficiently to allow the rail to breathe on the tie or essentially to "float". In the conventional structure, if this does not occur, the tie lifts in the ballast, creating the "pumping" phenomenon, which is most undesirable.

Generally speaking, accelerations greater than 100 Hz have been discounted, since most vibration is quickly damped and of short duration. Recently, however, renewed interest has been shown in the frequency bands and their harmonics and repeating patterns. The highest activity is found where the continuity of the rail surface is broken or where flat spots on wheels impact the railhead. These impacts have been measured at greater than 80 g and 800 Hz.

Probably one of the reasons vibrations have been disregarded is the lack of transmission through a wood tie into the substructure. When the rail is "floating" on the conventional structure, vibration is only transmitted periodically when the rail base is in contact with

the tie plate, and what is transmitted is damped by the wood. Changes in load, speed, and location change the magnitude of the vibratory effects. In some initial results in field studies being run by Portec, Inc., it appears that vibration effects on various types of structures are the same in the rail—through the fastening and into the tie regardless of track stiffness. The structure of the tie, however, has a great effect on the amount of the forces transmitted to the ballast and subgrade.

Having isolated three of the acting forces in the rail-tie interface—i.e., longitudinal loads, uplift, and vibration—it can now be shown what effect these three forces have on the fastening problem and why what is being done today may be more detrimental than beneficial to the track system.

Until the 1950s, asking a track designer to fasten a rail and tie together was unthinkable, but that is precisely what is being advocated today through the introduction of the direct-fixation systems. The concept comes from Europe and was introduced originally in the 1930s in the form of the "GEO fastener". This was abandoned after some test installations because of cost, complexity, and poor performance in track (pumping ties). In the 1950s, the introduction of concrete ties revived this concept. Since a spike cannot be driven in concrete, it was necessary to provide some other method. These fasteners have now begun to appear on wood ties as well.

In the conventional track construction of tie plates, spikes, anchors, and wood ties, the loading factors are absorbed from rail to tie through a number of separate pieces. The uplift is generally ignored, since the rail is not constrained vertically. The plate is constrained to the tie so that other loads are transferred through the plate and spikes to the tie and the anchors transfer the longitudinal loads from the rail to the tie. Vibration is somewhat damped in the wood.

In the fastening system, a single device reacting against the rail base produces a "toe load" that is suppose to accomplish restraint longitudinally and vertically. This is done through the use of various types of springs that are supposed to make the fastener flexible. They are instead semirigid. This concept is in itself a design enigma. On the one hand, this spring device must have the capability to restrain longitudinal rail running, and therefore this toe load must be high. Conversely, the spring must be flexible enough to allow the rail to move upward without affecting the tie and ballast. This, then, requires either a lower toe load and/or a spring with a very low spring rate. Unfortunately, it is next to impossible to achieve both with a single device, and generally the compromise is toward higher toe loads because the designer feels that longitudinal restraint is more important than the uplift effect.

In defense of these systems, and remembering the European origin, testing has shown that the original systems lack longitudinal restraint but that they do allow the fastener to breathe with the rail. With lighter wheel loads, the uplift is minimized and the accelerations applied to the system are reduced. This, coupled with the lighter spring system, allows the rail to move upward so that the uplift is absorbed into the fastener and the tie or ballast is not disturbed. Unfortunately, track parameters in North America are quite different from those in Europe, and most fasteners fell far short of the necessary loads.

In order to meet the longitudinal requirements, most manufacturers modified their systems to provide a stronger spring but also a more rigid fastener. Most marginally meet the longitudinal parameters but have now increased the spring rate, which, coupled with the

larger steel section, has changed the characteristics of the system. In addition, the higher wheel loads increase the uplift forces.

Now, with the higher spring constant, greater uplift loads, and the same rate of loading, the stiffer spring cannot absorb the force rapidly enough so that the load is transferred to the tie. The uplift force being larger than the weight of the tie, it tends to move the tie vertically. Even though these excursions are relatively small, they are the beginning of ballast migration, center binding, pumping, and fines rising to the surface.

Under real-world operating conditions, one wheel with a single wave does not occur. There are many wheels, complex wave motions, and a myriad of bands and intensities of vibration traveling in some six directions at any given point under the train. As a train approaches a given point, the rail preceding the lead wheel begins to vibrate. Anyone who has walked along continuously welded rail can attest to the audible "singing" of the rail sometimes long before a train appears. It must also be remembered that this vibration is traveling in the opposite direction back of the wheel and that this pattern is repeated for the second, the third, and all wheels. The same is true of loads on the rail. Over a given fastener, the loadings and the frequency spectrum of the vibration are constantly changing, and this causes sharp changes in the motion of the spring. This confusion may cause the spring to stagnate so that the loads are transferred directly to the tie; it may cause the spring to resonate, which may account for the massive movements seen in track ties; or, because of differences in mass, it may cause the tie and the rail to move in opposing directions vertically.

Let us look for a moment at the effect of fasteners on the design of concrete ties. Since its introduction, this concept has changed considerably until the tie we know today, which meets AREA requirements, is a 340-kg (750-lb) behemoth designed according to criteria far in excess of loads measurable in track performance. In addition, when the present structure is used with concrete, it must be ballasted with coarse, hard ballast since the concrete tie abrades ballast. Initially, it was thought that concrete ties could be put on centers as high as 77 cm (30 in), but today, although the ties are designed to the 77-cm parameters, they are rarely spaced beyond 61.5 cm (24 in).

Conversely, there is an installation in which concrete ties are installed on 77-cm centers in volcanic ash ballast. The tie is designed to much lower standards and weighs only 255 kg (560 lb), considerably less than the AREA tie. This installation has been in track since 1970 on a class 6, 113-km/h (70-mile/h) track and has seen more than 181 million gross Mg (200 million gross tons) of traffic. During this period, the track has been surfaced once and gravel ballast has been added. The track has performed satisfactorily. By comparison, adjacent tie installations that have the semirigid type of fasteners have not done as well with many problems of tie skewing and pumping.

The common denominator of these installations on concrete is the fastener. There is undoubtedly general agreement that today's concrete tie designs are successful and that they have performed admirably at the Facility for Accelerated Service Testing. Successful or not, the fact remains that they do move under dynamic loading. Isn't the reason for the hard-ballast requirement perhaps the fact that the movement of the tie grinds or crushes the softer ballast, creating fines that ultimately foul the ballast or migrate to the surface? If there were no tie movement, would this ballast requirement be the same? In addition, one might ponder the fastener effect on design and spacing. Obviously,

in view of the tie movement on the semirigid fasteners, the dynamic requirements of the concrete will be much higher than in the free-floating concept, where the tie is more or less inert in the ballast. From such evidence, one might be tempted to arrive at the wrong hypothesis. It must be agreed that there are many unknowns at this point and much to learn.

The direct-fixation system has one big advantage, and that is the simplicity of its parts. This, of course, is reserved for the drive-on type of system. Usually, the removal of one part on each side of the rail frees the rail from the tie. This, compared with removing anchors and pulling spikes, makes the new system most attractive. This would be particularly true in curved sections, where heavy traffic loads require frequent transposition or relay of the rail. For this reason, direct fixation has found its way into wood-tie application. Use of these ties mounted on tie plates allows the rail to be removed without pulling spikes or removing anchors. The only questions I would ask are the following: Since the uplift reaction has now been transferred to the tie surface, how will the interface between tie plate and tie react? If a 340-kg (750-lb) concrete tie lifts in the ballast, what will happen to the 68-kg (150-lb) wood tie?

At this point, one might think the direct-fixation fastener has very little merit in the present-day track system. Quite the contrary, this system has much to offer in stabilizing the track and decreasing maintenance. The fact that what we know today presents problems and the technology is incomplete should only add spice to the challenge of resolving the problem.

This paper only serves to point out what we consider to be shortcomings in current devices in the hope that users will recognize these areas and either be prepared to live with them or demand better fastening systems. The fastener designer should recognize the effect the designs have on the overall performance of the track and at the very least be prepared to provide corrective solutions and ultimately to design to meet the requirements.

There is one bright spot in this situation that will alleviate, if not correct, the present problem. Remember that most of the present systems are adaptations of lighter systems that lose much of the original performance when stiffened. North American suppliers are now beginning to recognize the merits of direct fixation, and new devices are entering the marketplace that are designed to meet the heavier requirements unhindered by past designs of lighter systems. These systems may make the best compromise for all the known loadings and, although they are not the ultimate solution to the total problem, they are a great improvement to track performance.

At this point in time, there is a great deal about fastener performance that is unknown. To unlock these secrets from the track will require a return to basics by the researcher. This means the accumulation of data from the structure itself. In areas where questions are unanswered, modeling will not suffice. This information gathering is not a short-term proposition but will require several years. My own organization has been doing this for three years, and we have barely scratched the surface. We find that much must be done in instrumentation, for without good means of measurement the data are either incomplete or useless. Data should be taken under every possible condition, and analysis done with extreme caution.

The answer is there and will ultimately become obvious. In achieving this goal, each step must be taken carefully and fully documented. Through this

method, we stand to improve design and performance rather than hinder it.

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Comparison of Performance of Wood-Tie Fasteners at FAST

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The results of experiments with wood-tie fasteners at the Facility for Accelerated Service Testing are reported. Since the beginning of the use of 91-Mg (100-ton) freight cars, there has been an increasing problem with wood-tie fasteners. The resulting high axle loads have caused an increase in the deterioration of wood ties from spike killing and tie-plate cutting and have taxed the cut-spike fastener to the limit in preventing rail rollover and wide gage. The objective of the wood-tie fastener tests at the Facility for Accelerated Service Testing is to find an alternative to the cut spike that would alleviate some of the problems that have occurred in revenue service. Two test cycles have been completed, and a third is currently being run. In the first test, an excessive amount of rail wear, attributed to high flanging forces and a lack of effective lubrication, resulted in two rail transpositions. The rail was regaged each time, which eventually "spike killed" the ties. In the second test, in the elastic-clip segments, a large number of the hold-down fasteners failed, which resulted in wide gage. This led to a redesign for the current test to incorporate four hold-down fasteners, twice as many as in the second test. The results have not yet demonstrated that there is a wood-tie fastening system that will perform better than the cut spike. The results of the third test, however, may change this conclusion.

For the past 10-15 years, the increasing dynamic forces imposed on track by the 91-Mg (100-ton) cars on North American railroads have, in many instances, created conditions in which the traditional cut-spike fastener has not performed well. In particular, the heavy wheel loads in curved track have resulted in rapid rail wear, which has led to frequent transposition, relay, and replacement of rail. These maintenance activities and heavy axle loads have resulted in wide gage from spike-killed ties. In addition, it is apparent that on sharp curves the cut-spike fastener is less than optimal in preventing rail rollover and the looseness of the fastening system that can lead to tie-plate cutting.

Many railroads, including the Atchison, Topeka, and Santa Fe Railway Company, the Bessemer and Lake Erie Railroad Company, and the Canadian National Railway, have recently been testing alternative fastening systems in main-line track in curves that would resist gage widening and rail rollover, eliminate respiking, and restrain the rail longitudinally without the use of rail anchors. The systems that are being tested include a variety of elastic fasteners and compression clips that are designed to alleviate the problems associated with the cut spike.

At the Facility for Accelerated Service Testing (FAST), similar fastening systems and others that are not currently being used in revenue service are being tested to find the elusive alternative to the cut spike as a wood-tie fastener.

BACKGROUND ON FAST

A general description of the FAST track, the consist used, and the test conditions is given in the paper by Steele and others elsewhere in this Record. The diagram of the FAST track shown in Figure 1 pinpoints section 7, where wood-tie-fastener testing is being conducted.

A record of the traffic load accumulated to July 1979, before a major summer rebuilding, is shown in Figure 2. The traffic load to that date was 381 million gross Mg (419 million gross tons) (traffic loadings throughout this paper are in gross megagrams and gross tonnage). This rapid accumulation of load greatly accelerates the wear and fatigue life of the track components. Track components that might normally experience 27 million Mg (30 million tons) in revenue service in one year will accumulate 136 million-182 million Mg (150 million-200 million tons) at FAST.

In addition to the heavy traffic loads at FAST, other factors should be taken into consideration in evaluating FAST results in relation to revenue service. These factors are

1. The lack of flat wheels in the consist;
2. The speed range of 64-72 km/h (40-45 miles/h);
3. The 5- to 7.6-cm (2- to 3-in) underbalanced conditions in the curves;
4. The short test duration and relatively mild, dry climate, which tend to reduce environmental effects; and
5. The grade and track configuration of each test section with which comparisons are being made.

TEST DESCRIPTION

The wood-tie-fastener tests are conducted in section 7 of the FAST track, which consists of a 303-m (1000-ft) long, 5° reverse curve with a 0.07 percent grade that has been divided into test segments. Since the test section is a reverse curve and, as shown in Figure 3, the train speed through the curve is generally between 68 and 72 km/h (42 and 45 miles/h), the curve is one of the most severe environments at FAST. Histograms of the vertical and lateral forces produced by the consist operation are shown in Figures 4 and 5. These data were taken on the high rail. In this curve, with a 5- to 7.6-cm (2- to 3-in) underbalanced condition, the high rail has higher dynamic loads than the low rail. The mean lateral forces are greater for the lead axles, which