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Development of a Model for Describing Nonlinear Lateral Resistance of Track Ballast

David Allen and Gary Fry (TAMU*)
David Davis (TTCI)

Summary

Engineering faculty in the Association of American Railroads' (AAR) Affiliated Laboratory Program at Texas A&M University developed a model for predicting the history dependent and nonlinear resistance of track foundations to lateral deformations. Such a model is essential to the ability to predict rail structure misalignments caused by thermal buckling. The model consists of two parts: (1) the development of a new and substantially improved small-scale experimental single tie push test (STPT) and (2) the construction of a model for predicting the lateral resistance of rail/track foundations as a function of both vertical and lateral loading history, track structure and foundation geometry, and material properties of both the track and foundation. The model is validated via a series of full-scale experiments. The results of the research are intended to produce a model of foundation lateral resistance that can be utilized to dramatically improve the ability to predict lateral deformation induced failures (i.e., track buckles) in rail/track structures.

The current state of practice on track maintenance is insufficient for managing rail longitudinal stresses and their undesired outcomes of track buckles and tensile fractures. The stress-free temperature of rail is known to some degree of precision when rail is installed. However, the stress-free temperature can change with train operations and track maintenance activities. Even if the longitudinal force in the rail is known, the lateral support conditions of the track are largely unknown. Thus, the ability to predict and prevent track buckles is limited.

A newly formulated model has been developed herein for the purpose of improving the ability to predict the onset of thermally induced rail/track buckling. The approach consists of a model for predicting lateral resistance of rail/track structures as a function of loading history. As such, it may be useful for the purpose of predicting, and therefore also avoiding, the onset of thermally induced rail/track buckling. The prediction of rail/track buckling using this model will be the subject of a companion digest by the authors.

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*AAR's Affiliated Laboratory Program, Texas A&M University

Please contact **David Davis (719) 584-0754** with questions or concerns regarding this *Technology Digest.* E-mail: David_Davis@ttci.aar.com.

INTRODUCTION

A common cause of misalignment in rail structures is thermal buckling, as demonstrated in Figure 1.

Figure 1. Photograph Showing Thermally Induced Buckling of a Rail Structure

A recent study ranked track buckling as a top reason for track failure caused derailments on U.S. mainline tracks between 2010 and 2013.[1]

Significant research has been reported in the open literature on the subject of lateral deformation in rails.[2-6] Most importantly, a rigorous mechanics based model has been developed by Kerr,[4] and Tvergaard and Needleman have extended this model with the use of a finite element algorithm to account for track imperfections and nonlinear lateral resistance of the track foundation.[6]

Although the research by Tvergaard and Needleman considered the two critical issues of track imperfections and nonlinear lateral resistance, they did not carry this research to the point of a useful design tool. Specifically, their research did not address the question as to what causes the track imperfections. Other research has hypothesized that these imperfections can be induced by thermal cycling,[7] foundation weakening,[3] and/or lift-off of the track adjacent to a wheel.[6] These physical phenomena, coupled with the nonlinear and history dependent nature of the track lateral resistance,[8] require further model development before an accurate predictive tool can be developed for the purpose of predicting lateral failure of track structures. Thus, there is a need to develop a model for predicting the nonlinear and history dependent nature of lateral resistance of track foundations.

Track Buckling Prediction Model

In order to model this problem, one might attempt to construct a three-dimensional simulation of the track structure, ballast, and base material, and model the track structure response to loading history using a finite element method. However, the complexities of this approach can undermine its accuracy. For example, the mechanical constitutive behavior of the ballast layer is granular in nature. As shown in Figure 2, because of the nature of the underlying foundation, the track structure tends to undergo the following three stages of deformation during (lateral) loading of the track structure:

1. Quasi-linear elastic deformation, during which the ballast and track structure remain locked together, and the ballast consolidates
2. Sliding between the crossties and ballast
3. Slip and failure of the ballast adjacent to the track shoulder

The last two of these stages are both nonlinear and loading history dependent in nature. Unfortunately, the physics of these two processes are not yet well understood. Thus, a fully three-dimensional finite element analysis of the track structure and accompanying foundation is unlikely to be accurate.

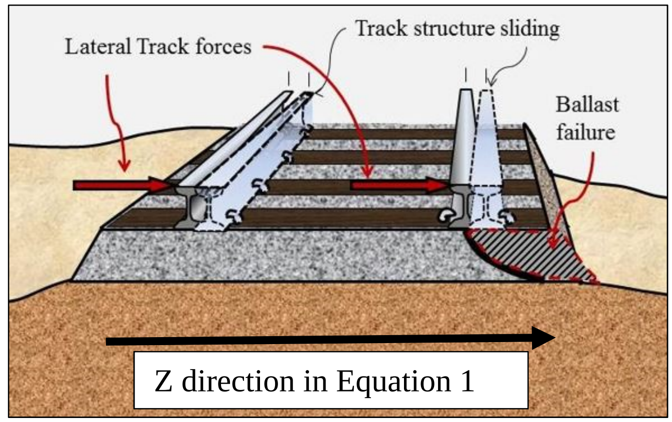

Figure 2. Schematic Depicting Deformation Mechanisms in Track Structure Due to Lateral Loading

Therefore, a simplified approach is taken herein. Toward this end, consider the governing differential equation for the lateral deformation of a beam on an inelastic foundation:[3,4,6]

$$EI_{yy}\frac{\partial^4 w_0}{\partial x^4}+P^T\frac{\partial^2 w_0}{\partial x^2}+f_z=p_z \qquad (1)$$

where

E is the modulus of elasticity of the rail material
I_{yy} is twice the moment of inertia of the rail about the y centroidal axis
w_0 is the displacement of the centroidal axis of the track structure in the z coordinate direction
P^T is the thermally induced axial load
f_z is the lateral resisting force per unit length due to the track ballast
p_z is the lateral force per unit length due to rolling stock on the rail structure.

As described above, the physics of deformation of the track foundation are such that the lateral resisting force per unit length, f_z, is highly nonlinear and loading history dependent. And while a more detailed analysis may lead to a better understanding of the nature of the interaction between the track structure and the underlying foundation, in the current approach a model that reflects observed behaviors will be developed for the purpose of predicting f_z as a function of the loading history. The construction of a model for predicting this property is the primary objective of this digest.

Development of a Track Lateral Resistance Model from Available Field Data

Using available data from track panel shift tests (TLV surfaced) and single tie push tests (STPTs), one can determine the nonlinear lateral track stiffness – lateral displacement relationship needed to predict track buckles. Neither test is ideal because they are single load cycle tests. Additionally, the track panel shift test is a complex loading case with poorly defined boundary conditions. As Figure 3 shows, results from the two tests may show similar trends, but different lateral track resistance values.

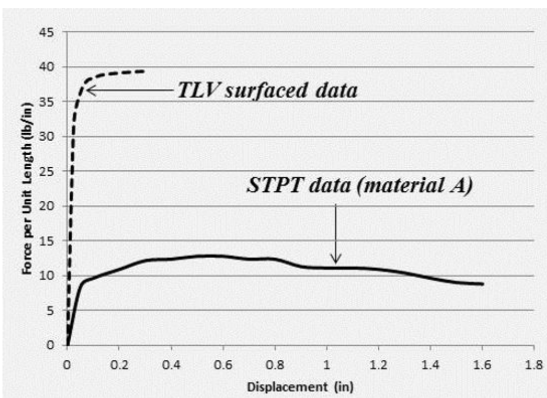

Figure 3. Comparison of Lateral Resistance Obtained from TLV and STPT Tests

Using the thermally induced axial load method in research conducted by Allen and Fry, a model for lateral track resistance can be developed from a simple STPT or track panel shift test. The resultant model, as depicted in Figure 4, shows the attributes of lateral track resistance seen in the field. To make such a model as simple as possible, it is assumed herein that the relationship between the resisting force per unit length and the lateral displacement (although history dependent) is independent of the loading rate. In fact, such an assumption leads to a formulation that is not unlike that employed to develop rheological models.[9]

In the schematic of the model, shown in Figure 4, the y axis represents the nonlinear lateral resistance coefficient of the track. On the x axis, the point w_o^{RM} represents the point when the tie begins to slide in the ballast.

Figure 5 shows the results of calibrating the model to two ballast materials in test at the Facility for Accelerated Service Testing. The properties and performance of these materials as ballasts is well documented.

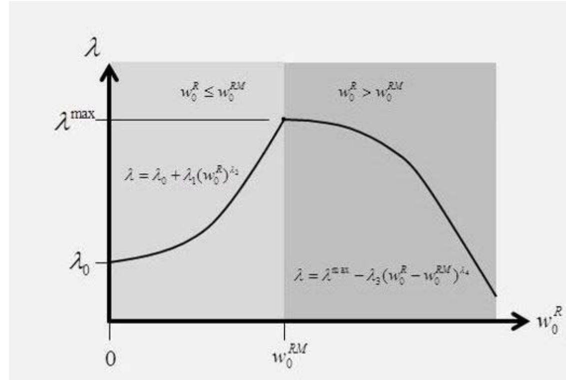

Figure 4. Schematic Depicting Method for Determining Nonlinear Lateral Resistance Coefficient ($\lambda(f_z)$) from a STPT Test

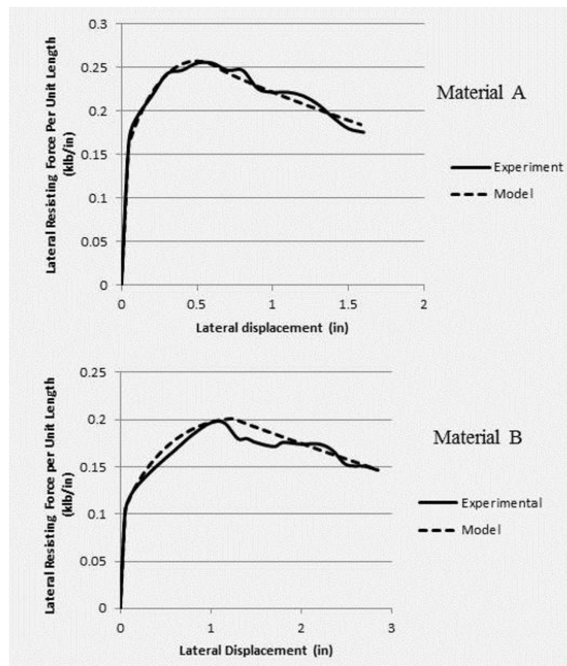

Figure 5. Model Prediction vs. Experiment for Two Representative Ballasts

Of course, Figure 5 depicts nothing more than the ability of the model to reproduce the data that are input to the model. The test of the capability of the model lies in its ability to predict both unloading and cyclic loading. Toward that end, a careful study has been made to produce representative coefficients for material A.

Figure 6 shows the predicted lateral force per unit length applied to the rail structure for six cycles of applied displacements. Note that all three types of lateral resistance (ballast in solid deformation, tie sliding in ballast, and ballast granular failure) are clearly evident in the prediction.

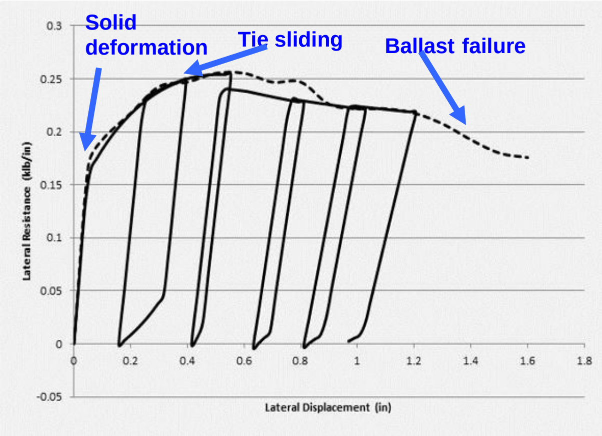

Figure 6. Predicted Lateral Resistance vs. Applied Lateral Displacement for Material A

With the development of the relationships shown in the example in Figure 6, a multicycle lateral loading test can be used to produce the residual displacement-load cycle relationship shown in Figure 7. These data, can be used to solve the governing differential equation for the lateral deformation of a beam on an inelastic foundation.

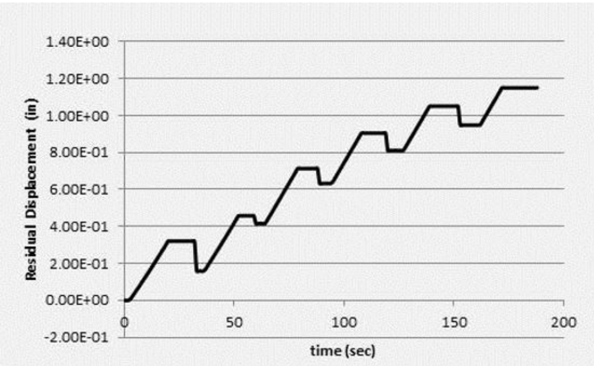

Figure 7. Predicted Evolution of Residual Displacement of the Rail Structure during Cyclic Loading

CONCLUSIONS

A newly formulated model has been developed herein for the purpose of improving the ability to predict the onset of thermally induced rail buckling. The approach consists of a model that reflects observed behaviors for lateral resistance of rail structures as a function of loading history. As such, it may be useful for the purpose of predicting, and therefore also avoiding, the onset of thermally induced rail buckling. The prediction of rail buckling using this model will be the subject of a companion digest by the authors.

The resulting model will require inputs of track lateral strength that are currently difficult to obtain. Development of a method to measure the required track lateral strength properties (i.e., a cyclic STPT) and populating a database of track strength properties are needed.

FUTURE WORK

The objective of the model development is to develop a nonlinear computational algorithm that is capable of predicting the temperature necessary to induce lateral buckling of the rail structure for the following given set of inputs: the measured lateral residual displacement of the track, length of the rail structure over which the residual displacement is measured, the anticipated lateral loads to be applied to the track, the current temperature, and the current estimated track-ballast lateral friction coefficient versus lateral displacement curve. With the exception of the lateral track-ballast coefficient, the above parameters can be determined experimentally on the fly. It is expected that experiments performed at TTCI, using a new Cyclic Single Tie Push Test (CSTPT) will give reasonable estimates of the track-ballast lateral friction coefficient versus lateral displacement curve, so that the algorithm will be a means of predicting when the track structure is sufficiently degraded to warrant intervention.

Informed by this new approach, another area of investigation will be to investigate effective means of intervention. Specifically, knowing the influence of the key parameters on buckling temperature, various candidate mitigation and repair strategies can be compared for effectiveness. The new CSTPT can be also be used to for this purpose.

ACKNOWLEDGEMENTS

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