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Using Differential Shear Strain Measurements to Monitor

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ABSTRACT

This thesis details a comprehensive numerical analysis of load determination, and crosstie support assessment and monitoring using strain gauges to measure differential rail shear strain in ballasted railroad tracks due to applied railcar wheel loads. These differential shear strain measurements can be related to applied wheel loading and crosstie support reactions through the geometric and constitutive properties of a given rail section. The basic theory behind the measurement technique was reviewed and investigated using finite element models of varying complexity. The impact of field conditions such as differential ballast and subgrade support, track stiffness, crosstie spacing, gauge installation location, and circuit calibration methods were explored, as well as the nature of the interaction between vertical and lateral loads on accurate load determination. The results of this theoretical study indicate that differential shear strain measurements are a robust method for load and crosstie support assessment and monitoring and can be used for accurate measurement of both vertical and lateral loads.

INTRODUCTION

Wayside measurement of bending-induced shear strains in railway rails is a practice that has been used since the 1970's in various research efforts studying the mechanical behavior of ballasted railway tracks under static and dynamic loading (Ahlbeck et al., 1976;Milkovic´ et al., 2013; Borinder, 2014; Tutumluer et al., 2015; Mishra et al., 2015; Cortis et al., 2017, etc.). A specific application of this practice is in the estimation of wheel loads and the corresponding support conditions of underlying crossties. The basic theory for estimating wheel loads and support conditions is based, in its simplest form, on Bernoulli-Euler beam theory and uses the principle of constant shear between the applied wheel load and the associated supports. Two circuits are typically used: one in the crib section of the rail (the unsupported rail section between two crossties), and one surrounding a crosstie. Each circuit is typically comprised of four dual-element shear strain gauges. Two gauges (one on each side of the rail) are placed at a distance of approximately ten inches from another set of two gauges, with both sets of gauges centered on the crib or crosstie respectively as shown in Figure 1.1. These gauges are used to measure shear strains on either side of the wheel load as it moves through the circuit location. A vertical force balance relates the wheel load or support reaction to shear force. Based on the relationship between shear force and shear strain, measured shear strains can be related to applied wheelloads and support reactions.

Previous Investigations

One of the earliest applications of wayside strain gauge measurements to determinerail loading conditions was proposed by Ahlbeck et al. (1976) drawing on the prior work of Peterson et al. (1971) and Kudryavtsev et al. (1973). The method for measuring vertical wheel/rail forces proposed included the use of eight strain gauges. Two strain gauges (separated by an angle of 90°) were placed at the neutral axis of the rail section oriented at 45° from the longitudinal axis of the rail. Two more strain gauges were similarly placed onthe opposite side of the rail. Another set of strain gauges was placed a distance of ten inchesfrom the first set with both sets centered on a crib section of the track as shown in Figure 1.1. As the difference in shear strain between both ends of the circuit are proportional to any applied load between them, an estimate of wheel load was made using a calibration curve created by applying known loads and measuring induced shear strains.

A similar approach was used to determine lateral wheel loads. However, for lateralloads, strain gauges were placed on the foot of the rail section. Unlike for vertical loading, the neutral axis of the rail due to lateral bending passes through the top and bottom of the rail. Consequently, strain gauges cannot be placed at the neutral axis under lateral bending and are thus placed at the rail foot. Strain gauges placed in this location are influenced by the interaction or 'crosstalk' between vertical and lateral loads. To mitigate errors inducedby this influence, the gauge output (for both vertical and lateral load circuits) was arrangedin a full Wheatstone bridge circuit configuration. This configuration eliminated crosstalk between vertical and lateral loads by separating vertical load-induced strains from lateral load-induced strains and consequently provided robust vertical and lateral load measurements.

LITRETURE REVIEW

Cortis et al. (2017) conducted an analysis of lateral rail forces using finite element methods. The model results correlated well with field data and were additionally validated with a small-scale bench study. A method was proposed for determining lateral forcesbased on a constant support stiffness relating measured web bending strains to lateral force,and the results of the finite element analysis and experimental data were in close agreement.Tutumluer et al. (2015), and Mishra et al. (2015), conducted an in-depth investigation of the effects of bridge transitions on railbed mechanical behavior. As part ofthat investigation, strain gauge circuits similar to those proposed by Ahlbeck et al. (1976) were installed in open-track locations, and at near-bridge locations. To monitor changes incrosstie support conditions, an additional circuit was added. This circuit was centered overa crosstie in which support conditions were to be monitored. The circuit was used to measure the crosstie reaction by finding the difference between the applied load determinedin the crib circuit and the applied load determined in the crosstie circuit. The percentage ofwheel load supported by the crosstie was thus determined from the difference between thecrib circuit output and crosstie circuit output. Based on a common assumption that a loadedcrosstie carries approximately 40% of the wheel load for a well-maintained track, themeasured difference in output between the two circuits should correspond to an approximate load of 40%. The measurements recorded in this study were consistent with this assumption and by using this technique the researchers were able to monitor changes in support conditions over time. It was generally found that for well supported crossties (no crosstie/ballast gaps), the percentage of load carried by the crosstie near the bridge transitions exhibited much more variation than open track locations consistent with the complex dynamic behavior expected near bridge transitions resulting in load amplification.

EFFECT OF TRACK CONFIGURATION AND LOADING CONDITIONS ON VERTICAL WHEEL LOAD MEASUREMENTSUSING THE DIFFERENTIAL SHEAR APPROACH

ABSTRACT

Measurement of vertical wheel loads on railroad tracks using strain gauges mountedon the rail web is common practice. This measurement approach makes use of thedifferential shear concept: “the difference in shear force between two points along a beamequals the magnitude of the vertical load applied between those two locations”. Although the applicability of this concept is easy to verify for simple beams, its validity for field applications under different track configurations including support and loading conditionsis relatively unexplored. This manuscript presents findings from an ongoing research effort that has utilized numerical models to assess the effects of different track and loading configurations on vertical wheel load measurements using the differential shear approach. The underlying theory behind this measurement approach is first introduced, and different scenarios are compared using a simple 1-D model. This is followed by detailed analysis of the effects of different vertical, lateral, and axial loading combinations on the measured shear strain values. Finally, a 3-D Finite Element Model is used to study the dependence of the measured wheel loads and calibration approaches on track support conditions. Findings from the analyses clearly establish the applicability of this measurement approach across different scenarios observed in railroad tracks.

Introduction

One of the most common wayside instrumentation techniques employed for the determination of vertical railcar wheel loads is the placement of strain gauges on the rail web to measure differential shear strain. The basic theory behind this method was first presented by Ahlbeck et al. (1976) and is based on a simple principle: the difference in vertical shear force between two locations along a beam is equal to the magnitude of the vertical load applied between those locations. Reasonably accurate estimates of wheel loadmagnitude can be obtained by measuring the differential shear strain between two locationsusing strain gauges and relating those measurements to the vertical shear force (and therebyvertical loading) through rail geometric and constitutive properties. This basic technique forms the backbone of the Wheel Impact Load Detector (WILD), one of the most widely used wayside monitoring systems by the railroad industry.

A recent study at Boise State University in the US focused on investigating the effects of different calibration procedures, installation locations, support conditions, and track configurations on the shear strain values measured using the differential shear approach. Extensive numerical modeling was carried out using the Finite Element Method (FEM) to simulate the strain-based load measurement approach in the field. The effects ofdifferent load and support conditions were studied, and their effects on the magnitudes of the backcalculated loads were quantified. This manuscript presents initial findings from this research effort. Results pertaining to the effects of localized soft spots in the track substructure and how this theory can be extended to evaluate the support conditions underneath crossties will be presented in subsequent manuscripts.

Research Objective and Scope

The primary objective of this research effort was to evaluate how strain gauge placement and calibration, various track configurations, and support and loading conditions can affect the accuracy of vertical loads backcalculated using the differential shear approach. First, a simple 1-D model of a beam supported at multiple locations was analyzedunder different loading conditions to link the differential shear magnitudes to the applied load levels. This was followed by FE analysis of a 3-D track structure incorporating typicalrail and tie geometries. This 3-D model was analyzed under different tie spacing, rail sections, and support conditions to assess the impact that these factors have on the accuracy of differential shear measurements and back calculated load magnitudes.

Basic Theory

As already mentioned, the concept of the difference in shear force at two points along a beam being equal in magnitude to the load applied between is easy to verify undersimply supported or similar statically determinate structural configurations. However, a rail is supported at multiple points by crossties (which can be idealized as elastic supports), and therefore represents an indeterminate structural configuration. The first task in this research effort was to use a simple 1-D model to analyze a simplified rail segment supported by multiple elastic springs. The wheel load determined using this principle (Equation 2.3) in actual field applications is approximate. The true 3-D strain state is more complex than the simplifiedpure shear state shown in Figure 2.2. Normal and shear stresses from longitudinal and lateral loading can cause a rotation of the principal strain axes and additional out of plane deformations. These factors along with geometric and material property variations make itnecessary to calibrate strain gauge circuits under typical load and support conditions. Nevertheless, with proper calibration and placement, accurate and reliable load estimates can be obtained. However, changes in cross sectional properties or large deviations from the initial placement in respect to the neutral axis, for example due to excessive rail wear, may necessitate recalibration.

Impact of Loading Conditions on Vertical Load Estimates

The model was 1-m long and was centrally loaded with vertical and lateral loads under different support constraints. Virtual strain gauges were placed at the neutral axis ofthe rail section at the longitudinal quarter points on both faces of the rail web. The virtual strain gauge consisted of a 4 mm x 4 mm square element with a diagonal length (gauge length) of 5.7 mm. The type of element chosen for this model was the ABAQUS® 3D8I element which is a linear hexahedral element with additional internal degrees of freedom to reduce parasitic shear and artificial stiffening due to bending (ABAQUS, 2015). This element performs nearly as well as quadratic elements provided they are rectangular in shape, but at much lower computational costs. The mesh was assigned a global size of 5 mm, and this configuration resulted in nearly cubical elements within the web of the rail.

Impacts of Installation, Calibration and Support Conditions on Vertical LoadEstimates

A layered elastic, axisymmetric FE model of an AREMA 132RE rail section was developed, as shown in Figure 2.4. The model was developed to gain insight into the impactthat various installation locations, calibration procedures, and crosstie support conditions have on strain gauge measurements. The model comprised a rail on seven crosstiesmodeled with an axisymmetric boundary at the track center.

A sensitivity analysis was performed to assess the effect of model extent on the values of interest in this study; results from the parametric analysis indicated that a modelcomprising seven crossties was sufficiently accurate for the purpose of this study. The crossties were placed on a ballast layer with a modulus of elasticity (E) of 230 MPa overlying a sub-ballast layer (E = 140 MPa) which in turn was placed on top of a subgradelayer (E = 70 MPa).

The crossties were placed at 610 mm (24 in.) center-to-center, and were modeled as concrete, with an elastic modulus value of 20.7 GPa. A zone of variable modulus was introduced to study the impact that weakly supported or hanging crossties may have on vertical load estimates. The initial gauge installation locations (A and B in Figure 2.4) weretaken from the configuration used by Mishra et al. (2015).

For vehicle speeds below the critical track velocity and assuming minimal dynamic railcar/railbed interaction, static and dynamic track behavior is comparable; a static FE analysis can therefore provide reasonably accurate results (Kouroussis, 2015; Feng, 2011). These underlying assumptions were key in choosing only static or quasi-static simulations for this research effort. Though ignoring dynamic effects, a static analysis can provide an understanding of some of the key parameters affecting strain gauge measurements. A biased meshing scheme was used to provide increased nodal densities in areas ofinterest while reducing computational effort in other areas. Care was taken to ensure the mesh for all parts (layers, rail, and crossties) shared nodes at all interaction boundaries to aid in mesh convergence and help decrease runtimes. The model was meshed with C3D8Relements for their low computational requirements (ABAQUS, 2015). While this linearly interpolated element may not be the most accurate element available, the reduction in computational effort compared to other element types was desirable.

Installation

One of the implications of Figure 2.1 is that the shear force instantly changes direction from one side of the applied load to the other. However, actual instrumentation data obtained in the field shows there is a 'shoulder' on either side of an applied load in which the shear more gradually changes direction and achieves its maximum value. This is true for both the applied load as well as the crosstie reactions. For accurate vertical load estimates, the strain gauges must be placed outside the impact zone of these boundary effects. To gain insight into the relative size of these boundary areas, and thereby determine the ideal gauge installation locations, the percent estimated load was calculated from shearstrain values taken symmetrically on both sides of the crib center.

The contours represent the estimated load (calculated by finding the difference between the shear strain at a given location and its symmetric pair on the opposite side of the crib center) as a percentage of the applied load. The contours show significant impacts from the load and sleeper boundary areas resulting in a reduced area where strain gauge installation would lead to accurate load estimates. The largest boundary effect is due to theload as the shear at the point of loading is zero. This results in a shift in the optimal placement location away from crib center toward the crossties.

For the 610 mm (24 in.) center-to-center crosstie spacing used in this study, the shear distribution reaches a maximum value within a relatively small region indicating it may be difficult to achieve the same accuracy with shorter crosstie spacing. To investigatethe impact of crosstie spacing on strain gauge measurements, crossties placed at distancesof 493 mm (19 in.) and 787 mm (31 in.) center-to-center were also modeled; a comparativeplot has been presented in Figure 2.6. With longer crosstie spacing, the region of maximumshear strain increases in length toward the crosstie face providing more leeway in gauge placement. Conversely, reducing the spacing from 610 mm (24 in.) to 493 mm (19 in.), resulted in a slight decrease (2.5%) in the accuracy of the estimated percent load. Based onthese results, for crosstie spacing significantly less than 493 mm (19 in.), estimation of the applied load levels using the differential shear concept may be difficult due to boundary effects.

Calibration

The next step in this study involved studying the effects of different calibration approaches on strain gauge measurements. The most common method used to calibrate thedifferential shear strain gauge circuit involves the use of a hydraulic jack to incrementallyapply a known load and measure the induced strain. A load cell attached to the jack monitors the applied load as the jack applies a vertical load to the top of the rail. In addition to the measured downward vertical force, the A-frame applies a compressive axial force and a vertical uplift force on the rail. It is these forces and the changes in the relative magnitude of these forces with the size of the A- frame used to calibrate the circuit that have led to discussions on the impact of various calibration configurations.

Support Conditions

One of the implications of Figure 2.1 was that support conditions do not significantly impact the magnitude of the differential shear. As a final check of this conclusion and the Bernoulli-Euler beam assumption made in the associated shear analysis,the modulus of a portion of the ballast beneath a crosstie adjacent to the gauged crib section(Figure 2.4) was varied from 20 MPa to 230 MPa. As shown in Figure 2.8, the change in support condition leads to an asymmetrical distribution of shear strain with a reduction in shear strain near the weakly supported crosstie and an increase in shear strain near the normally supported crosstie.

Conclusions

This manuscript presented findings from an ongoing research study at Boise State University aimed at evaluating how different track configurations and loading conditions can affect the vertical load magnitudes backcalculated using the differential shear approach. A preliminary model of a 132RE rail section was developed and centrally loadedto compare the differences between the theoretical 2-D strain states with the 3-D behavior of physical strain gauge measurements under various loading conditions. It was found thatloading conditions, primarily lateral loading conditions, do have an impact on the accuracyof strain gauge measurements. High lateral loads (L/V= 1) can reduce the accuracy of vertical load estimates by as much as 30%. However, these impacts are minimal for straight sections of track with low dynamic railcar/trackbed interaction. On curved track sections, adjustments to vertical load estimates could be made using additional circuits to measure lateral loads and using lateral loading data similar to the data in Table 2.1 to adjust measured vertical loads.

A layered elastic full-track FEM model was developed and analyzed to find the optimal strain gauge installation locations, and the impact of calibration techniques and support conditions on vertical load estimates. It was found that the optimal horizontal placement changes as crosstie spacing increases and the optimal vertical placement remains unchanged. Based on these results, the optimal horizontal placement from the crosstie face for a typical concrete tie spacing (610 mm center-to-center), is 62 mm (2.4 in.) from the crosstie face. Placing the gauges near this location leads to the optimal performance of the measurement circuit. Additionally, proper circuit placement within the crib ensures that strain gauge measurements are independent of geometric configuration of the calibration equipment. Finally, it was validated that support conditions do not impact vertical load estimates. Current research efforts are focused on how differential shear measurements can be applied to quantify support conditions under crossties; relevant findings will be reported in future manuscripts.

ELIMINATING THE WHEATSTONE BRIDGE

Abstract

Real-time measurement of vertical wheel loads applied to the rail is commonly carried out using strain gauges. One standard approach involves measurement of shear strains at the rail neutral axis and use of the differential shear concept. Strain gauges are typically mounted on the rail neutral axis between two adjacent ties (over the crib section). A set of four strain measurements (two each, pointed at 45 degrees up and down from the horizontal) are carried out at each end of the crib section, and the measured strains are used to calculate the shear strain magnitudes; this shear strain is in turn used to calculate the applied load. In practice, the four individual strain measurements on each end of the crib (on either face of the rail) are arranged in a single Wheatstone bridge circuit. The purpose for using this common strain measurement configuration lies in the circuits' ability to eliminate crosstalk or strain unrelated to the load being measured, e.g., bending strain or strain due to lateral loading, etc. This paper will propose a new measurement approach whereby eliminating this Wheatstone bridge configuration and measuring eight independent strain signals will enable direct quantification of the vertical as well as lateral load magnitudes. Instead of having to install additional strain gauges on the rail base to measure the lateral loads, the same strain gauges mounted on the rail neutral axis can be used to measure both vertical as well as lateral loads. This proposed technique will simplify the process of vertical and horizontal wheel load detection and may increase the applicability of these circuits to detect loads in curved sections of track as well as near special track work.

Introduction

One of the most common wayside wheel load monitoring techniques employed in the rail industry is to mount chevron-style strain gauges to the crib section of the rail. The strains measured by these gauges are then related to applied wheel loads through rail material and geometric properties. Due to crosstalk between vertical and lateral load- induced strains, two separate strain circuits are employed: one for vertical load and one for lateral load. The vertical load circuit comprises four chevron-style strain gauges placed at the rail neutral axis (N/A) to measure strains at ± 45° as shown in Figure 3.1. Two gauges are placed symmetrically about the crib center between the crib center and the face of adjacent crossties on each face of the rail web. The distance D is chosen such that the induced strains are not affected by the boundary effects of the load and crosstie supports (Rabbi et al., 2019).

Different methods have been identified that can successfully decouple wheel loads into their vertical and lateral components. One recent example of this was presented by Cortis et al. (2017). Building on the work of Moreau (1987), Cortis et al. (2017) proposed a new technique using rail bending strain to decouple vertical and lateral load components. It was found that this technique was able to accurately determine both vertical and lateral load with an error of less than 10% in a laboratory bench study. This approach certainly has merit and may represent the future of wheel load detection technology. However, it is hoped that a more open search, free of theoretical underpinnings (e.g. beam theory), may uncover other useful relationships which can increase the functionality of wheel load detection circuits. One potential example of this, as stated previously, could be the determination of contact position based on strain gauge measurements. Current efforts to investigate whether such relationships can be established are ongoing.

The model used in the study was 1-m long and was centrally loaded with meshed combinations of vertical and lateral loads. A vertical point load was applied at the center of the rail crown, and a lateral point load was applied at the lower tangent of the crown fillet. The load combinations consisted of vertical and lateral loads ranging from 0 to 250 kN in increments of 10 kN resulting in a total of 625 simulations. Virtual strain gauges were placed at the neutral axis of the rail section at the longitudinal quarter points on both faces of the rail web. The virtual strain gauge comprised a 4 mm x 4 mm square element with a diagonal length (gauge length) of 5.7 mm. The type of element chosen for this model was the ABAQUS® 3D8I element which is a linear hexahedral element with additional internal degrees of freedom to reduce parasitic shear and artificial stiffening due to bending (ABAQUS, 2014). The nodal mesh was assigned a global size of 5 mm, and this configuration resulted in nearly cubical elements within the web of the rail. Nodal displacements for each simulation were used to calculate the infinitesimal strain for virtual strain gauges defined by the diagonal surface nodes of the gauge element. Table 3.2 presents the strain output for three (3) select cases of vertical and lateral load. Based on prior observation, it was known that vertical and lateral loads could be accurately determined from a linear combination of the shear strain values output by the FEM model. However, as these values are theoretical in-plane values only, it was unclear as to whetherthis observation would hold for a physical strain gauge.

As previously shown by Rabbi et al. (2017), the loads estimated from the in-plane component of shear strain can accurately establish the vertical load magnitude independent of the lateral load magnitude. However, when using nodal displacements to estimate the 3D strain behavior of a physical gauge, increasing lateral load causes an increase in the error of vertical circuit load measurements. This behavior suggests interdependence between vertical and lateral load that may or may not be linear. Therefore, a linear regression of the eight (8) strain measurements for each simulation was conducted to ascertain whether a linear relationship can be found to relate the strain measurements of the vertical load circuit to vertical and lateral load magnitudes.

The relationships between vertical circuit strain gauge measurements and the magnitude of vertical and lateral load presented here are for a single load position. It is likely that as the load contact point moves, the values of the regression parameters shown in Table 3 will change. Additional work is required to investigate how the regression parameter values change as a function of load position. To implement this theoretical relationship in the field, it may be necessary to find a relationship between longitudinal load position and strain gauge measurements. One way to avoid this is to employ signal processing techniques capable of identifying the time at which the load is at a specific pointwithin the gauged section, e.g., at the crib center. Using this approach, the regression constants presented in Table 1 should provide ‘fair’ estimates of wheel loads as there is some error (though small) associated with the lateral contact position. A quantification andcorrection of this error is another current area of investigation. In addition, the impact that support conditions (e.g., crossties and fastening systems) have on vertical strain circuit measurements will also need to be investigated. Finally, the method proposed here may notrepresent a significant improvement to current load sensing technology. This will largely depend on the signal conditioning and post processing costs associated with processing eight (8) signals as opposed to only two (2); simply halving the number of gauges requireddoes not guarantee a reduction in total cost. However, the ability to determine lateral load, vertical load and potentially the load position could provide a significant functional improvement that may justify any additional infrastructure costs.

Summary and Conclusion

This manuscript presented findings from an ongoing research effort aimed at discovering relationships between the strains measured in a vertical wheel load detection circuit and the applied vertical and lateral loads. To investigate the nature of the interdependence (crosstalk) between vertical loads, lateral loads and strain gauge measurements, the Wheatstone bridge circuit was removed, and individual strain gauge measurements were analyzed. A parametric study of 625 load combinations of vertical and lateral load, ranging between 0 and 250 kN, was conducted on a simply supported section of AREMA 132RE rail. The induced strains from each simulation were used in a linear regression analysis to find a quantitative relationship between wheel-load induced strains and the corresponding magnitudes of vertical and lateral loads. It was found that a linear combination, including two-way interaction terms, of the eight (8) strain gauge signals in a typical vertical wheel load circuit was able to accurately determine both the vertical and lateral load magnitudes when the load position remains laterally and longitudinally constant. Additional work, in the form of laboratory or field verification tests, is required to assess whether the method presented here is viable for field implementation or not. Current research efforts are aimed at finding an additional relationship to account for the longitudinal position of the applied load. If successful, typical vertical circuit gauge configurations can be used (sans the Wheatstone bridge) to simultaneously determine the vertical load, lateral load, and wheel load contact position, providing a time-history of wheel load as it passes through the circuit.

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USING DIFFERENTIAL SHEAR STRAIN MEASUREMENTS TOMONITOR CROSSTIE SUPPORT CONDITIONS IN RAILROAD TRACKS

Introduction

With the validity of the differential shear strain method verified on a theoretical basis in the first paper, and with an increased understanding of the response of rail shear strain to vertical and lateral load, gained through the efforts of the second paper, the final task was to answer the remaining research question: whether the approach used byTutumluer et al.

(2015) is valid from a theoretical standpoint. One approach to answering this question is to leverage the relationship in Equation 3.1 between shear strain measured in the vertical load circuit and the applied load. If the relationship between circuit strain response and applied load remains unchanged regardless of whether the circuit is a crib circuit or a crosstie circuit, then the primary differences between the two circuits, i.e. different loading conditions and deflected shape due to rail pad/crosstie reaction, do not significantly impact the output of the circuit. Therefore, it would be theoretically valid to apply the calibration curve determined in an adjacent crib circuit to the crosstie circuit, as was done in Tutumluer et al. (2015). This is important for the practicality of the method ascalibrating the crosstie circuit would require inserting a load cell between the rail and crosstie; considered impractical for routine use by field practitioners.

Research Approach

To determine whether the calibration curve from the crib circuit can be used to calibrate the crosstie circuit, the full-track FE model developed in Chapter 2 was modified and loaded at the crib circuit under various vertical load magnitudes to determine the regression coefficients in Equation 3.1. With these coefficients determined, the crosstie circuit was subsequently loaded, and Equation 3.1 was used to estimate the applied load. Close agreement between the crosstie reaction at the crosstie circuit and the estimated crosstie reaction using the coefficients determined from the crib circuit would prove that the differences between the two circuits are not significant in the determination of applied load. This implies that the calibration curve, or the relationship between applied load and strain response, from the crib circuit can be used to calibrate both circuits.

The 5 mm thick rail pads shown in Figure 4.3 were defined with an elastic modulus of 5 MPa and a Poisson's ratio of 0.45. These pads were added to the model with a frictional contact interaction between the rail and rail pad. The frictional contact was defined as a surface-to-surface contact using a penalty formulation and a frictional coefficient of 0.64 which is a typical value for rubber/steel contact. The purpose of this modification was to model the interaction between the rail and rail pad. As the rail deflects under load, the rail will tend to bend away from the surface of the rail pad. In the previous models, a tie constraint was defined for the rail/crosstie interface. However, this type of constraint may have an impact on the rail deflected shape (and corresponding shear strain) as it constrains the rail from lifting away from the crosstie as the rail deflects under load. The point of loading was also moved inward from the rail section center to the top of the inside rail section fillet as shown in Figure 4.4 for both crib and crosstie circuit loading. This location is similar to the actual wheel/rail contact area and provides a better representation of actual wheel loading conditions. It should be noted that circular and oval contact pressures were also applied to the rail in some model simulations resulting in no appreciable differences in shear strain response from simulations with concentrated point loading. These simulations have accordingly been omitted for brevity. With all the model changes discussed above, the modified model was comprised of 545,370 model elements.

Results

However, this is still an over-simplification of actual field conditions as the interaction of the rail clip and its corresponding impact on the deflected shape of the rail is not modeled. The difference between the deflected shape of the rail between the crib and crosstie circuits is shown in Figure 4.6, again at a scale factor of 200. The area of exaggerated vertical deflection shown in these figures is due to the singularity introduced from the concentrated point load. Due to this singularity, local strain magnitudes are unreliable. However, this boundary condition does not significantly impact the accuracy of strain values in the area of interest for this study. As the figure shows, there are significant differences in the deflected shape of the rail under load between these two circuits. It is these differences in deflected shape that may cause errors when using the Cribcircuit calibration to calibrate the crosstie circuit.

As discussed previously, to determine whether or not these differences in deflected shape lead to significant differences in strain response between the two circuits, a parametric analysis of the crib circuit was conducted to determine the regression coefficients of Equations 3.1. Table 4.1 lists the load magnitudes used in the parametric analysis along with the associated regression coefficients. The crosstie circuit was then loaded with a 100 kN load in four (4) scenarios of varying ballast strength. Crosstie reactions were calculated using the regression parameters in Table 4.1 and these values were compared with direct crosstie reaction measurements. As shown in Figure 4.7, the percent support predicted by Equation 3.1 is within approximately 2% of measured values.

This result is another validation of the differential shear strain approach to applied vertical load determination. Measurements of shear strain in the vertical direction are not significantly impacted by the differences in deflected shape between the two circuits as the total shear on a given section of the rail is almost entirely related to the applied vertical load with little impact due to additional strains from out of plane bending and twisting. In other words, the relationship between shear strain response and applied load is unchanged by the differences between the crosstie and crib circuits. Therefore, the calibration curve of the crib circuit can theoretically be applied to the crosstie circuit. This result, in theory, validates the approach used by Tutumluer et al. (2015). However, field validation is required to determine if these results can be replicated in the field. Another implication of 4.7 is that, if the differences in deflected shape between thecrib and crosstie circuits don't have a significant impact on shear strain values, it may be possible to use the crosstie circuit alone to predict subgrade strength without the use of a separate crib circuit. A regression analysis trained on load and overall ballast/subgrade strength may be able to provide suitable relationships to predict not only load, but also subgrade support strength without separately determining vertical load in the crib circuit. To test this hypothesis, the model in Figure 4.1 was loaded with a 100kN vertical load under the same ballast strength parameters used in Figure 4.7 (50, 100, 150, and 230 kN, respectively). The corresponding crosstie circuit shear strain values were used in another regression analysis to find a relationship between stain values under a known load to crosstie support strength. The results of this analysis established that fairly accurate predictions of ballast strength can be made using quadratic Support Vector Machines (SVM) trained on shear strain response under known load. As shown in Figure 4.8, this approach provided an RMSE value of 19.77 MPa and a Coefficient of Determination valueof 0.95. Thus, ballast strength predictions using machine learning can theoretically be usedfor assessing track support conditions. A series of SVM models can be trained on a large range of expected vertical load values and these models can then be used in postprocessingalgorithms to determine crosstie support strength based on measured vertical load. To measure the vertical load, Equation 3.1 can be used with the coefficients determined fromthe shear strain response of the crosstie circuit rather than the crib circuit. A much more powerful potential approach would be to use a multivariate regression analysis using bothload and ballast strength responses. If a reasonably accurate multivariate regression modelcould be found however, the approach would still require a lengthy parametric analysis toobtain a large database of strain values (predictor variables) under various load and ballaststrength combinations (response variables) which is beyond the scope of this research effort. It should be noted that this approach would also require further analysis over variousother track parameters such rail section geometry, tie spacing, rail/tie connection configurations, etc. to make these predictions globally valid over a large range of railroad track configurations. However, the approach does demonstrate the power of post- processing all eight strain gauge outputs (as opposed to combining them in a Wheatstone bridge) to determine vertical, load, lateral load, and crosstie support conditions.

Conclusion

This numerical investigation primarily dealt with determining whether the approach used by Tutumluer et al. (2015) to assess and monitor crosstie support conditionswas valid. The approach used an additional crosstie circuit to monitor percent crosstie support, and to calibrate this additional circuit with the calibration curve determined fromthe adjacent crib circuit. It was found that this approach is valid from a theoretical standpoint. However, laboratory or field instrumentation is required to validate this conclusion under changing field conditions. Additionally, the sensitivity of the method wasfound to be limited for relatively stiffly supported crossties. However, as crosstie support continues to diminish, the approach provides an effective method for assessing weakly supported crossties. Additionally, it was found that quadratic SVM predictions of ballast strength based on the eight (8) strain gauge responses under known load are reasonably useful in assessing crosstie support conditions.

SUMMARY, CONCLUSION AND RECOMMENDATIONS FORFUTURE RESEARCH

This thesis details an investigation of the use of strain gauges to determine wheel loads and crosstie support reactions in railroads using finite element methods. The use of strain gauges to measure applied loads first began in the 1970's and is still widely used today in WILD systems and other load sensing devices, and in various research efforts to determine rail/railbed interactions. Strain gauges are placed near the neutral axis of the railweb to measure vertical load, and on the rail foot to measure lateral load. As a wheel passesthrough the instrumented section of track, differential shear is measured and related to applied loads. Tutumluer et al. (2015) modified the method to include an additional circuit encompassing an adjacent crosstie. By measuring the difference in loads between these two strain gauge circuits, crosstie reactions were estimated and used to assess track stiffness and the level of crosstie support provided by underlying ballast and subgrade materials. However, questions regarding the accuracy of the method were raised in the industry. The impact of various field conditions on crosstie reaction measurements were unknown and the methods used to calibrate the crosstie circuit had yet to be validated. Thespecific purpose of the numerical investigations detailed in this thesis was to answer theseprimary questions.

Summary

Manuscript 1: Effect of Track Configuration and Loading Conditions on Vertical Wheel

Load Measurements Using the Differential Shear Approach

Several finite element models were developed and analyzed to test the theoretical validity of various aspects of the differential shear strain approach, beginning from a basic 1-D analysis of a beam on spring supports; and progressing to models of simply supportedrail geometries and to full-track models representative of typical parameters measured in the field. The models were loaded under a range of material and geometric configurationsand under various load combinations. The induced shear strains were then used to estimateapplied vertical load and to assess the impact that these various factors have on the accuracyof vertical load estimates.

The investigation began with several analyses aimed at gaining a solid theoretical understanding of the underlying mechanics involved in the differential shear method. First,a 1-D beam on both rigid and spring supports was loaded to see how support compliance impacts shear force distribution along the beam (Figure 2.1). Additionally, one support wasremoved from the model leading to asymmetrical load/support conditions to investigate theimpact of loosely supported or ‘hanging’ crossties.

The impact that crosstie spacing may have on vertical load estimates was investigated using a full-track model consisting of seven (7) crossties and typical ballast and subgrade strength values. Models using crosstie spacings of 19, 24, and 31 inches respectively were developed and the shear strain distribution along the longitudinal axes of the rail was plotted (Figure 2.6). Additionally, calibration load frames with different geometric configurations were modeled and used to load the rail. The induced shear strainsunder these various load-frame configurations were plotted (Figure 2.7) to investigate the impact that these load frame configurations have on vertical circuit calibration and associated vertical load estimates. Finally, the impact of weakly supported crossties was investigated by creating a ‘weak zone’ or an area of reduced ballast strength in the full- track model. The model was then loaded, and the strain distribution was plotted (Figure 2.8) and used to calculate estimated load.

Manuscript 2: Quantification of Vertical and Lateral Loads Using Strain Gauges—

Eliminating the Wheatstone Bridge

The next task in the investigation was to explore the interaction of vertical and lateral load in the strain gauge circuit. As typical instrumentation procedure is to combine all four gauges at each end of the circuit into a full Wheatstone bridge circuit and thereby eliminate crosstalk between vertical and lateral load, it was necessary to conduct this investigation without modeling the behavior of the full bridge. Instead, nodal deformations were used to model eight individual strain gauges (four at each end). A parametric study of a simply supported rail section under various combinations of vertical and lateral load was performed (Table 3.2) and the resulting shear strain data was used in a linear regression analysis to find relationships between induced shear strain and both vertical and lateral load, Equations 3.1 and 3.2 respectively. The regression coefficients in these equations were determined and presented in Table 3.3 and used in a test case to determine the accuracy of these relationships using measured shear strain values (Table 3.4).

Using Differential Shear Strain Measurements to Monitor Crosstie Support Conditions in Railroad Tracks

The final task in the analysis was to validate the approach used by Tutumluer et al.(2015) to assess and monitor crosstie support conditions. First, another parametric study was performed on a full-track model revised to more closely represent typical field conditions found in highspeed rail applications. The model was then loaded under severalloading scenarios to measure the load/strain response of the crib circuit.

Next, the crosstie circuit was loaded, and crosstie reactions were determined from Equation 3.1 and compared to the measured crosstie reactions output fromthe FE model (Figure 4.7). Finally, the shear strain values under known load (from the previous analysis) were used to as predictor variables along with ballast strength values used as response variables in a linear regression analysis to find a predictive relationship between measured strain values under a known load and ballast strength.

Conclusion

Manuscript 1: Effect of Track Configuration and Loading Conditions on Vertical Wheel
Load Measurements Using the Differential Shear Approach

From the analysis of a simple 1-D beam on rigid and spring supports (Figure 2.1), shear forces imparted to a rail section from an applied load remain constant between any two supports and the difference in internal shear force on either side of an applied load areequal to the applied load through a simple force balance. By using strain gauges and measuring induced shear strains on either side of the applied load, the load magnitude can be determined through rail geometric and constitutive properties. By loading a simply supported 132RE rail section under various combinations of vertical, lateral, and axial load, it was found that axial load has very little impact on the accuracy of vertical load determination. However, due to interactions between vertical and lateral load in vertical load circuits, lateral load was found to have a significant impact on applied load estimates (Table 2.1). An analysis of the accuracy of load determination based on strain gauge installation location (Figure 2.5) shows the impact of boundary conditions on the accuracy of load determination. The largest boundary impact is at the point of loading with much smaller impacts near the crosstie supports. The ideal placement location of strain gauges was found to be approximately 2.5 inches from the face of the crosstie support near the neutral axis for vertical load determination.

Crosstie spacing was found to have little impact on the accuracy of vertical load measurements (Figure 2.6). However, spacing less than 19 inches will lead to errors due tothe boundary effects of closely spaced crossties. Calibration load frame geometries do nothave a significant impact on induced shear strain values (Figure 2.7) and associated calibration curves indicating that accurate vertical load measurements can be made regardless of the load-frame used to calibrate the circuit. It was also found that differentialballast support between crossties does not impact vertical load measurements (Figure 2.8).In summary, it was found that none of the factors above have a significant impact on the accurate measurement of vertical load using strain gauges. These results are consistent withfield data as the determination of vertical load using strain gauges has long been found to be a robust measurement method.

Recommendations for Future Research

Two major implications of this research effort are related to the crib and crosstie circuits respectively. For the crib circuit, based on Equations 3.1 and 3.2, it is possible to determine both vertical and lateral load with a single circuit rearranged to separately output all eight (8) strain gauge outputs. However, the practicality of doing this in the field needs to be investigated, and it is unclear if this approach would provide any significantadvantage over the current practice of using separate circuits to process vertical and lateral load. Also, the coefficients of Equation 3.1 and 3.2 would need to be determined for each circuit installation as the coefficients presented in this thesis are local to the model used (a simply supported rail section). A large parametric study of various material, geometric and loading conditions corresponding to expected field conditions may be able to provide a set (or sets) of globally valid coefficients making field calibration unnecessary.

The same approach to determining vertical and lateral load may also be used in the crosstie circuit. By determining the coefficients of Equation 3.1 and 3.2 from loading the crosstie circuit under known vertical and lateral load magnitudes, it would be possible to determine both load magnitudes from eight (8) separate strain gauge measurements. Again,with a large parametric study over various expected track conditions, these coefficients could potentially be made global rather than local to each installation.

Finally, exhaustive field instrumentation and measurement is recommended to validate the theoretical findings of this thesis and provide globally valid relationships over a variety of railroad track field conditions such as rail section material and geometric properties, crosstie spacing, crosstie geometric and material properties, rail pad and rail clip configurations, and ballast/subgrade support strengths.

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