An Onboard Load Measuring Device for Off-Highway Log Trucks

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ABSTRACT

This paper was motivated by the current concern of brake failure in off-highway log trucks descending steep grades and the lack of onboard weighing systems for off-highway log trucks. This paper considers using the leaf spring U-bolts as load transducers and is divided into two stages: preliminary strain measurement with a partially loaded off-highway tractor and finite element modelling (FEM) of a U-bolt from the tractor's leaf spring suspension. Preliminary results showed that incremental strain at two locations on the U-bolt varied linearly with payload, for an incremental load of 22.5 kN. FEM of the U-bolt was carried out to predict the maximum incremental strain occurring on the U-bolt surface for an incremental load of 105 kN. Incremental strain on the top of the curved portion of the U-bolt was found to be relatively constant and close to the maximum level of incremental strain and is recommended as a preferred position for the strain gauges.

Keywords: *strain measurement, load transducer, log truck, weight scale*

Introduction

Heavy-duty off-highway log trucks commonly consist of a tandem drive axle tractor and a tandem axle pole trailer. The typical loaded weight of these trucks is between 1049 and 1196 kN, with payloads of approximately 667 kN to 840 kN (Oakley and Marshall 1989). These trucks were designed for off-highway operation where axle loads and vehicle dimensions are not subject to regulations applied to public roads. In addition to the differences in size and weight between highway and off-highway log trucks, there are structural differences.

Due to the heavy payloads, drivers of these off-highway log trucks may have difficulty braking on steep hills. Road grade, speed, and the mass of the truck must be carefully managed when descending steep grades so that the required retardation power does not cause excessive brake temperatures resulting in brake fade (Parker 2004). The Workers Compensation Board (WCB) of British Columbia (WBC 2003) reported a fatal accident for a truck driver descending a steep grade with a heavily loaded off-highway truck. The recommendations in the WCB report suggested loads should be reduced for steeper grades to ensure vehicle control can be maintained.

Off-highway truck payloads are difficult to assess because these trucks are not equipped with on-board weighing systems and variations in wood density and load dimensions make visual estimates highly inaccurate. To date on-board weighing systems have not been developed for off-highway log trucks because it is common to load them until their volumetric capacity is reached rather than restricting loads to some maximum allowable axle weight.

In 2004, the British Columbia WCB asked the Forest Engineering Research Institute of Canada (FERIC) to develop a guideline for predicting the safe maximum grade for descending with various off-highway truck payloads. Utilizing the guideline will require limiting the load size of trucks by measuring their axle loads during loading. Numerous on-board load-measuring systems are available for highway log trucks. These systems typically employ strain gauge technology or air pressure gauges mounted on the air suspension. The differences between off-highway and highway log trucks make it challenging to adapt highway type load-measuring systems for use on off-highway tractors. Most notably the bunk roller ring diameter is much larger in the off-highway tractor unit, and it is an integral part of the tractor frame; therefore, it is not possible to mount the bunk pedestal and bunk roller ring on beams instrumented as load cells. Since it is not possible to use a load cell to measure the total load applied to an off-highway log truck tractor unit, it will be necessary to develop a load transducer from the suspension system.

The U-bolts that fasten the leaf spring packs to the trunnion shaft were considered a candidate location for a load transducer. In order to be a useful indicator of payload, the strain in the leaf spring U-bolt should vary linearly with payload, vary in a repeatable manner, and vary sufficiently over the range of axle loads to provide adequate resolution. The main advantage of having a linear calibration curve is that this greatly simplifies calibration of a system of multiple load transducers. This could be an important consideration when

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off-highway log trucks are working in remote locations without ready access to technical support or weigh scale stations.

Preliminary measurements indicated the incremental strain in the bottom leaf of the leaf spring pack could be an order of magnitude larger than the incremental strain in the U-bolt; however, the strain rate in the leaf spring is a nonlinear function of the load applied to the vehicle. In addition, the leaf spring gauge location on the bottom surface of the leaf spring pack was the most exposed of any suspension member considered, and reliability of the leaf spring strain rate due to unnoticed cracks in the leafs was identified as a concern. Thus, the leaf springs are not considered a candidate for a load transducer in this paper.

An advantage of using the leaf spring U-bolts as load transducers is the ease of replacement of damaged strain gauges which is important given the severe operating environment experienced by off-highway truck suspensions. Leaf spring U-bolts, however, are pre-stressed in order to clamp the leaf spring pack, and this creates high initial strains that could mask the incremental axial strains due to log loads. In order to measure a strong signal on the U-bolt, it may be important to locate the strain gauges where a combination of axial and bending strains occurs.

The objectives of this paper are to:

1. collect preliminary strain data from the leaf spring U-bolt of an off-highway log tractor,
2. develop a Finite Element Model (FEM) of the leaf spring U-bolt system, and
3. consider preferred locations for the strain gauges on the leaf spring U-bolt.

Preliminary Strain Measurements

Sensor Location on the Hayes HDX Suspension

The installation of strain gauges to the Hayes HDX tractor and subsequent load testing was conducted in June 2004 at Hayes Forestry Services maintenance facility in Port Alberni, British Columbia. Two gauges were installed on the U-bolt and aligned to measure strain along the axis of the U-bolt (**Fig. 1**). These strain gauges were located on the shank portion of the U-bolt in order to avoid measurement variation caused by contact interaction between the U-bolt and the spring pad.

Instruments Used

The strain gauges used were type CEA-13-240UZ-120 (uniaxial gauges) from Measurement Group, Inc. The stated gauge factor was 2.12 ± 0.5 percent at 24°C. Each strain gauge was connected to a channel box (an SB-10 Switch and Balance Unit) as a single active arm of a Wheatstone bridge (**Fig. 1**). A Measurement Group System P3500 strain indicator was used to measure and record the strain values with a resolution of 1 microstrain. Four portable pad scales (model PT300) were used to measure the weight of each drive wheel assembly in response to different payloads.

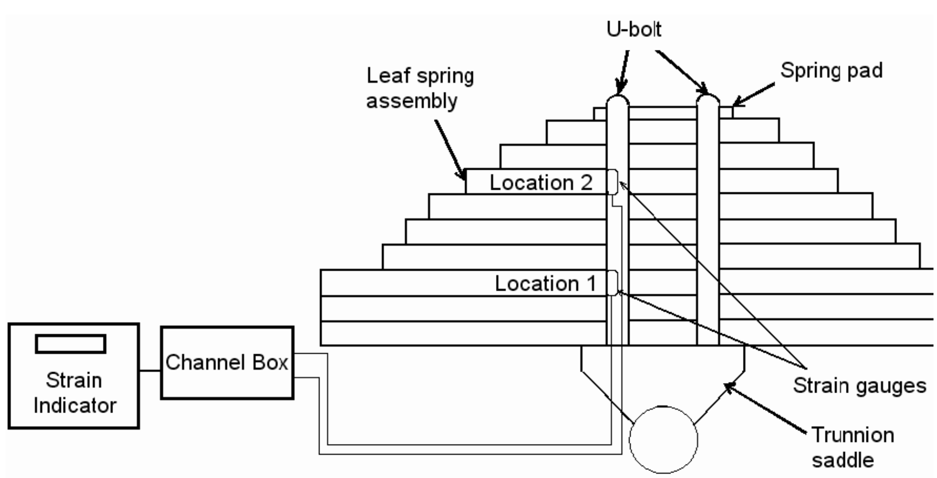

Figure 1. ~ *Strain gauge locations.*

Methodology

The preliminary strain data requires measurement of the U-bolt strain increment for a given increment in load applied to the tractor unit. The simplest way to vary a known load applied to the tractor unit is to vary the volume of water in a slip on water tank. Due to fire season constraints, only limited access was available to the water tank loaded HDX tractor. This necessitated applying the strain gauges to the U-bolt when the water tank was full and measuring the change in strain as the tank was emptied. Incremental strains and the wheel loads were measured in response to different payloads carried by the tractor on a flat surface; no test loads were measured on a slope. The procedure for measuring tractor payload and load transducer output was:

1. a slip-on water tank was installed on the log bunk of the Hayes HDX tractor,
2. strains were measured in the U-bolts while the volume of water in the slip-on tank was varied from full to empty, with the weight of water carried by the tractor at any time being the volume of water in the tank multiplied by a density of 1000 kg/m^3, and
3. the drive axle wheel loads were measured with the tractor parked on four portable pad scales on a level paved surface.

Results and Discussion

The maximum weight of water added to the tractor corresponded to approximately 21.5 percent of a typical full drive axle group payload for a Hayes HDX. The incremental differences show a strong correlation between the weight of water carried by the truck and the total drive axle group weight. For example, a total of 90 kN of water were removed from the tank and the resulting decrease in total drive axle group weight was 87 kN. This indicates that additional payload added to the truck would be carried almost entirely by the drive wheels and little or none would be transferred to the steer wheels when the truck is on level ground. For travel on slopes, the load shift onto or off of the steering axle could be estimated using a simple geometric relationship.

Figure 2 presents the measured strains on the shank portion of a leaf spring U-bolt in response to incremental load. The resolution of the strain indicator used in this test was 1 microstrain and the increments in the applied load were approximately 10kN. Given the strain rate of the U-bolt due to the incremental loads it could take two to three load steps for the strain indicator to read 1 microstrain change in strain (**Fig. 2**). This resulted in a load resolution of approximately ± 18 kN for the range of incremental loads tested. If this resolution was consistent over the full range of loading, the measurement error for a fully loaded drive axle group would be 3.3 percent (i.e., 18 kN/540 kN).

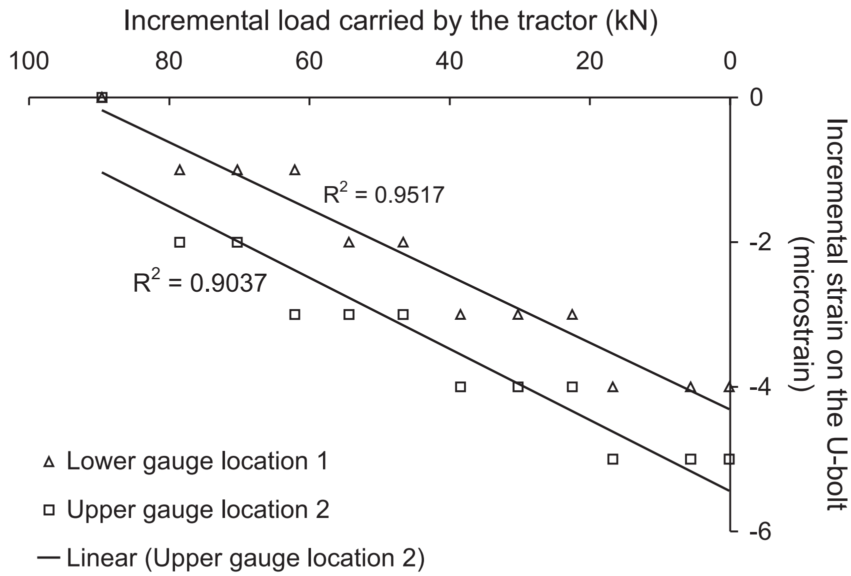

Figure 2. ~ *Incremental axial strain measured in two locations on a leaf spring U-bolt during unloading with strain gauges applied when tractor was loaded.*

The incremental strains from both strain gauges had very similar slopes for the range of incremental loads measured. The strain at location 2 on the U-bolt also was consistently about 1 microstrain higher than at location 1 for the range of incremental loads measured. Given the limited amount of testing, it cannot be conclusively stated whether the difference in measured incremental strains at locations 1 and 2 was due to differences in strain instrumentation or whether the leaf spring U-bolts are subjected to bending. The result shows the linear relationship between the incremental load and the incremental strain; however, the magnitude of the strain variation with payload was small (i.e., no more than 5 microstrains up to a maximum incremental payload of 90 kN).

U-bolts in the Hayes HDX suspension are normally tightened (preloaded) in order to ensure the leaf springs remain clamped, and therefore are under high axial tension even when the truck carries no payload. The preload in the U-bolt could be estimated using the following formula (Dayton Parts Ltd. 2001) that relates torque and bolt cross-sectional area (diameter) to preload:

$$Preload = \frac{Torque}{K \times Diameter} \qquad [1]$$

The torque coefficient, *K*, is a measure of the friction between the nut and the U-bolt threads and the thread pitch. A value of 0.2 was specified for *K*, as per conventional practice which assumes that the bolt is new and lubricated (Dayton Parts Ltd. 2001). The torque for the leaf spring U-bolts was taken to be 1760 N-m, based on discussions with Hayes Forest Service about their torqueing practice. Using the above parameters, Equation [**1**] estimates a preload of 231 kN for a 38.1-mm diameter U-bolt. The external load transferred from the trunnion saddle to the rear drive axle was estimated to be 22.5 kN (i.e. one-fourth of 90 kN payload from the water). The small strain variation for the range of payloads tested may have been due to the large amount of preload in the U-bolt (Norton 1996) and because the maximum test payload was only about 25 percent of a full payload. The linear relation in **Figure 2**, however, indicates that U-bolts have some potential as load transducers provided that their strain rate is repeatable.

FEM Construction

Overview

Preliminary measurements indicated that the axial strain developed in the leaf spring U-bolts varied linearly with increasing payload. A FEM will be created to examine the strain distribution over the entire U-bolt surface in order to optimize the placement of the strain gauges. Due to their design, U-bolts can be subject to a bending load. The FEM will allow an examination of the U-bolt surface for areas subject to increased strain due to a combination of axial and bending strains. Two aspects of the U-bolt problem complicate the analysis. First, the interaction between the U-bolt and leaf spring is a contact problem. Second, the U-bolt is under a significant preload, which results in reduced incremental strains due to external loads (Norton 1996). Both of these complicating aspects can be modeled using ANSYS®.

FEM Description

The FEM begins with the construction of a three-dimensional geometric model of the U-bolt, leaf spring pack, and trunnion saddle assembly (**Fig. 3**). Friction between the leaf spring leafs and between the leaf and the spring pad was assumed to be high enough to restrict differential motion between them in the region of the U-bolt. Given this simplification and that our interest was confined to the U-bolt and its zone of contact with the spring pad and leaf springs (hereafter called the leaf spring), the leaf spring was modelled as a single block. A similar assumption was made in the region of the U-bolt ends and nuts and this allowed them to be modelled as if they were glued together and to the bottom of the trunnion saddle. In addition, the trunnion saddle had a complex geometry, so it was modelled as a block to reduce its modelling requirements. The overall number of nodes available for modelling was limited, and these simplifications resulted in more nodes being available for modelling the U-bolt. More nodes were required for modelling the U-bolt because an accurate strain distribution was needed for comparison with the field measurements and for investigation of the U-bolt surface to identify suitable gauging locations.

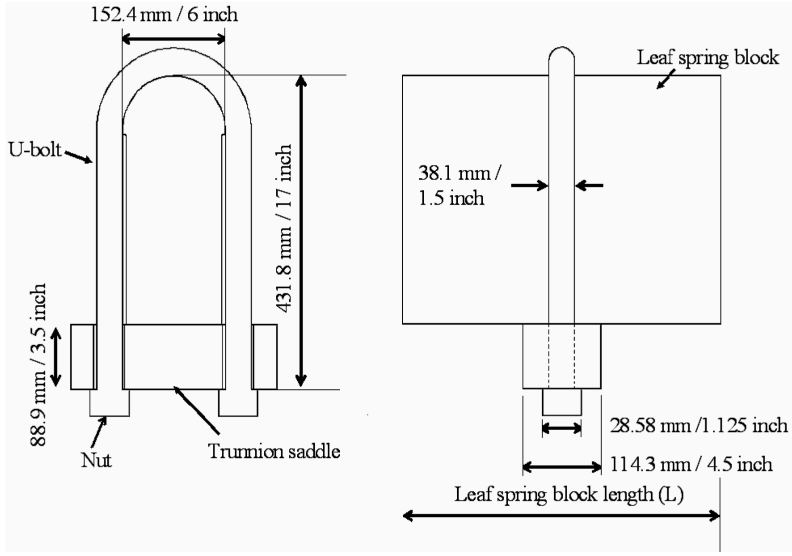

Figure 3. ~ *Schematic of the U-bolt assembly.*

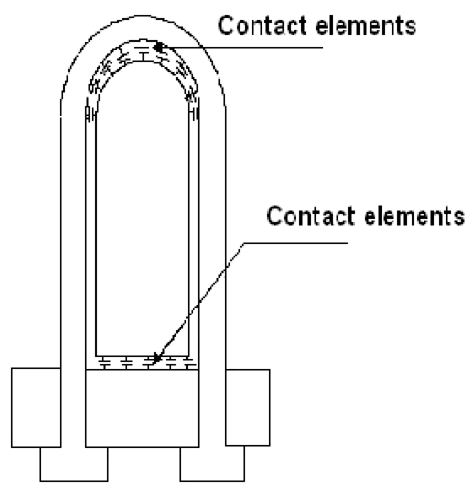

Figure 4. ~ *Location of contact elements.*

Next a structural model was created with SOLID92 elements sourced from the ANSYS element library. These quadratic three-dimensional tetrahedral elements were used instead of simpler three-dimensional linear tetrahedral elements because the SOLID92 elements are more suitable for estimating strains in curved sections and are generally more accurate (ANSYS 2002). The SOLID92 element has 10 nodes with three degrees of freedom at each node.

When loaded, the U-bolt assembly undergoes a relative displacement at the contact interface. This must be accounted for in order to obtain an accurate predication of strain along the surface of the U-bolt. To model the relative displacement, surface-to-surface contact elements were placed between the curved portion of the U-bolt and leaf spring block, and also between the leaf spring block and the trunnion saddle (**Fig. 4**).

Surface-to-surface contact elements were modelled using ANSYS contact 174 and target 170 elements. These types of elements are capable of transferring forces and stiffness between the surfaces. The contact elements take the shape of the underlying elements (10-node tetrahedron in this FEM) and therefore appeared as triangular-shaped elements. The material used in the FEM was assumed to be linear elastic. The physical properties of individual suspension components are listed in **Table 1**.

Table 1. ~ *FEM component physical properties.*

Component	Type of steel	Property direction	Modulus of elasticity	Poisson's ratio	Thermal expansion coefficient at 21°C
			(GPa)		(10^{-6} m/m/°C)
U-bolt	4140 (Alloy)	Isotropic	210[a]	0.291[a]	12[b]
Leaf spring	5160 (Alloy)	Isotropic	200[c]	0.300[c]	13.5[c]
Trunnion saddle	Cast	Isotropic	200[c]	0.300[c]	13.5[c]

[a] Walsh 2000.
[b] Speck 1997.
[c] ASM 1999.

Meshing of the FEM

The meshing algorithm in ANSYS allows the degree of mesh coarseness to be selected by the analyst from a scale of 1 to 10, with 10 being coarsest. The entire U-bolt was meshed moderately densely (i.e., with a mesh coarseness of 6). A denser mesh (i.e., with a line refinement level of 2) was applied around the outside surface of the curved portion of the U-bolt and around the inside surface where the U-bolt contacted the leaf spring. A finer mesh results in the boundary of the body in the model being closer to the actual shape of the body and this reduces the effect of stress concentrations due to meshing (Saravi and Lyons 2004). The rest of the FEM components (i.e., leaf spring and trunnion saddle) were meshed coarsely (i.e., with a mesh coarseness of 8) because the overall number of nodes available was limited. **Figure 5** illustrates the FEM of the U-bolt assembly.

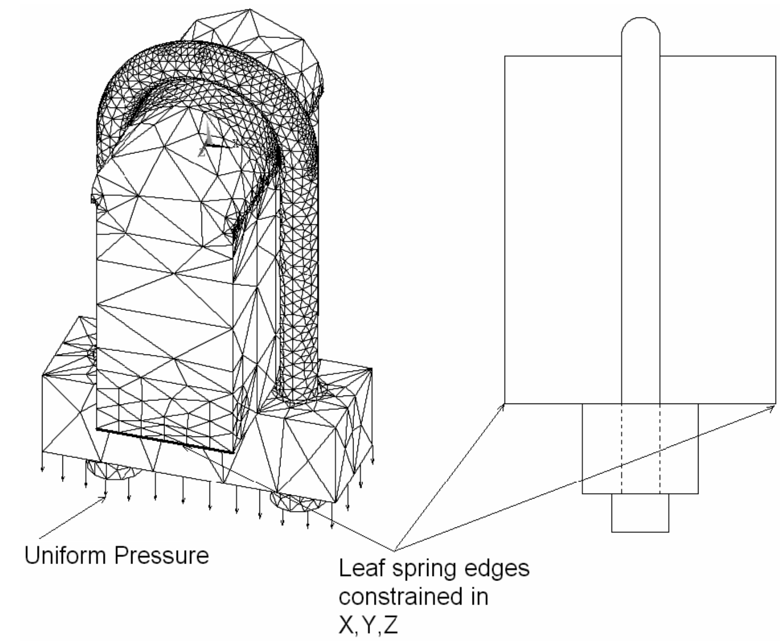

Figure 5. ~ *Boundary conditions and meshing.*

Load Steps and Boundary Conditions

For all load steps, the lower edges of the leaf spring were constrained to prevent translation in the X, Y, and Z direction (**Fig. 5**). In the first loading step, the U-bolt was preloaded using a thermal strain as suggested by Stalling and Hwang (1992). The procedure for modelling preload in the U-bolt was:

1. assign an appropriate coefficient of thermal expansion to the suspension components,
2. specify a uniform temperature (21°C) to the components,
3. specify a subzero temperature for the shanks of the U-bolt (**Fig. A.1**),
4. compute the U-bolt axial tension, and
5. iterate until the desired preload is achieved.

In the second loading step, an external load was applied to the bottom part of the trunnion saddle as a uniformly distributed pressure (**Fig. 5**).

Post Processing

The longitudinal strain was calculated along the U-bolt surface using the PATH command (ANSYS 2002). This command interpolates stress, strain, and displacement results between adjacent nodes along a straight line between two specified end points. In order to estimate the strain distribution along the U-bolt surface, the straight shank portion was analyzed separately from the curved portion. The strains along the U-bolt shank were expressed in conventional global coordinates: x, y, and z (**Appendix A**). Strains in the curved portion of the U-bolt were expressed in local coordinates (i.e., oriented in longitudinal, transverse, and normal directions to the surface). Strains along the curved portion of the U-bolt were transformed from global to local coordinates (**Appendix A**). Following these calculations, the incremental strain due to the external load applied to the U-bolt was calculated as the difference between the strains obtained in load step 2 (i.e., preload and incremental load) and load step 1 (i.e., preload only).

FEM Results

Parameter Analysis

Although many variables affect U-bolt behavior under external load, this analysis specifically investigated the effects of preloading, friction between the U-bolt and leaf spring block, and spring block length. A range of typical friction coefficients (from 0.1 to 0.3) was considered because the surface roughness was not known. A range of preload values from 142 kN to 303 kN was selected with the estimated preload being mid range. The results of the parameter analysis indicate the incremental strain is relatively insensitive to the magnitude of the coefficient of friction and to preload; therefore, mid-range values of 0.2 for the friction coefficient and 231 kN for the preload (that estimated from the field tests) were used in the subsequent analysis.

The phenomenon of interest in this paper is the incremental strain in the leaf spring U-bolt, and it is assumed this will not be affected by rigid body displacement of the U-bolt due to deflection of the leaf spring pack. Thus, the leaf spring pack was modelled as a solid block (with the spring leafs glued to one another) and also was shortened in order to reduce the number of nodes required to model it. The boundary condition used at the bottom edge of the leaf spring (**Fig. 5**) can create stress concentrations. It was expected that these stress concentrations would reduce the accuracy of strain estimates in the U-bolt, and that shortening the leaf spring block would exacerbate this effect. Therefore, a parameter analysis was performed to determine the minimum leaf spring block length that would reduce the effect of the boundary conditions. As noted by Oakley and Marshall (1989), the maximum payload on off-highway log trucks is 840 kN. Assuming the maximum payload is shared equally between the drive and trailer axles, and that the load directed to the drive axles is shared by four U-bolts, then the maximum load expected on a U-bolt is 105 kN. Thus, the uniform load applied to the bottom of the trunnion saddle was equivalent to 105 kN. The parameters used in the analysis of leaf spring block length and their values are listed in **Table 2**. Leaf spring block length was varied between 165 and 521 mm. The upper limit for the leaf spring block length was dictated by the maximum number of nodes that could be modelled holding the coarseness of the element mesh fixed at moderately coarse for the leaf spring block.

Figure 6 illustrates the relation between leaf spring block length and incremental strain at gauge location 1 on the U-bolt. It can be seen that variation in the incremental strain with respect to increasing spring block length is reduced for leaf spring block lengths of over 470 mm. The same finding was true for incremental strains at gauge location 2. Therefore, a leaf spring block length of 521 mm was used in all subsequent analyses.

Table 2. ~ *Run sequence inputs to evaluate leaf spring block length.*

Preload (kN)	231
Incremental load (kN)	105
Coefficient of friction	0.2
Leaf spring length (mm)	165, 216, 267, 368, 419, 470, 521

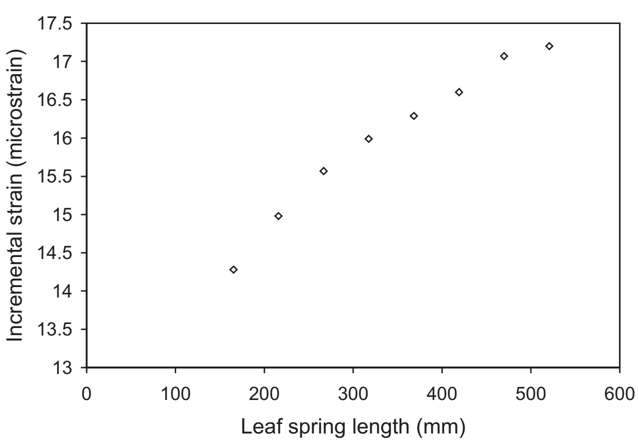

Figure 6. ~ *Incremental strain at gauge location 1 on the U-bolt for various leaf spring lengths (incremental load of 105 kN, preload of 231 kN, and U-bolt to leaf spring coefficient of friction of 0.2).*

Analysis of Incremental Strain

Figure 7 presents both the measured incremental stain and the incremental strain predicted by the FEM at gauge location 1. The measured and predicted incremental strains both vary linearly with the incremental load and have similar slopes. In the FEM, the magnitude of parameters such as preload and the coefficient of friction were selected independently of the measured data; therefore, the similarity between the measured and predicted incremental strains suggests the FEM is a reasonable approximation of the true system in the incremental load range used for the measured data. The FEM results indicate the relationship between the incremental strain and the incremental load remains linear up to the incremental load expected from a full load of logs.

Based on the results from the parameter analysis, the distribution of incremental strain along a line along the outside surface of the U-bolt was calculated using a leaf spring block length of 521 mm, an estimated preload of 231 kN, external load of 105 kN, and a coefficient of friction of 0.2 (**Fig. 8**). **Fig-**

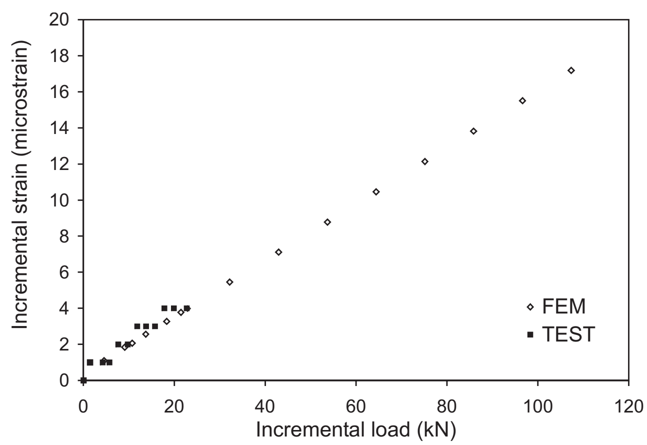

Figure 7. ~ *Comparison of the FEM data to the test data and strain prediction at full load for gauge location 1.*

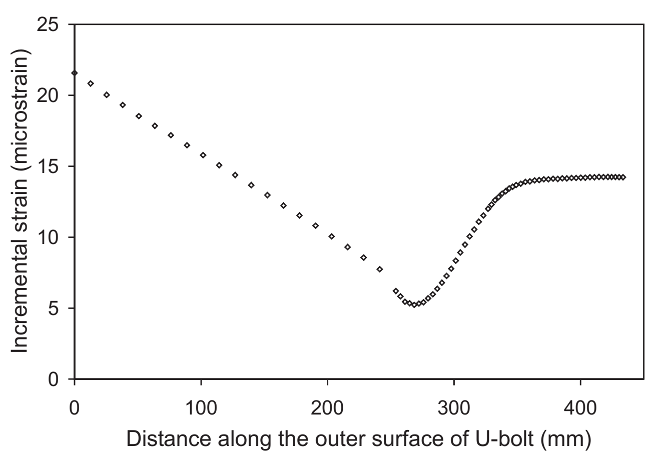

Figure 8. ~ *Distribution of incremental strain along the outer edge of the U-bolt surface (incremental load of 105 kN, preload 231 kN, and friction of coefficient of 0.2 between the U-bolt and the leaf spring).*

ure 8 indicates that the maximum incremental strain occurs close to the trunnion saddle and that it decreases uniformly from 0 to 220 mm along the U-bolt. Where the curved portion of the U-bolt joins the straight shank portion, the incremental strain changes rapidly and reaches a minimum (5.23 microstrain) at 268 mm. Incremental strain is relatively constant in the curved portion of the U-bolt from 353 to 433 mm (i.e., within 80 mm of either side of the apex of the curve). To investigate the source of bending the incremental strain on the inner surface of the U-bolt was calculated and compared to that of the outer surface. The strain curves for the inside and outside surfaces of the U-bolt shank were symmetric about the line *Incremental Strain* = 13.5 microstrain; therefore, the strains were likely generated by a superposition of both axial and bending loads.

One possible source of the bending in the U-bolt shank observed in the FEM may be a result of the curved portion of the U-bolt trying to retain its curvature while it is pulled in the loading direction. In response, the shank portion of the U-bolt is bent inwards at the intersection with the curved portion (**Fig. 9**). This inward deformation would be resisted by the fixed support at the bottom of the U-bolt shank. The U-bolt end is considered to be fixed because the shank portion of the U-bolt and nut are glued to the trunnion saddle in the FEM.

An objective of this paper was to propose the location of a strain gauge that will provide the strongest signal for the load transducer. The bending load identified in the FEM resulting from the displacement of the curved portion of the U-bolt may not provide a reliable signal. This is because the clearance between the shank portion of the U-bolt and the leaf spring is variable and if the shank is in contact with the leaf spring the bending load described above will not develop. Thus, a more reliable location for the strain gauge is the curved portion of the U-bolt where the magnitude of the incremental strain is almost as great as that found at the bottom of the shank, and it is relatively constant over the curved region.

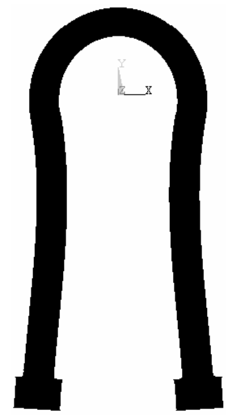

Figure 9. ~ *U-bolt deformed shape.*

Conclusions

In this paper the leaf spring U-bolt of an off-highway log truck was evaluated for use as a load transducer. The preliminary strain measurements indicated that the load-strain response of the U-bolt was linear for unloading over the tested range of external loads. A three-dimensional FEM was created to check the outer surface of the U-bolt for locations that developed the largest strain responses. The modelling was carried out in two loading steps. First, the U-bolt was preloaded, and then an external load was applied to the bottom of the trunnion saddle.

A parameter analysis indicated the incremental strain in the U-bolt was relatively insensitive to the magnitude of the coefficient of friction and the preload. The FEM predicted that U-bolt incremental strain was a maximum near the trunnion saddle and a minimum at the intersection of the shank and curved portions, and again near the maximum at the top of the curved portion. The predictions of strain in the U-bolt shank could be less reliable because they assumed no contact between the leaf spring block and U-bolt shank. In practice, there may not be sufficient clearance to develop the bending forces that generated the predicted strains in the shank. The incremental strains in the top of the curved portion of the U-bolt were relatively constant and were close to the largest observed in the U-bolt. Given the uniform strain distribution and the magnitude of the incremental strains in the curved portion of the U-bolt, it is the most promising location for strain gauging.

As seen in field testing and in the FEM results, the incremental strain in the U-bolt was small. The ability of strain gauges to detect small changes in strain is considered to be infinite; however, a resolution of 0.1 microstrain is the smallest practical value attainable because of the limitation of instrumentation and other performance factors (Window 1992). Given the equipment used in the preliminary strain measurements, the error estimated for a fully loaded drive axle group was found to be 3.3 percent; however, this error could be reduced by increasing the signal strength or the sensitivity of the strain indicator. The signal output of strain gauges can be increased by increasing the strain gauge sensitivity (gauge factor) or adding a signal amplifier. Strain gauge sensitivity can be improved through the use of higher resistance strain gauges supplied with higher input voltage. If an amplifier is used it should be located close to the strain gauges so that a minimum of noise from connecting wires is amplified. The next stage in development of the U-bolt load transducer is to build a prototype that takes advantage of higher resistance strain gauges and amplifiers and to test this on in-service trucks to determine if the signal is repeatable.

Acknowledgments

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APPENDIX A

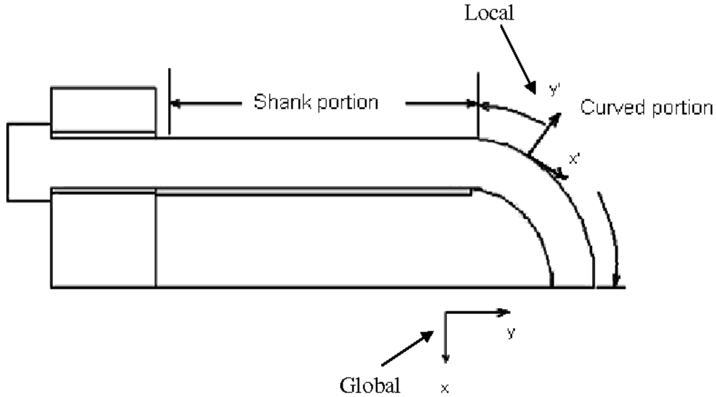

Figure A.1. ~ *Strain transformation along the curved portion of the U-bolt.*

If $\varepsilon_x, \varepsilon_y, \varepsilon_z, \gamma_{xy}, \gamma_{yz}$, and γ_{zx} are the three-dimensional strain components aligned with *xyz* coordinate system, then the strain component ε'_x with respect to node aligned along with the $x'y'z'$ coordinate system (Ragab and Bayoumi 1999) is:

$$\varepsilon'_x = \varepsilon_x l^2 + \varepsilon_y m^2 + \varepsilon_z n^2 + \gamma_{xy} lm + \gamma_{yz} mn + \gamma_{zx} nl \qquad [\mathbf{A1}]$$

where:

$\varepsilon_x, \varepsilon_y, \varepsilon_z$ = normal strains,

γ_{xy}, γ_{yz}, and γ_{zx} = engineering shear strains, and

l, m, and n = the directional cosine vector which was calculated from the unit tangent vector in ANSYS.

Note: ANSYS reports the engineering shear strain which is twice the tensor shear strain

$$\text{i.e.,}\quad \begin{aligned} \gamma_{xy} &= \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right) = 2\varepsilon_{xy} \\ \gamma_{yz} &= \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right) = 2\varepsilon_{yz} \\ \gamma_{zx} &= \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial y}\right) = 2\varepsilon_{zx} \end{aligned} \qquad [\mathbf{A2}]$$

where:

u, v, and w = the displacements in the *x, y,* and *z* directions, respectively, and

$\varepsilon_{xy}, \varepsilon_{yz}$, and ε_{zx} = the tensor shear strains.