25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-0212
STRESS MEASUREMENTS IN RAILWAY RAILS USING THE ULTRASONIC METHOD

Shirley Alexandra Garcia Ruano
Thairon Reis Costa
University of Campinas – UNICAMP, Campinas, São Paulo, Brazil,13083860
shirleyruano@fem.unicamp.br
thairon_reis@hotmail.com

Auteliano Antunes dos Santos Junior
University of Campinas – UNICAMP, Campinas, São Paulo, Brazil,13083860
aute@fem.unicamp.br

Abstract. *The present work demonstrates the application of the ultrasonic technique for the measurement of axial stresses in a steel rail loaded by a transversal force at its center. A single steel rail was subjected to a three-point flexure test on a universal testing machine. The maximum applied load did not exceed the elastic limit of the material. For each load increase, the uniaxial stress along the rail was measured using the ultrasonic method and 4 areas in the rail were evaluated. A simple numerical model was developed to compare the obtained results. The comparison between the measured stresses by the ultrasonic method and the stresses obtained by numerical simulation showed a good agreement.*

Keywords: *stress measurements, ultrasonic evaluation, steel rail, non-destructive evaluation*

1. INTRODUCTION

The constant demand for mass transportation in the railroad industry has encouraged several types of research in different areas. For the instrumentation field, the development and innovation of measurement techniques have always been of great interest, especially when they allow the prediction of the material's behavior.

One of the main concerns of the railroad sector is the Detail Fracture, a type of transverse fatigue-crack defect found in rails (Orringer, 1986). When the wheel passes over the rail, cyclic stresses are developed inside the material. If the load increases, the magnitude of the stresses may affect the failure propensity. Therefore, having an accurate system for stress determination on the rail would be very important for any service life estimation (Reis, 2018).

This work attempts to show the application of the ultrasonic method for stresses measurement. An ultrasonic probe was placed in a steel rail segment subjected to a static flexure test, a common laboratory test for mechanical characterization of rails. The flexure test represents the vertical load of the pressure transmitted through the wheels to the rail. This load produces tensile stresses on the base of the rail and compression along the railhead. When these stresses occur cyclically, the nucleation and propagation of cracks due to fatigue are favored. For this work, the stress measurements were performed in static regime at the laboratory; however, the system can be improved to be used on rails in service.

As shown by Eagle and Bray (1976), longitudinal ultrasonic waves propagating along the stress axis showed a significant variation in the wave velocity by the change of axial deformation for the railway steel. This phenomenon is known as the acoustoelastic effect. The potential use of this effect has been used in several works in order to evaluated applied and residual stress. In 1998, thermal stresses in continuously welded rails were monitoring using the ultrasonic method (Szelazek, 1998), shear waves propagated in the rail height direction, and longitudinal subsurface waves propagated along the rail were employed for the tests. The longitudinal waves showed highest sensitivity to stress, so it was possible to evaluate forces in track sections with longitudinal stresses. Minicuci et al (2006) used longitudinal critically refracted waves L_{cr} to evaluate stress variation in new railroad forged wheels, the measured stresses were compared with stresses obtained through a finite element approach presenting consistent results. Gokhale (2008) proposed a methodology using Rayleigh waves to determine the longitudinal stress in a rail specimen; he also compared analytical models for longitudinal, shear, Rayleigh, and Lamb waves for stress measurements. Recent work (Ruano, 2017) used the ultrasonic method to determine the residual stresses in a welded plate. A very similar procedure was used to perform the experiments in the current work.

The main goal of this study is to demonstrate the application of L_{cr} ultrasonic waves to measure the longitudinal stress produced by a flexure load applied on the rail. The results are compared with the stresses found in an element finite model.

The validation of this method could support the development of a nondestructive system for continuous stress measuring along the tracks.

2. THEORETICAL BACKGROUND

For this section, the principle of the ultrasonic method is briefly shown and for the element finite simulation, the proposed model will be described.

2.1 Ultrasonic method

The stress measurement using the ultrasonic method is based on the acoustoelastic effect, the linear relationship between the wave velocity variation and the stress changes in the material. For this propose, longitudinal waves that propagate parallel to the axial stress axis were used. These waves are known as critically refracted waves or L_{cr}. The ultrasonic wave is transmitted between two transducers: one for emission and the other one for reception. The transducers are positioned at a fixed distance; thus, the wave velocity variation can be found through the measurement of the time-of-flight (TOF) of the wave between them.

The acoustoelastic theory was initially formulated by Cauchy and has been extensively developed. For isotropic materials, the stress can be calculated using the “Eq. (1)”, as published by Bray and Stanley (1996).

$$d\sigma=E(t-t_0)/(L_{11*}\, t_{ref}) \quad (1)$$

In the previous equation, σ is the axial stress, E is the elasticity modulus, L_{11} is the acoustoelastic coefficient of the longitudinal wave propagating along the axis of the axial stress, t_{ref} is the theoretical propagation time of the wave within the tested material, t_0 is the wave propagation time for the stress-free state, and t is the measured TOF.

The velocity of the ultrasonic wave is also influenced by other than stress factors: material chemical composition, material texture, and temperature (Thompson et al, 1995). It was considered that the composition and texture of the material remain constant for the same measuring position. Thus, it is necessary to consider the temperature influence on the TOF variation. In addition, the calculated stresses are not punctual, they represent the stress variation along the ultrasonic wave path.

2.2 Finite element model

A simple three-point flexure test was simulated using the finite element method or FEM. The FEM model consists in a three-dimensional rail represented by 714070 Eight-Node Linear Hexahedral Solid Elements with size of 2 mm, approximately. Concerning to the boundary conditions, a central surface was defined, which is free to translate only along to the *z* direction. To represent the supports, the base rail nodes placed at 200 mm from the ends of the rail were restricted to translate along the *z* direction. The load *F* was applied at the center of the rail on a line in the railhead. “Figure 1” illustrates the central surface and the support points represented by P1 and P2. The simulation was performed in ABAQUS® software.

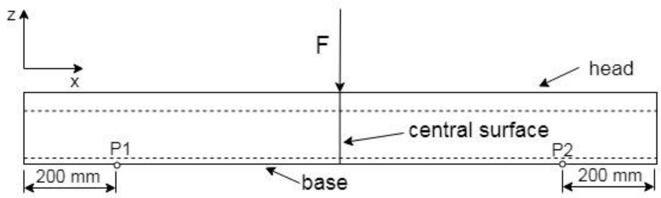


Figure 1. Schematic representation of the FE model.

3. EXPERIMENTAL SETUP

The L_{cr} wave propagates parallel to the surface due to the oblique incidence of a longitudinal wave between two media. According to Snell's law, an angle of 27 degrees on a PMMA wedge produces a L_{cr} wave in the rail steel. The measurement device is composed by an ultrasonic probe formed by transducers, wedges for L_{cr} wave generation, and a support plate that keeps the set of transducers and wedges in a fixed distance; a USB pulser-receiver with 50MSPS A/D converter; and a notebook (see “Fig 2”). The data processing was developed within LabView® platform.

A two meters long TR57 steel rail was placed in a universal testing machine for a common three-point flexure test. The supports were placed at 200 mm from the ends and the load was applied at the center of the rail. The ultrasonic probe was fixed to the rail at the measurement positions using magnets.

The axial stress was measured on the head and on the base of the rail. For the head, two positions were selected: just below the applied load on the lateral surface of the head (H1) and 300mm from the center of the rail on the same surface (H2). The base of the rail was evaluated in a similar way, at the center (B1) and 300mm away (B2); in both cases, the probe was aligned to the middle line of the rail base. “Figure 3” shows the probe position on the rail.

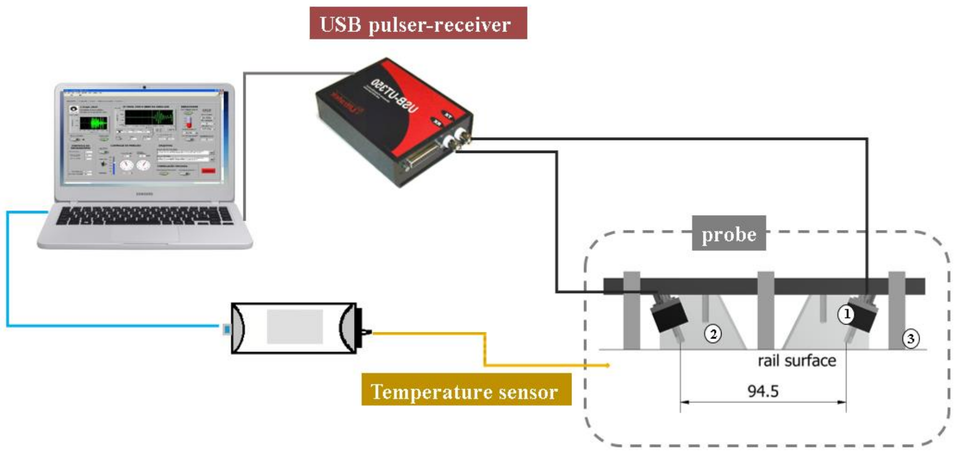


Figure 2. Measurement device. (1) Transducer (2) PMMA wedges (3) Magnetics in the contact.

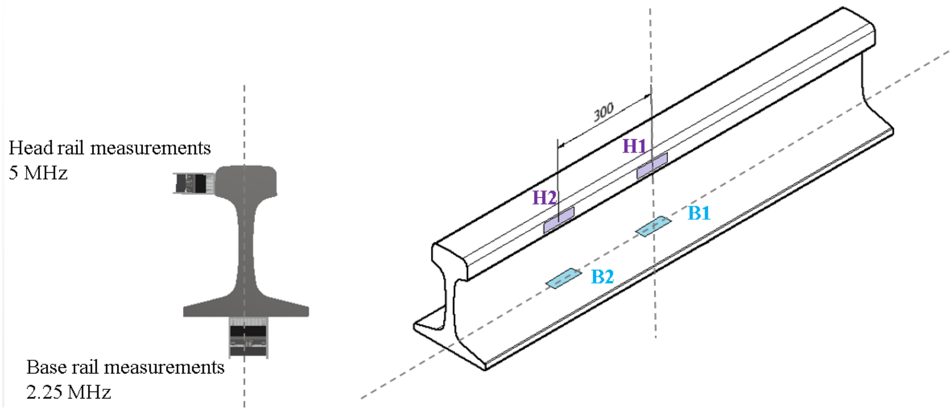


Figure 3. Position of the probe on the rail.

With the probe fixed to the rail, the TOF of the wave was measured for the stress-free state. Without removing the probe, the center load was applied, increasing in steps of 20 kN. For each load increase, the wave propagation time was registered. To ensure only elastic deformation in the material, the maximum applied load was 200 kN. This procedure was repeated at each measurement position. 5 MHz transducers were used for the measurements on the head and 2.25 MHz for the measurements on the base of the rail. The frequency of the transducer is related to the depth of the wave penetration. The higher the frequency, the lower wave propagation depth. Previous studies (Fraga, 2007) revealed that this depth is approximately equivalent to 1.8 times the wavelength, at most.

4. RESULTS AND DISCUSSION

Two types of results are present in this section. The influence of temperature on the wave TOF is evaluated to correct the time measured in the experiment. Then, the calculated longitudinal stresses are presented and compared with those obtained from the simulation based on finite element method.

4.1 Temperature influence on L_{cr} waves

For the evaluation of the wave velocity variation as a function of temperature, a calibration experiment was carried out. A specimen of the rail was taken to a laboratory with temperature control. Thereby, using the same probe, the TOF of the wave was recorded while the temperature changed, the results are shown in “Figure 4”. The relation between the TOF and the temperature is practically linear, the slope of the straight line indicates that the travel time increases with a rate of 12.6 ns/°C. Using this parameter, the measured TOF in the experiment was corrected for a standard temperature of 24 °C.

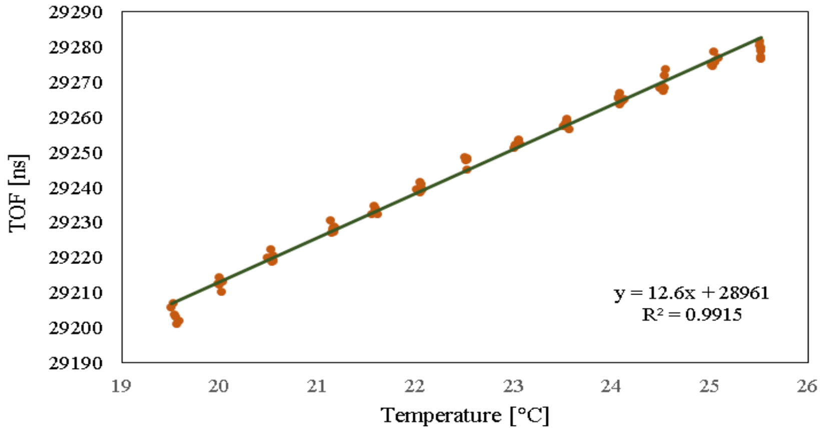


Figure 4. TOF of the L_{cr} wave as a function of temperature.

4.2 Stress evaluation

The σ_{11} stress measured experimentally is shown in "Tab. 1". To find these values, an elastic modulus of 210 GPa and an acoustoelastic constant of 2.45 were used (Eagle and Bray ,1976). To calculate the theoretical reference of the propagation wave time (t_{ref}), the velocity of the longitudinal wave in steel of 5900 m/s was used. The distance between the transducers was 94.5 mm.

Table 1. Stresses at the measured positions determined using L_{cr} waves.

Applied load [kN]	Axial stress σ_{11} [MPa]			
	Head rail		Base rail	
	H1	H2	B1	B2
20	-22.56	-11.70	16.22	21.27
40	-49.10	-20.48	33.80	43.83
60	-66.83	-29.17	62.88	54.63
80	-79.45	-39.76	82.77	61.35
100	-98.80	-55.78	100.71	69.84
120	-114.67	-80.40	136.67	72.69
140	-130.81	-98.09	143.43	92.44
160	-142.11	-109.89	180.64	109.00
180	-168.58	-118.91	194.65	114.97
200	-191.78	-128.08	214.57	131.42

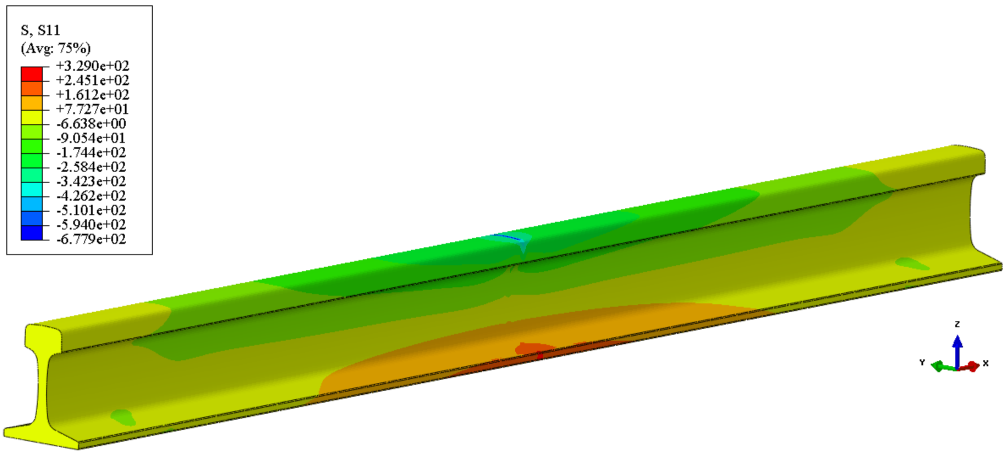


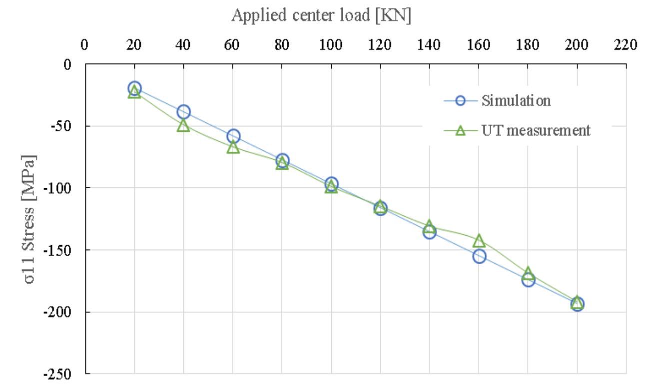
Figure 5. Longitudinal stress distribution.

The longitudinal stress distribution obtained by the finite element method is presented in "Figure 5". In order to have values closer to those determined experimentally, an average among all the nodes in the mesh that belong to the ultrasonic path was considered. For this case, the path is the area defined by the distance between transducers and the penetration depth of the wave. The penetration depth is 4.7 mm at the base of the rail, and it is 2.12 mm at the head of the rail.

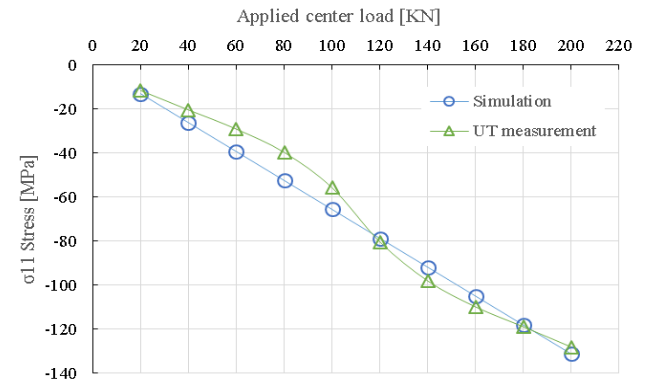
The mean values are shown in "Tab. 2". The stresses were obtained for each level of applied load in order to compare them with the experimental results. The setup of the model is symmetrical; therefore, either side can be considered as the lateral measurement position.

Table 2. Axial stress at the measured positions from the FEM simulation.

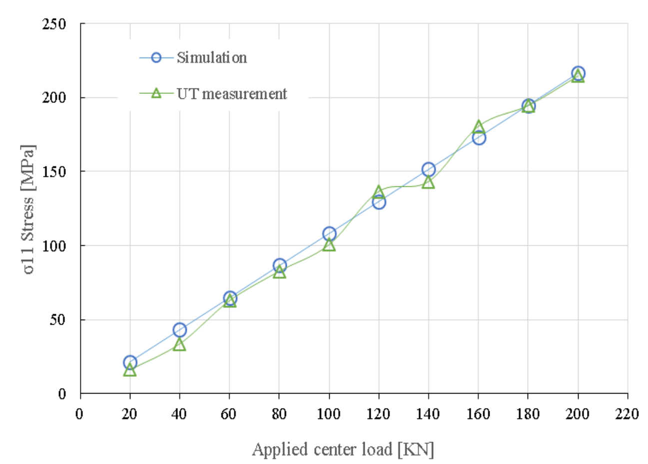
Applied load [kN]	Axial stress σ_{11} [MPa]			
	Head rail		Base rail	
	H1	H2	B1	B2
20	-19.32	-13.13	21.65	13.39
40	-38.64	-26.25	43.31	26.79
60	-57.96	-39.38	64.96	40.18
80	-77.28	-52.51	86.62	53.57
100	-96.60	-65.63	108.27	66.96
120	-115.93	-78.76	129.93	80.36
140	-135.25	-91.88	151.58	93.75
160	-154.57	-105.01	173.24	107.14
180	-173.89	-118.14	194.89	120.53
200	-193.20	-131.26	216.55	133.93



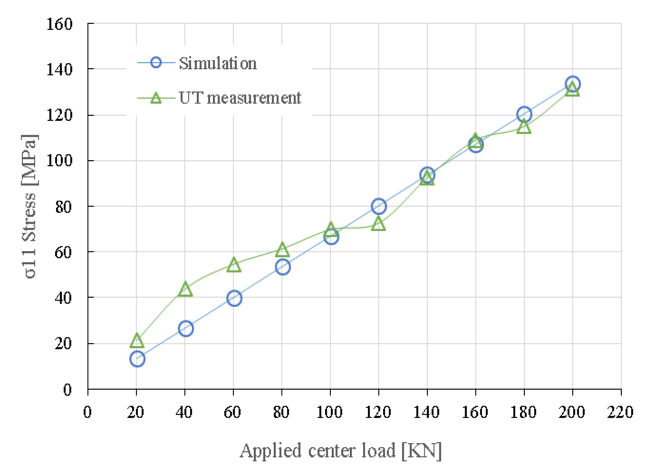
Lateral surface of head rail, center.
H1 position.



Lateral surface of head rail, 300 mm from the center.
H2 position



Bottom surface of base rail, center.
B1 position.



Bottom surface of base rail, 300 mm from the center.
B2 position

Figure 6. Experimental and simulation results comparison

The results for the findings are showed in "Fig. 6". From the experimental and the numerical simulations, we can see that the obtained values are very consistent. The maximum difference found is approximately 15 MPa. Previous studies with the ultrasonic method have reported a dispersion up to 5% of the yield limit (Andrino et al, 2007). Considering this criterion, the difference between the measured and the simulated values could be admissible. It can also be noted that the most dispersed results are those corresponding to the measurement of the base, which could be explained by the difficulties involving the fixation of the probe.

5. CONCLUSIONS

The results obtained employing the ultrasonic method agreed with the stresses obtained with simulation based on FEM. It is clearly appreciable that there is a variation of the wave time due to the change of the stress state inside the material and it was possible to identify the regions subjected to traction and compression. It shows that the ultrasonic technic is a potential tool to identify stress values, especially in elastic regimes.

Some differences between results could be explained by the fact that the ultrasonic path is volumetric, and we only considered the area formed by the distance between transducers and the penetration depth, which it is clearly an approximation. Another possible cause of the differences, especially at low stresses, is related to fixation of the probe. It was placed at the region of greatest deformation, which could alter the distance between transducers.

Although there are some improvements to be applied to the measurement procedures and the ultrasonic technique here employed, this work proved that the stress measurement with L_{cr} waves can be employed to evaluate stress in rails, allowing the development of new equipment for inspection of tracks.

6. REFERENCES

Andrino, M.; Caetano, S.; Santos, A. e Gonçalves, R., 2002. "Avaliação das tensões em chapas de alumínio 7050 utilizando o efeito acustoelástico". In *Proceedings of 6th Conference about Technology for Equipments-COTEQ*. Salvador, Brazil.

Bray, D. E., and Stanley, R. K., 1996. *Nondestructive evaluation: a tool in design, manufacturing and service*. CRC press.

Egle, D. M., and Bray, D. E., 1976. "Measurement of acoustoelastic and third-order elastic constants for rail steel". *The journal of the Acoustical Society of America*, Vol. 60, No. 3, pp. 741-744.

Fraga, R. D. S., 2007. *Avaliação da profundidade de penetração de ondas longitudinais criticamente refratadas.* Master thesis, Universidade Estadual de Campinas, Campinas, Brasil.

Gokhale, S. A., 2008. *Determination of applied stresses in rails using the acoustoelastic effect of ultrasonic waves.* Master thesis, Texas A&M University, USA.

Minicuci, D. J., dos Santos Júnior, A. A., Andrino, M. H., and de Carvalho Santos, F., 2006. "Stress evaluation of railroad forged wheels by ultrasonic testing". *Journal of Testing and Evaluation*, Vol. 35, No. 1, pp. 66-74.

Orringer, O., Morris, J.M., and Jeong, D.Y., 1986. "Detail fracture growth in rails: test results". *Theoretical and Applied Fracture Mechanics*, Vol. 5, No. 2, pp. 63-95.

Reis, T., Lima, E., Bertelli, F., and dos Santos Júnior, A. A., 2018. *"Effect of plastic accumulation on the nucleation of cracks in railroad rails due to bidirectional loaded traffic." International Journal of Fatigue*, Vol. 117, pp. 196-205.

Ruano, S. A. G., Bertelli, F., and dos Santos, A. A., 2017. *"Evaluation of 7050 Aluminum Plates Joined by Friction Stir Welding Using Acoustoelastic"*. In *ASME 2017 International Mechanical Engineering Congress and Exposition*. Tampa, US.

Szelazek, J. J. E. N. T., 1998. *"Monitoring of thermal stresses in continuously welded rails with ultrasonic technique." Electromagnetic Nondestructive Testing.* Vol. 98.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.