Non-destructive ultrasonic measurement of longitudinal stress in railway tracks

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Abstract. The stress state of rail is a crucial parameter which impacts rail safety and reliability through altering the risk of track buckling and pull-apart events. Understanding the stress state of existing rail networks is therefore of great importance to rail operators. Current stress measurement techniques for railway tracks are either destructive, slow, inaccurate, complicated or require calibration. Ultrasonic measurement of rail stress could potentially alleviate some of these deficiencies. In this work, ultrasonic sensor assemblies were constructed using piezoceramic elements to generate both longitudinal and shear waves. The ultrasonic waves were transmitted across the rail web in pulse-echo and reflections captured were processed to deduce the longitudinal stress. The method was validated through laboratory testing and subsequently with onsite field trials to a minimum accuracy of ±45 MPa.

Introduction

Prior to the mid-1960s, railway tracks were laid in sections of 60 ft in length and bolted to the next section through fishplates. The gap between the rail sections allowed for thermal expansion during hot weather however at the expense of poor track alignment, increased maintenance [1] and reduced ride characteristics (comfort, train speed) [2]. To alleviate this, continuously welded rail (CWR) was introduced in the mid-1960s, and this make up most of today's modern railway tracks in the UK with over 500,000 km of CWR laid across the world [3]. Due to the elimination of expansion joints, CWR are prone to thermally induced longitudinal stress [4]. Ambient temperature fluctuations ranging from -10 to +40°C [5] could induce rail buckling or pull-apart in hot or cold extremes. Such instances could cause derailment which subsequently impacts rail safety and reliability. Consequently, monitoring of longitudinal stresses in CWR is of considerable interest to rail operators. A wide range of methods exist for measuring longitudinal rail stress. Current practice is based around two techniques: rail cutting and rail lifting [6]. Both methods produce accurate rail stress measurement, however, are destructive, time consuming and require costly track closure, maintenance personnel and machinery [6]. Alternate methods include strain gauge [7], magnetic [8], x-ray diffraction [9], and fibre optic [3]. These techniques either require calibration, surface preparation, lengthy preparation time, high equipment cost or knowledge of the stress-state and properties of rail prior to installation. Ultrasonic approaches [10,11] were attempted in the past with relative success and as such will be the focus of this study. Ultrasonic sensor assemblies consisting of longitudinal and shear sensors were constructed using piezo ceramic elements. The aim of this study is to validate the ultrasonic stress measurement technique.

Background

The propagation speed of ultrasonic waves traveling within a medium is influenced by the stress state in the medium. This is termed the "acoustoelastic effect". Eq. 1 and 2 shows the variation in propagation speed of shear waves polarised orthogonally relative to each other and travelling perpendicular to the principal stress, where V_{zx} and V_{zy} are speed of shear waves propagating in the z-axis and polarized in the x and y-axis respectively, ρ_0 is the unstressed density, v is the Poisson ratio, ε_x is the strain in x-direction, λ and μ are second order elastic constants and l, m, n are third-order elastic constants [14].

$$\rho_0 V_{zx}^2 = \mu + \left[(\lambda + 2\mu + m)(1 - 2v) + \tfrac{1}{2}nv\right]\varepsilon_x \quad (1)$$

$$\rho_0 V_{zy}^2 = \mu + \left[(\lambda + m)(1 - 2v) - 6v\mu - \tfrac{1}{2}n\right]\varepsilon_x \quad (2)$$

Subtracting Eq. 1 with 2 yields the birefringence relationship which relates the difference in propagation speeds between two shear waves polarised orthogonally, $\left(V_{zx}^2 - V_{zy}^2\right)$ with the stress, σ experienced by the material. Thus, through experimentally measuring the constants μ and n for rail steel, longitudinal stresses within rail track can be measured using shear sensors.

$$\rho_0\left(V_{zx}^2 - V_{zy}^2\right) = \left(1 + \frac{n}{4\mu}\right)\sigma \quad (3)$$

Methodology

Laboratory validation tests were carried out on an EN24T test specimen loaded in a hydraulic tensometer. Fig. 1(a) & (b) shows a schematic and photo of the experimental setup. EN24T was used as its material properties are similar to that of rail steel. The specimen was instrumented with strain gauges and thermocouples. Two sensor assemblies consisting of piezo ceramic elements were clamped onto the specimen to allow ultrasonic waves to propagate in the direction perpendicular to the applied tensile stress. A thin layer of couplant was applied between the sensors and test specimen to maximize signal transmittance. The test specimen was loaded in tension and ultrasonic measurements were captured at 5 kN loading steps between 0 to 60 kN and 6 sets of data were captured with each consisting of a loading and unloading cycle. Fig. 1 (c) shows the setup for on-site field trials where 3 sensor assemblies were mounted within a rectangular bar and clamped onto the rail. Initial onsite trials were carried out on rail with R260 56E1 profile.

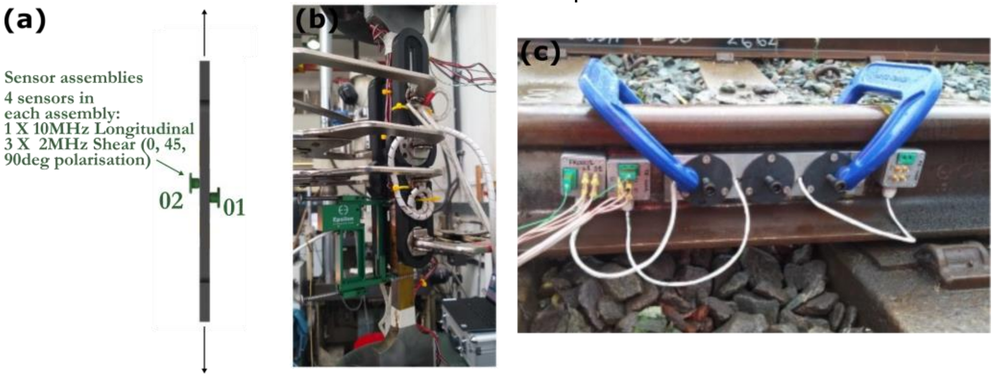

Figure 1 – (a) Schematic and (b) photo of the EN24T laboratory validation test and (c) photo of on-site field trial

Results

Fig. 2 shows the ultrasonically measured tensile stress through laboratory testing on an EN24T specimen using two different sensor assemblies (1 & 2) with zero-compensation. Zero-compensation was necessary due to varying values of offsets at zero stress for each loading and unloading cycle. This was thought to be resulted primarily from the varying clamping pressure applied to the sensors across each test data. After compensation, the ultrasonically measured stress agreed well with the applied tensile loading. Interestingly, measurements from Sensor assembly 2 show less scatter compared to Sensor assembly 1.

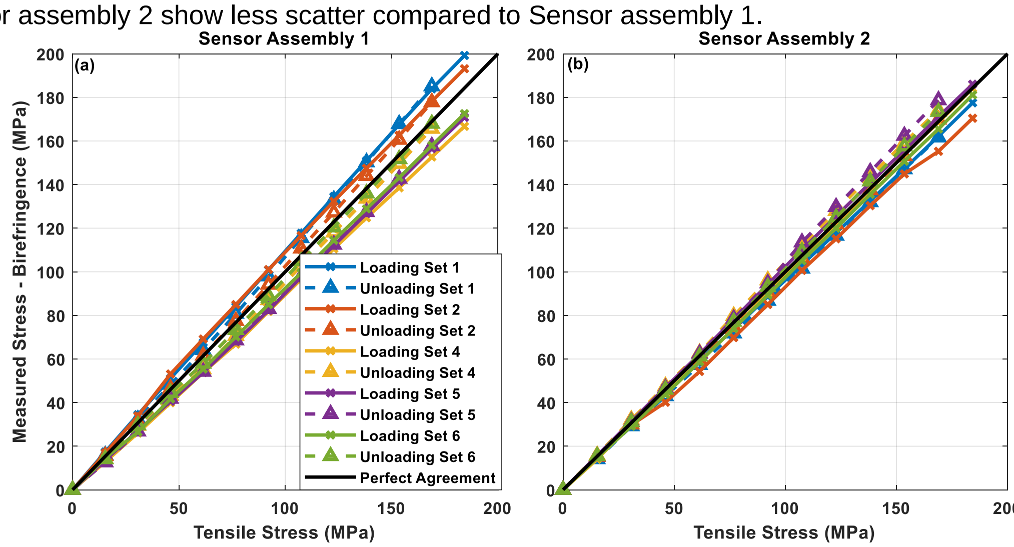

Figure 2 – (a) Applied tensile stress against measured birefringence stress for 6 loading and unloading steps using sensor assemblies (a) 1 and (b) 2 with zero-compensation

Conclusion

Ultrasonic shear waves propagated perpendicular to the primary stress were successfully used to measure the longitudinal stresses within an EN24T specimen as well as 56E1 rail to a minimum accuracy of ±45 MPa.

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