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Non-Destructive Methods to Appreciate the State of Stesses and Cracks in Wheels and Railroads

The paper proposes three non-destructive experimental methods in order to establish some criterions for the maintenance inspections of the railroads.. The first experimental method consists in drilling the railroad in different areas (head, basement and core of the rail profile).The bending capacity of the railroad is not adulterated after the drilling procedure . The residual surface stresses vanished around the hole, the deformations along 3 directions are measured with a rosette transducer and the values of the previous residual stresses will be calculated . The periodical ultrasonic inspection has been performed with a portable ultrasonic crack detector.

***Keywords**: tram, rail, maintenance, transducer, strain*

1. Introduction

The city of Timişoara is located in the south-west Romania`s side ,closely to the border with Serbia & Montenegro and Hungary. Timişoara cover a surface of 44 km^2 and has a population of 335.000 inhabitants. An ancient and meaningful tradition of the urban public transportation is represented by two important dates: 1869,July,8,when the first tram line for horse traction trams has been inaugurated respectively 1899,July,27, when the electric driving tram public transportation began into operation. The main public operator is the Autonomous Transport Administration Timişoara (R.A.T.T.) which continues a tradition of 130 years. Today R.A.T.T. provides 57,7% of the city transportation, which means 52 millions of people transported in a year. The tram line network pass through narrow streets on a total distance of 90,2 km.The swampy soil is non-adequate for an underground transportation ,so the surface transportation is prevalent. A part of the railroads have a very old design (1928-1935).During last years ,the wear of the rail and the level of noise strongly increased. So, the modernization of the tram line network became a necessity. Moreover, the European Community`s requests regarding the safety and the comfort of the passengers impose the implementation of a new system. Today, a lot of the tram lines are under a complete modernization process. Because of saving costs reasons ,some of the railroad lines have to be kept in service and rectified from time to time without dismantling.

2.The Strain Gage Measurements

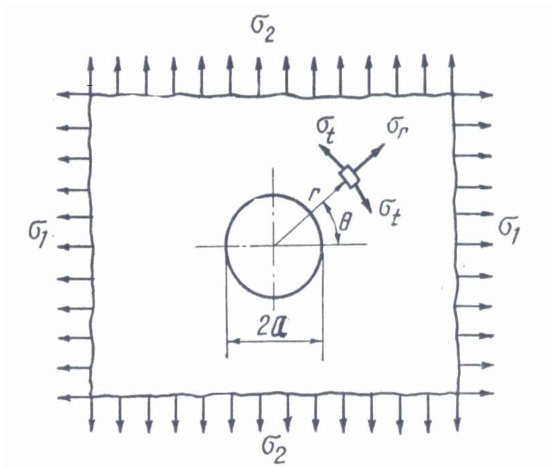

Figure 1. The state of stress in polar coordinates in a plate around a hole

At first, the strain gage "drilling method" and the experimental results are presented , [1],[2]. The method consists in drilling the railroad in different areas (head, basement and core of the rail profile).Usually the hole diameter is of 6 mm and the depth is of 9mm.The bending capacity of the railroad is not adulterated after the drilling procedure and it may be kept in service. As a consequence of the drilling process, the residual surface stresses vanished around the hole, the deformations after three directions are measured with a 3/120 rosette transducer and the values of the previous residual stresses will be calculated with a special software. There are noticed in figure 1: 2a-the hole diameter; σ_r -the radial stress; σ_t –the circumference stress; σ_1-the main maximum stress; σ_2-the main minimum stress; r-the radial distance between the center of the hole and the point of interest; θ-the central angle.

For a reference plate without any hole (a=0) ,the radial and circumference stresses are,[2]:

$$\sigma_r` = \frac{1}{2}(\sigma_1+\sigma_2)+\frac{1}{2}(\sigma_1-\sigma_2)\cos 2\theta \ , \qquad (1)$$

$$\sigma_\theta` = \frac{1}{2}(\sigma_1+\sigma_2)-\frac{1}{2}(\sigma_1-\sigma_2)\cos 2\theta \ . \qquad (2)$$

Than, when the hole is drilled in the plate, the stresses became:

$$\sigma_r`` = \frac{1}{2}(\sigma_1+\sigma_2)(1-\frac{a^2}{r^2})+\frac{1}{2}(\sigma_1-\sigma_2)(1-4\frac{a^2}{r^2}+3\frac{a^4}{r^4})\cos 2\theta, \quad (3)$$

$$\sigma_\theta`` = \frac{1}{2}(\sigma_1+\sigma_2)(1+\frac{a^2}{r^2})-\frac{1}{2}(\sigma_1-\sigma_2)(1+3\frac{a^4}{r^4})\cos 2\theta, \quad (4)$$

and the variation in stress will be:

$$\Delta\sigma_r = \frac{1}{2}(\sigma_1+\sigma_2)\frac{a^2}{r^2}+\frac{1}{2}(\sigma_1-\sigma_2)(-4\frac{a^2}{r^2}+3\frac{a^4}{r^4})\cos 2\theta, \quad (5)$$

$$\Delta\sigma_\theta = \frac{1}{2}(\sigma_1+\sigma_2)\frac{a^2}{r^2}-\frac{1}{2}(\sigma_1-\sigma_2)\,3\frac{a^4}{r^4}\cos 2\theta. \quad (6)$$

For the point of interest, the radial respectively circumference strains (ε_r respectively ε_θ) will have the expressions:

$$\varepsilon_r = \frac{1}{E}(\Delta\sigma_r - \nu\,\Delta\sigma_\theta) = -\frac{1+\nu}{2E}(\sigma_1+\sigma_2)\frac{a^2}{r^2}+\frac{1}{2E}(\sigma_1-\sigma_2)[-4\frac{a^2}{r^2}+3(1+\nu)\frac{a^4}{r^4}]\cos 2\theta, \quad (7)$$

$$\varepsilon_\theta = \frac{1}{E}(\Delta\sigma_\vartheta - \nu\,\Delta\sigma_r) = \frac{1+\nu}{2E}(\sigma_1+\sigma_2)\frac{a^2}{r^2}-\frac{1}{2E}(\sigma_1-\sigma_2)[-4\nu\frac{a^2}{r^2}+3(1+\nu)\frac{a^4}{r^4}]\cos 2\theta, \quad (8)$$

and the variation in strains will be:

$$\varepsilon_r - \varepsilon_\theta = -\frac{1+\nu}{E}(\sigma_1+\sigma_2)\frac{a^2}{r^2}+\frac{1+\nu}{E}(\sigma_1-\sigma_2)(-2\frac{a^2}{r^2}+3\frac{a^4}{r^4})\cos 2\theta. \quad (9)$$

As a consequence of the drilling process, the residual surface stresses vanished around the hole, the deformations after three directions are measured with a $3/120^0$ rosette transducer (figure 2). There must be estimated the main stresses σ_1, σ_2 and the central angle θ.

For that purpose, the strains after the 3 directions are experimentally measured:

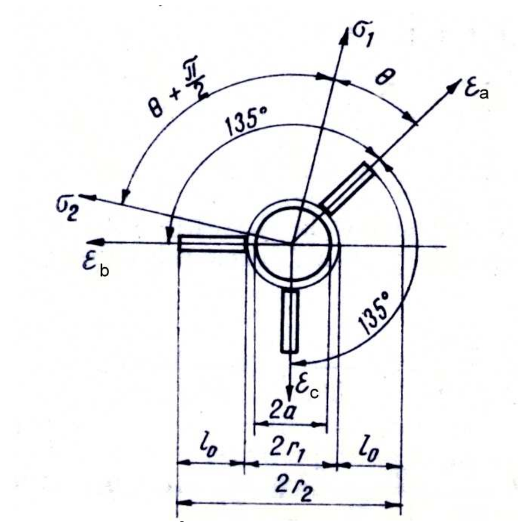

Figure 2. The 3/120^0 rosette strain gage transducer

$$\varepsilon_a = \frac{A}{E}\,(\sigma_1 + \sigma_2) + \frac{B}{E}(\sigma_1 - \sigma_2)\cos 2\alpha \tag{10}$$

$$\varepsilon_b = \frac{A}{E}\,(\sigma_1 + \sigma_2) + \frac{B}{E}(\sigma_1 - \sigma_2)\cos 2(\alpha + 135) \tag{11}$$

$$\varepsilon_c = \frac{A}{E}\,(\sigma_1 + \sigma_2) + \frac{B}{E}(\sigma_1 - \sigma_2)\cos 2(\alpha - 135) \tag{12}$$

where A and B are measuring constant values; E-Young`s modulus.

Than the values of the previous residual stresses (σ_1-maximum stress; σ_2-minimum stress) will be calculated with a special software:

$$\sigma_1 = \frac{E}{4A}(\varepsilon_b + \varepsilon_c) + \frac{E}{4B}[(2\varepsilon_a - \varepsilon_b - \varepsilon_c)^2 + (\varepsilon_c - \varepsilon_b)^2]^{1/2} \tag{13}$$

$$\sigma_2 = \frac{E}{4A}(\varepsilon_b + \varepsilon_c) - \frac{E}{4B}[(2\varepsilon_a - \varepsilon_b - \varepsilon_c)^2 + (\varepsilon_c - \varepsilon_b)^2]^{1/2} \tag{14}$$

$$\text{tg}\, 2\theta = \frac{\varepsilon_c - \varepsilon_b}{2\varepsilon_a - \varepsilon_b - \varepsilon_c} \tag{15}$$

The location of the rosette (triple) transducers ,in a portion of rail with the length of 1 meter, is indicated in figure 3:

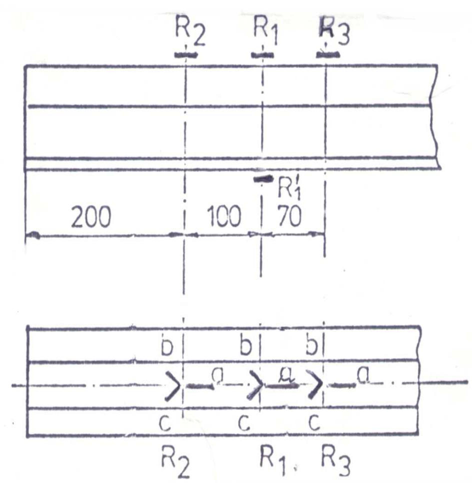

Figure 3. The location of the rosette (triple) transducers

Some experimental results (for the location of the rosette transducers in figure 3) and for a wide range of rail types are presented in table 1. The measured values of strains and the calculated values and directions of main stresses are presented below:

Table 1.

Rail-type	Nr.	ε_a [μm/m]	ε_b [μm/m]	ε_c [μm/m]	σ_2 [MPa]	σ_1 [MPa]
65-1	R_1	45	170	175	155	185
65-2	R_1	-288	-300	-250	215	230
65-2	R_2	-225	-35	-80	-15	100
65-2	R_1`	70	125	30	-65	-55
60-1	R_1	180	365	230	-250	-165
60-1	R_3	230	405	310	-280	-210
60-2	R_1	-190	220	-270	-175	-110
60-2	R_3	-495	-190	-255	-270	-255
49-1	R_1	150	170	75	-200	-50
49-2	R_1	-140	120	-40	-80	-30
49-2	R_1`	-25	-40	45	-50	20

3. The Ultrasonic Inspection

The ultrasonic crack analysis has been performed with a portable ultrasonic crack detector [4], a lightweight, compact and handy-portable flaw detector designed for use on large workpieces and in high-resolution measurements. The complementary equipment consist in a mobile push-cart on the rail and three palpeur heads (a normal one and two bending palpeur heads), [3].The equipment (figure 4) is able to detect fatigue cracks in the rail . The rail profile generates disturbed responses which have to be separated from the faults responses.

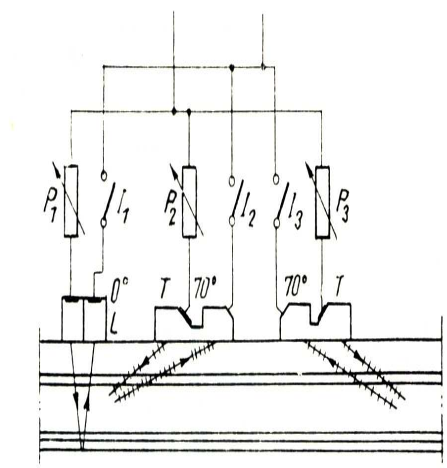

Figure 4. The mobile ultrasonic detection push-cart with three palpeur heads

When a normal palpeur is used for the rail head examination the amplitude of the waves from a fault and from the reflected waves by the rail head (figure 5) have to be separated: P_1-the reflection from the plexiglas-steel interface; C- the reflection from the curved internal shape of the rail profile; P_2-the second response from the interface plexiglas-steel; f-the response from the backside of the rail; d- the echo due to the interchanging of the vibration mode with a reflection from the bottom side of the rail ;P_I-the echo from the bottom side of the rail reflected by the plexiglas wedge. Because of the high amount of measured data ,special automated measuring wagons have been introduced in order to inspect portions of 20-40 km of rail. The automated ultrasonic control imposed the introduction of a special motor car with a palpeur block which consist in five palpeur heads: a vertical one, two inclined palpeurs at an angle of 35° and two inclined palpeurs at an angle of 70°.

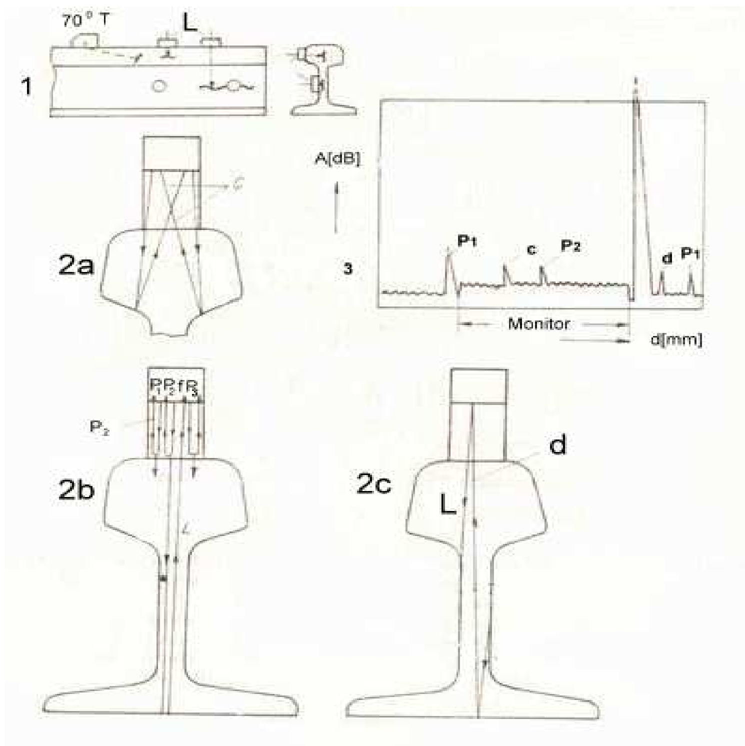

Figure 5. The responses of an ultrasonic detection

The fracture mechanics procedure is able to calculate : the stress intensity coefficient at the top of the crack, the propagation rate, the estimated life-time for different locations and lengths of the detected cracks.

4. Conclusions and proposals

- The values of the residual main stresses in the rail cover a stress range between –280 MPa and 230 MPa. The location of the extreme values of the maximum and minimum main stresses is on the rail head surface. In the near vicinity of that areas, the location of some cracks has been also detected. The association in the same region of the high stress values and faults or cracks may have a dangerous effect regarding the safety and comfort of the passengers, due to the possible crack propagation.

- In order to remove in depth the points of maximum stresses from the lateral rail head surface, the lubrication maintenance procedure is usually used. A mobile lubrication push-cart ensure the lateral lubrication of the linear portions of railroads, until a distance of 200 meters.
- In accordance with the level of stresses, the proposed maintenance inspections include a periodical combined strain gage measurements and an ultrasonic procedure at every 6 months in different points on the route.
- The rectification procedure of the rail head is allowed until a distance of 5 mm from the standard profile, because of the safety reason, The derailment coefficient (which means the ratio between the guidance lateral force from the rail and the vertical force on the wheel) must be less than 1,2. Because of saving costs reasons, the rectification and lubrication operations will be performed at first, but , because of safety reasons, the replacement of the railroad is imposed when the residual stresses reach 250 MPa and the length of crack reach 0,1 mm , [5] , [6].

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