

# Determining residual stresses in operating railroad tracks

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**Abstract.** The residual stresses occur in the material structure of unloaded solid bodies, reflecting their technological path, together with the history of mechanical and thermal loads incurred during their operation. It is important to underline that the residual stresses in a solid body have always the effect of a balanced system of forces. When they overlap with the stresses involved by the loads for which the body is intended, it is sometime possible for that body to be taken out of operation. Experimental tests covered by this work aimed to highlight some possible degradation occurring during the operation for the railroad tracks called '85 and '86, in order to establish to what extent they may still be used for another time interval. In this context, the size of residual stresses was experimentally determined, in some samples taken from the studied railroad tracks, and also from a piece of unused railroad track, in order to compare the results. Moreover, an analysis was made, using the specifications of the standard SR EN 13674-1:2011, on the variation of stresses that occur in the material during the rails cutting.

## 1. The influence of residual stresses on the load bearing capacity

The causes of residual stresses occurring may be of a mechanical nature (non-uniform plastic deformations, produced by overloading), or may be thermal (when some strong temperature gradients occur), or of a metallurgical type (volume and density changes accompanying phase transformations, when applying thermal treatments on the samples material). The effects of residual stresses may be favorable or unfavorable (as they are of the opposite, or respectively the same sign with the stresses arising from sample loading), and as a consequence they may increase, and respectively, decrease the load bearing capacity of the affected sample. It can be said that the compressive residual stresses frequently lead to positive effects.

Generally speaking, the residual stresses can produce the following main effects:

- deformation of semi-finished or finished products;
- disturbance of the parts dimensional stability;
- favoring the appearance of cracks in the sample, significantly decreasing fatigue resistance;
- favoring corrosion in the loaded state of the sample, and so on.

Decreasing the unfavorable residual stress values can be achieved by various technical measures:

- thermal stress relief - the most effective method (heating under the phase transformation limit, maintaining until the temperature is uniform in the part volume, then slowly cooling in the oven);
- vibration stress relief;



- natural stress relief, by prolonged exposure to natural environmental conditions (variations in temperature and moisture, freezing and thawing).

The residual stresses are divided into three categories:

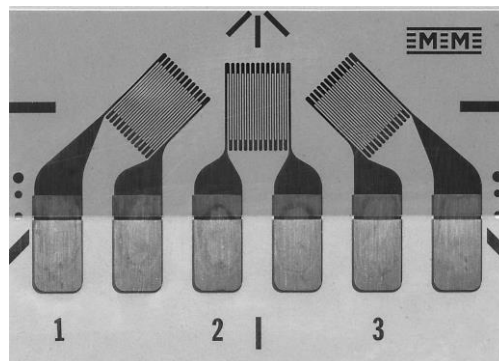
- of the first order, or macroscopic stresses - occurring in large material volumes, possible in the entire volume of the part;
- of the second order, or microscopic stresses - appearing at the metallic grains level (of micrometric dimensions);
- of the third order, or ultra-microscopic stresses - being exercised on the crystalline network, or even at the atomic scale (of nanometric dimensions).

## 2. Materials and equipment

Experimental determinations have referred only to macroscopic (first order) residual stresses. The rail track samples for experiments were provided by the beneficiary of the work, namely the National Railway Company CFR - SA, through the regional branch CF Iasi. The specimens were 1 meter long rail coupons, extracted from exploited tracks, that were produced in 1985, 1986, and respectively from a new, untapped track [1]. The longitudinal residual stress was measured using the standard methodology described in SR EN 13674-1:2011 [2]. It is established that, in the rail tread, the longitudinal residual stress must not exceed the value of 250MPa, in order for that rail to be accepted for use.

The experimental analysis of residual stresses uses some strain gages transducers that are glued on the rail tread surface, on the longitudinal symmetry plan [3]. The instrumented rail segment (of a small length,  $\pm 10\text{mm}$  to the strain gage center line) is detached from the sample, and thus the residual stress relaxation occurs, leading to an output signal on the strain gage transducer. The residual stresses in the rail are considered to have the same values but opposite signs to the transducer indications.

The transducers used in experiments were some rectangular Vishay 062UR-350 strain gage rosettes (Figure 1), having a grid length of 1.57mm, and a gage precision factor of  $\pm 1\%$ .



**Figure 1.** The rectangular Vishay 062UR-350 strain gage rosettes.

The strain gage rosette was placed on the sample with the central gage 2 on the rail axis direction, as shown in Figure 4, in order to measure the longitudinal residual stress in the sample. The requirement in the above cited SR EN standard is the use of a single strain gage transducer, but a three-gages rosette was chosen for the here presented experiments, for the following reasons:

- the gage 2 is used for determining the physical quantities that are stipulated in the standard;
- using the three rosette transducers one may additionally establish the main stresses (maximum and minimum) values, together with their orientation, for the measurement point.

For removing the oxidized surface layer, the rail tread was carefully abrasive processed: the material must not be overheated, and the removed superficial layer must be kept at a low thickness (no more than 0.5mm). The small voids on the tread surface were filled, on the rosette bonding place, without removing any rail material, using some adhesive mass (as a paste) X60, made by HBM; after

drying, that additional layer was polished with an abrasive paper; the surface was then degreased with acetone, and afterward two cleaning solutions were applied: an A conditioner (phosphoric acid MCA-1, made by Vishay), and a 5A neutralizer (ammonia, Vishay).

The gage rosette was glued using some Z70 special adhesive, from HBM. Each transducer was connected to a measuring channel of the P3 Vishay Tensometric Bridge. Primary isolation against water penetration was made with polyurethane lacquer (M-Coat A, from Vishay); a second insulation layer was obtained using some butyl rubber, which is commonly used to protect the connectors on the communication antennas (Radio Frequency Systems).

The cutting of rail segments (for residual stresses relief) was made using a continuous saw band machine Thomas 260 (Figure 2).

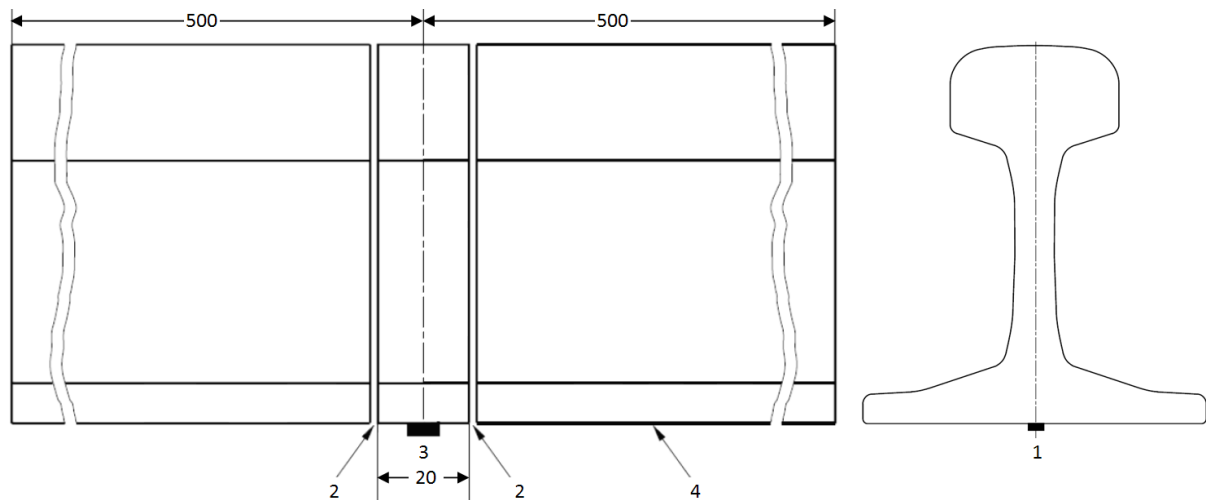


**Figure 2.** The rail samples cutting procedure.

The work area was heavily cooled, during the cutting process, in order to avoid the occurrence of any temperature gradients, followed by an eventual modification of the sample residual stress state. The rail segment was placed horizontally in the clamping jaws of the cutting machine, and the guiding arm of the saw blade could rotate around a joint located at 315mm from the closest gripping jaw. The strain gages output signals (indicating the sample strains variation, with respect to the initial level, established by balancing the measuring bridge channels) were recorded during the entire cutting operation (see Figure 3).



**Figure 3.** Data acquisition for the strain gages output signals.



**Figure 4.** Strain gage placement for measuring the longitudinal residual stresses on the rail tread surface: 1 - axis; 2 - cutting path; 3 - strain gage; 4 - rail tread.

The cutting was first done on the right side cutting path (see Figure 4), at 10mm from the chosen axis (where the strain gage rosette was placed), then on the symmetrical path on the left side. Through this cutting operation, the necessary rail material specimens with a width of 20mm were obtained (see Figure 5).



**Figure 5.** The rail coupons cut for the residual stresses measurement; from left to right - new (not used) rail; 85 rail (white); 86 rail (black).

### 3. Experimental residual stresses data for the analyzed railroad samples

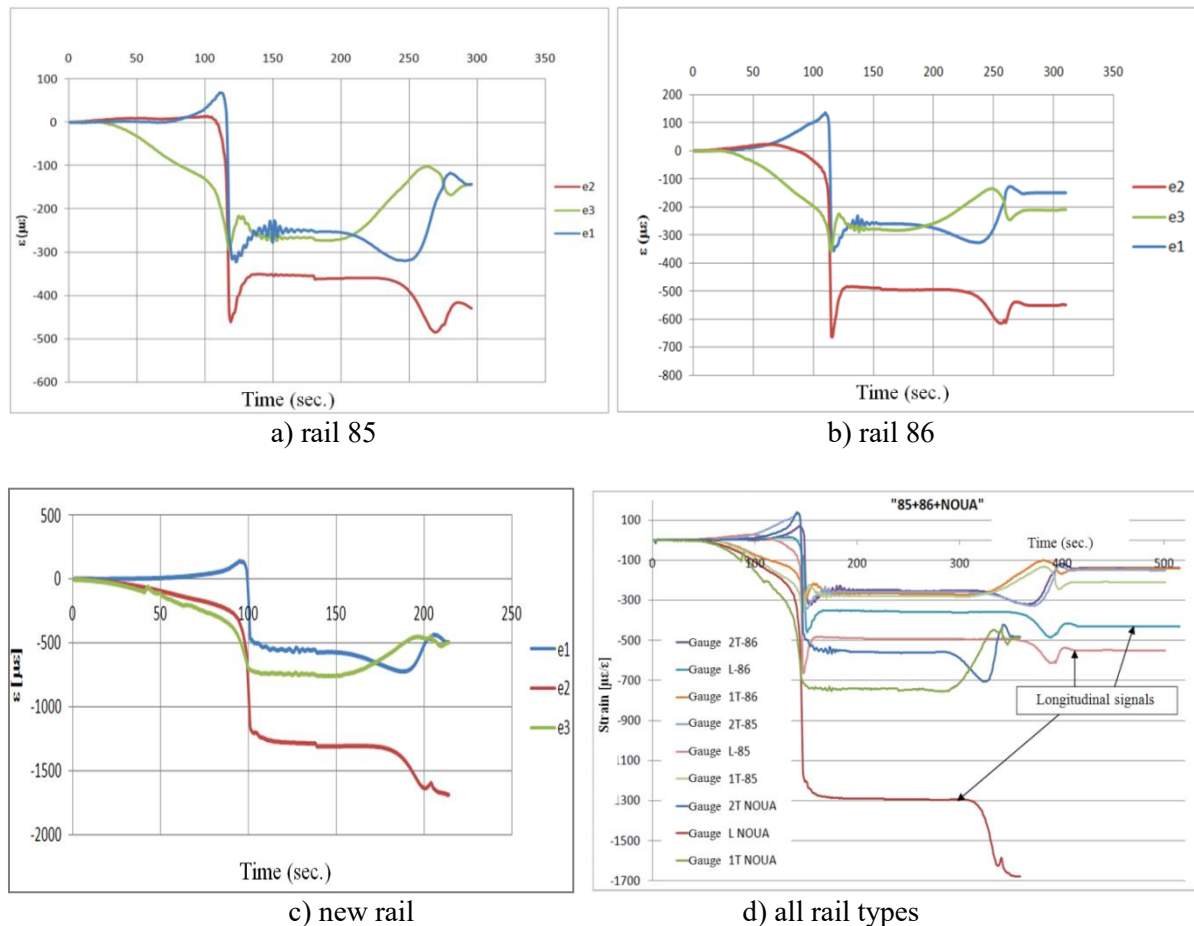
Some remarks can be made about the experimental results that are presented in the graphs below:

The SR EN 13674-1:2011 standard provides the calculus of residual stresses using the strain values that are measured after the complete sectioning of the 20mm thick rail segment. In addition to the standard provisions, the strain values were recorded during the entire rail cutting process (see Figure 6). According to the standard provisions, the residual stresses values from Table 1 were calculated using only the final strain values (after the complete sectioning of the rail specimen), provided by the central strain gage transducer 2, [4].

The residual stresses calculation is based on the differences between the values of the first and the second series of measurements; those differences were multiplied by the rail material Young's modulus value, also indicated by the above cited standard as being  $2.07 \times 10^5$  MPa.



Some experimental Young's modulus values were supplementary established, on samples cut from the three studied types of rail. The residual stresses values from Table 1 have been calculated with both the experimental modulus values, and respectively with the average value provided by the cited standard.



**Figure 6.** The registration of strain variation;  
the output signal e2 was provided by the longitudinal gage transducer 2.

**Table 1.** The values of final strains (TER 2), residual stresses and determined Young's modulus.

Rail type	Final strain value, from TER2 [ $\mu\epsilon$ ]	Residual stress for experimental modulus [MPa]	Residual stress for standard modulus [MPa]	Experimental Young's modulus [GPa]
85 rail (white)	-427	83,69	88,39	196
86 rail (black)	-548	103,02	113,43	188
new rail	-1689	348,17	349,62	206,14

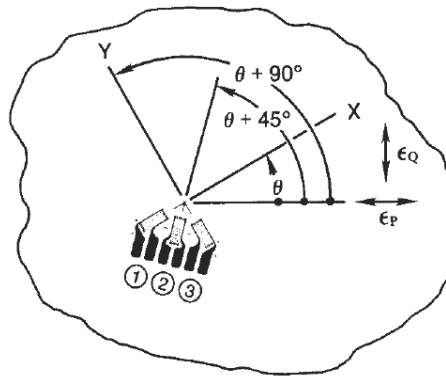
It is important to note that for the new (not used) rail sample (and only for it) the residual stresses exceed the standard indicated maximum limit of 250MPa.

#### 4. Calculation of the main values and main directions for strains and stresses

Calculations of this kind are not provided by the standard SR EN 13674-1:2011, so they are supplementary made in this paper. Some rectangular strain gage rosettes were used, as presented in Figures 3.1 and 7, and the calculation methodology is described below, in accordance with the specialized literature, [5].

The strain value on the direction that makes an arbitrary angle  $\theta$  with the major main axis may be calculated as follows, as a function of the main (maximum and minimum) strain values:

$$\varepsilon_{\theta} = \frac{\varepsilon_P + \varepsilon_Q}{2} + \frac{\varepsilon_P - \varepsilon_Q}{2} \cos 2\theta \quad (1)$$



**Figure 7.** Rectangular strain gage rosette, having the first grid inclined at an arbitrary angle to the main axis P.

Figure 7 presents a small area on the instrumented specimen surface, with a strain gage rosette having the reference grid 1 inclined at  $\theta$  degrees to  $\varepsilon_p$  axis. The main strains and  $\theta$  angle values may be calculated using the  $\varepsilon_1$ ,  $\varepsilon_2$  and  $\varepsilon_3$  strain values provided by the three gage transducers of the rosette, as follows:

$$\varepsilon_{P,Q} = \frac{\varepsilon_I + \varepsilon_3}{2} \pm \frac{l}{\sqrt{2}} \sqrt{(\varepsilon_I - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2} \quad (2)$$

$$\theta = \frac{1}{2} \tan^{-1} \left( \frac{\varepsilon_1 - 2\varepsilon_2 + \varepsilon_3}{\varepsilon_1 - \varepsilon_3} \right) \quad (3)$$

When the inclination angle of the rosette reference grid is measured in the opposite direction to the one indicated in Figure 7, a change of signs is required in eq. (3):

$$\phi_{P,Q=-\theta} = \frac{l}{2} \tan^{-1} \left( \frac{2\varepsilon_2 - \varepsilon_1 - \varepsilon_3}{\varepsilon_1 - \varepsilon_3} \right) \quad (4)$$

The actual measuring direction for the acute angle in Eq. (4) is counterclockwise for the positive sign, so the angle  $\theta$  is measured from the main axis to grid 1, while the angle  $\Phi$  is measured from the grid 1 to the main axis. Unfortunately, because  $\tan 2\Phi \equiv \tan 2(\Phi + 90^\circ)$ , the calculated angle may be reported to any of the two main axes, as indicated in Eq. (3) by the notation  $\Phi_{p,q}$ ; this ambiguity is easily removed (for a rectangular gage rosette), by applying a few simple rules:

- if  $\varepsilon_1 > \varepsilon_3$ , then  $\Phi_{P,Q} = \Phi_P$
- if  $\varepsilon_1 < \varepsilon_3$ , then  $\Phi_{P,Q} = \Phi_Q$
- if  $\varepsilon_1 = \varepsilon_3$  și  $\varepsilon_2 < \varepsilon_1$  then  $\Phi_{P,Q} = \Phi_P = -45^\circ$
- if  $\varepsilon_1 = \varepsilon_3$  și  $\varepsilon_2 > \varepsilon_1$  then  $\Phi_{P,Q} = \Phi_P = +45^\circ$

if  $\varepsilon_1 = \varepsilon_2 = \varepsilon_3$ , then  $\Phi_{P,0}$  cannot be determined (equal biaxial strain).

The experimental stress analysis has the usual purpose of establishing the main stresses values that correspond to the studied point, in a loading state of a body; in the present situation, the main stresses may be obtained from the known main strains values (together with the Young's modulus and

Poisson's coefficient of the rail material), using the generalized Hooke's law for a biaxial stress state, as follows:

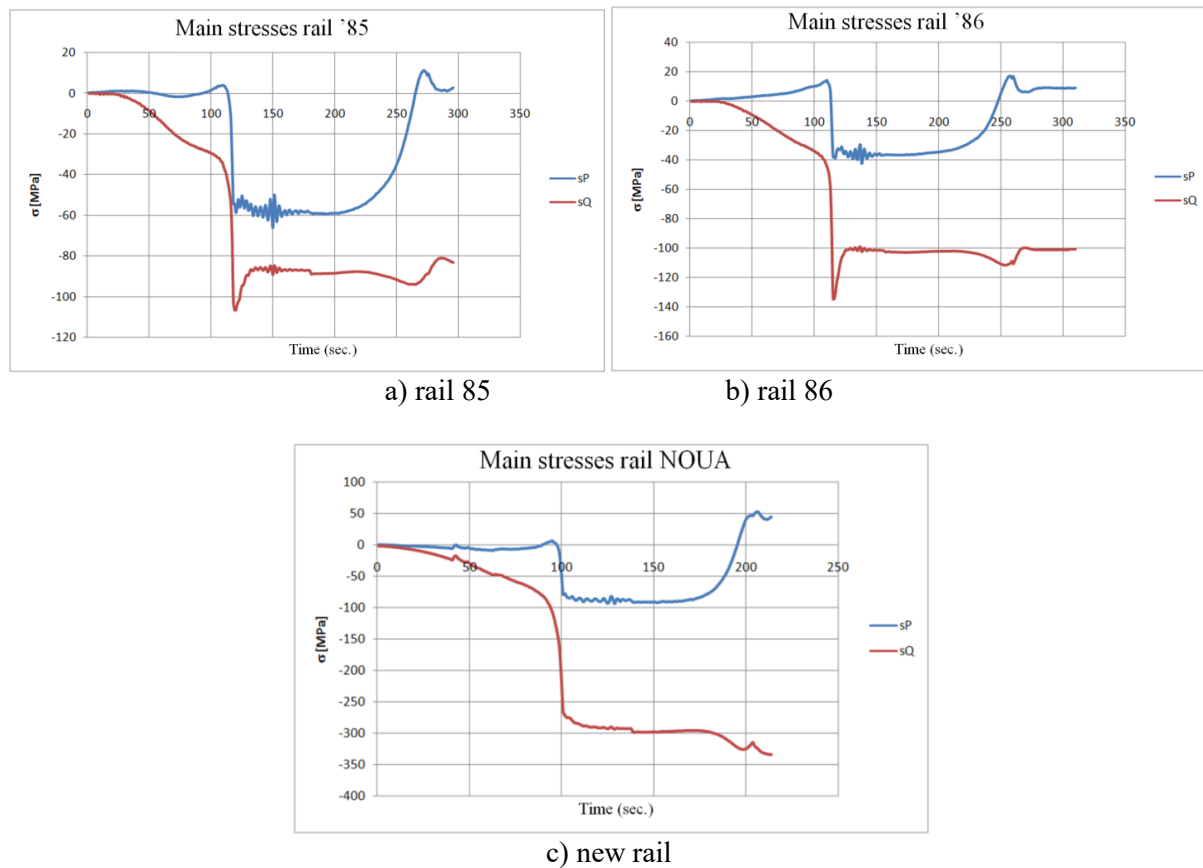
$$\sigma_P = \frac{E}{1-\nu^2} (\varepsilon_P + \nu \varepsilon_Q) \quad (5a)$$

$$\sigma_Q = \frac{E}{1-\nu^2} (\varepsilon_Q + \nu \varepsilon_P) \quad (5b)$$

## 5. The calculus of the main residual stresses values

This calculation involves the following steps:

- measuring the  $\varepsilon_1$ ,  $\varepsilon_2$  and  $\varepsilon_3$  strain values, using the three gage transducers from the rectangular gage rosette 062UR-350;
- using eq. (2), calculating the main strains (maximum and respectively minimum)  $\varepsilon_P$  and  $\varepsilon_Q$  values;
- using eq. (5), calculating the main stresses (maximum and respectively minimum) values.



**Figure 8.** Main stresses variation during the rail sample cutting process.

**Table 2.** Main stresses values experimentally determined for the studied rail samples

Rail type	Calculated minimum main stress [MPa]	Calculated maximum main stress [MPa]	Angle to grid 1 axis $\theta_P^*$ [°]	Angle to the rail longitudinal axis [°]
85 rail (white)	-83,25	2,71	-44,90	0,09
86 rail (black)	-100,84	8,90	-42,71	2,28
new rail	-334,46	44,89	-44,95	0,04

\*  $\theta_P$  is measured from the grid 1 to the main strain / stress direction

The main stresses variation graphs were plotted (in Figure 8), using the above obtained data, for the entire duration of the rail sample cutting process. The angle  $\Phi$  of the main direction P was calculated using Eq. (4), and the P and Q directions are mutually perpendicular. Table 2 summarizes the main residual stresses values, together with their main directions, from the studied rail specimens.

## 6. Conclusions

The residual stresses were experimentally determined, for many 1m long specimens, cut from railroad type 60E1 samples; some of the studied rails (made in 1985 and in 1986) have been exploited for many years, while others were not used in exploitation.

The residual stresses in the rail tread were measured using the methodology indicated by the standard SR EN 13674-1:2011.

By analyzing the experimental results (see Table 1 from above), it can be said that for the new (not exploited) rail (and only for it) the calculated residual stresses values (349MPa) exceed the standard indicated maximum limit of 250MPa.

In addition to the standard provisions, the variation of strain values (from the three gage transducers) was registered, for the entire duration of the rail sample cutting process, and the main stresses values and directions were determined.

## 7. References

- [1] Railway applications 2002 *Track - Rail - Part 1: Vignole railway rails 46 kg/m and above* FINAL DRAFT prEN 13674-1, EUROPEAN COMMITTEE FOR STANDARDIZATION
- [2] SR EN 13674-1:2011 *Railway applications - Track - Rail - Part 1: Vignole railway rails, 46 kg/m and above*
- [3] ASTM Standard E 837 - 1985 *Determining residual stresses by the hole-drilling strain-gage method*
- [4] Macura P and Kubala R 2003 *Experimental Analysis Of Residual Stresses At Products For The Railway Traffic*, Proceedings of XVII IMEKO World Congress, Dubrovnik, Croatia
- [5] Tech Note TN-503-5 1993 *Measurement of residual stresses by the hole-drilling strain gage method*, Vishay Measurement Group