

## Pattern of Residual Stress in Rail by FEM Analysis and Strain Gage Sectioning Technique

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**Abstract:** Final step of rail manufacturing is cold rolling straightening process and it has significant effects on mechanical properties, straightness, flatness and development of residual stresses. Measurement of residual stresses after straightening process is obligated by rail manufacturing standards. In the present investigation, an attempt has been made to evaluate residual stresses after straightening process by finite element method and strain gage sectioning technique. The straightening process has been simulated here using the FE package ABAQUS. All the input data were extracted from experimental tests according to rail manufacturing standard and homogenous and isotropic behavior of material were considered. Moreover, initial camber of the rail was measured after hot rolling and cooling process. Obtained results of numerical calculation has been validated by strain gage sectioning technique and compressive residual stresses in head and web and tension residual stress in foot of the rail has been observed. The roller arrangement used in this investigation could reduce the amount of residual stresses comparing with the previous results. Furthermore, straightness of the rail after straightening was satisfactory.

**Keywords:** Rail, Straightening process, Camber, Numerical calculation, Strain gage

### 1. Introduction

Rail manufacturing from the bloom includes three sequential steps of operations, namely hot rolling, cooling and straightening. The rail temperature after hot rolling is about 850°C and because of the rail cross section geometric condition, heat transfer is not uniformed in cooling process. The non uniform temperature distribution leads to the development of thermal stresses which may be higher than yield stress of the material at high temperature. Therefore thermal stresses affects will bend the rail during the cooling process in the form of circular arcs and hence its straightness will be lost. The bent rails are subsequently straightened in straightening machine.

Extensive investigation works on determining the residual stresses in rails have been carried out. Basua et al. [1] indicated that residual stress before straightening process is not significant. This conclusion is sensible because in the hot rolling steps, thermally activated deformation mechanisms and in the cooling process, plastic deformation (camber) reduce the residual stresses. Knowledge of residual stress in rail is important for evaluating the fatigue behavior during actual use. The cold roller straightening operation is the most critical process for the development of residual stress in rail during manufacturing [2]. Most of the experimental tests have been shown C shape pattern of residual stresses in the rail cross section. Hodgson [3] used strain gage for measuring the residual stresses and indicated C shape pattern. Webstare et al. [4] used neutron diffraction method and expressed similar results. Results of Johnson et al. [5] and Deoche et al. [6] indicated compressive residual stress in rail head that is different in comparison with [3] and [4]. In addition to experimental tests, some of the other researchers have used

numerical calculation for estimating the residual stress after straightening the process however, in contrast to experimental results, numerical calculation did not provide any unique pattern. Schleinzer and Fischer [2] through paying attention to elastic and plastic behavior of special grade of rail materials, indicated C shape pattern of residual stress however, results of Srimani et al. [5] and Betego et al. [6] were in zigzag shape. Different results of residual stress measurement are indicated in Figs. 1-4.

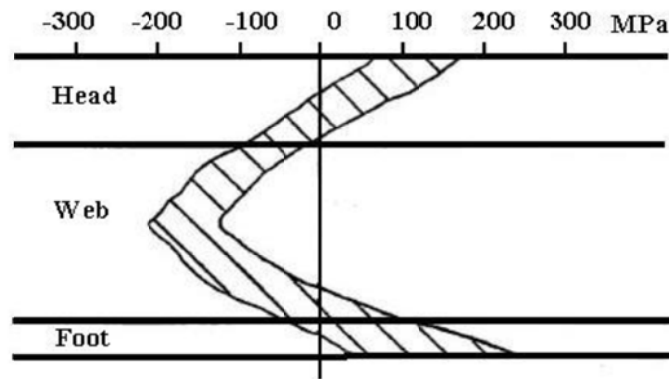


Fig. 1. Residual stress according to strain gage method [3].

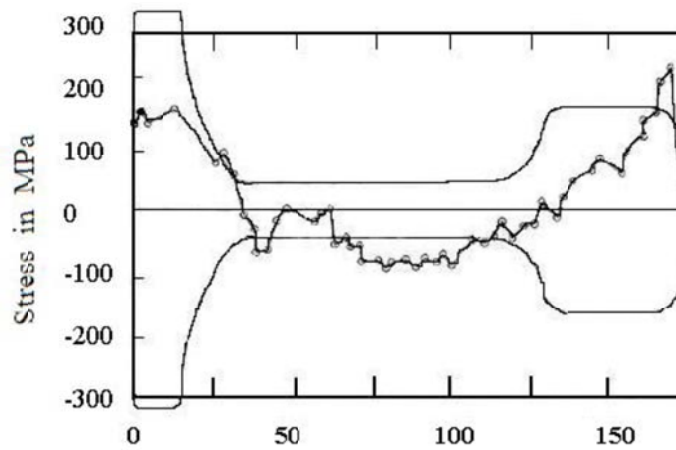


Fig. 2. Residual stress according to the neutron diffraction method [4].

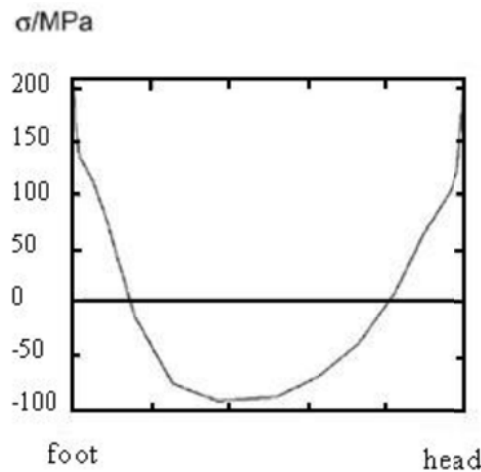


Fig. 3. Residual stress according to FEM method [2].

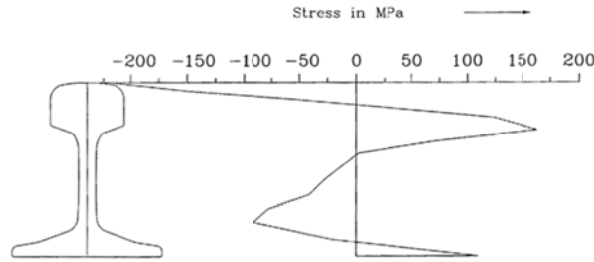


Fig. 4. Residual stress according to FEM method [5].

In order to know the reasons of difference between numerical calculation results, it can be mentioned that by knowing the issue that complete numerical calculation needs plenty of time, some simplification must be added and these simplifications have an important effect on the results. For example Bruning [7] used beam element and concluded that contact pressure between the rollers and rail has minimum effect on residual stresses, while Naumann [8] used 3D model and expressed the contact between rollers and rail is the reason of residual stress distribution in the rail. Geometrical and material parameters which researchers have been used for simulation were different from each other. For example, Schleinzner and Fischer [2] used straightening machine with 9 rollers and 1.4m distance between them ( Fig. 5), while Srimani et al. [5] used straightening machine with 6 rollers and 1.2m distance between the rollers (Fig. 6). Schleinzner and Fischer [2] used non linear kinematic hardening. Srimani et al. [5] used linear kinematic hardening and Rongbin et al. [9] used isotropic hardening.

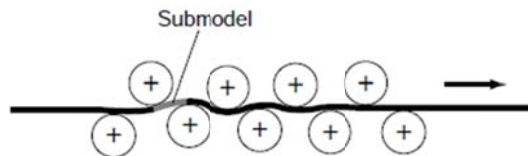


Fig. 5. Schematic of roller arrangement in straightening process [2].

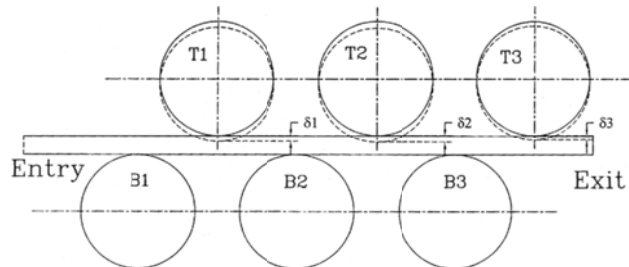


Fig. 6. Schematic of roller arrangement in straightening process [5].

For knowing reasons of the difference between numerical and experimental results it can be said that stress release methods are the main method which researchers have been used, similar strain gage, therefore the obtained results are the average of residual stress that measured in the test area [10] however, in calculation program, the residual stress is measured in certain node or element.

The present research wants to indicate the measurement of residual stress in rail 46E2 by strain gage sectioning technique and FEM analysis. All the input data in FEM analysis which include material properties and distances between rollers are extracted from experimental tests carried out by the authors.

## 2. Finite Element Procedure

Numerical calculations have been done by ABAQUS/ Explicit finite element software [11]. For modeling the rail, camber of the rail 46E2 after cooling process is measured and indicated in Fig. 7. Measurements indicated symmetry camber with maximum 250 mm inflection.

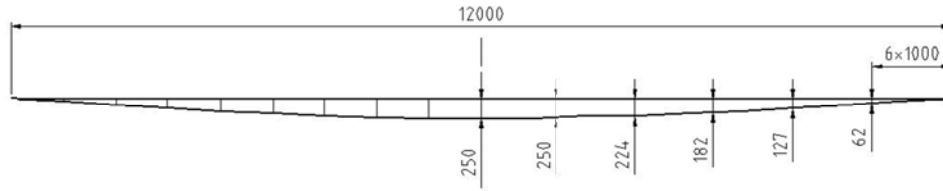


Fig. 7. Measured camber in rail (unit is mm).

Mechanical properties are achieved by tension test according to rail manufacturing standard [12] shown in Table 1.

Table 1. The tension test results

$\sigma_y$ (Pa)	UTS (Pa)	E (Pa)	% $\Delta l$
$590 \times 10^6$	$950 \times 10^6$	$207 \times 10^6$	14

Micrograph study then has performed for three portions of the rail, indicated in Fig. 8. All the structures (head, web and foot) are ferrite- pearlite. The chemical analysis of the rail material is indicated in Table 2. Considering the fact that mechanical properties and hardness of material are dependent, hardness of a cross section has been measured as illustrated in Fig. 9.

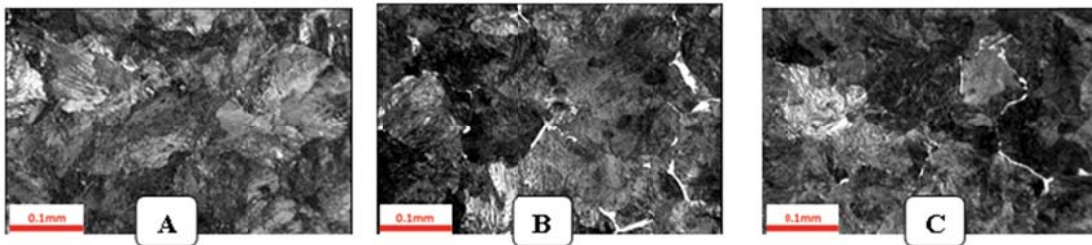


Fig. 8. Micrographs of the rail head (A), web (B) and foot (C).

Table 2. Chemical analysis of the rail.

Element	C	Si	Mn	S	P	Cr	Ni	Mo	V	Ti
Weight %	0.68	0.24	1.07	0.015	0.021	0.02	0.02	0.001	0.005	0.002

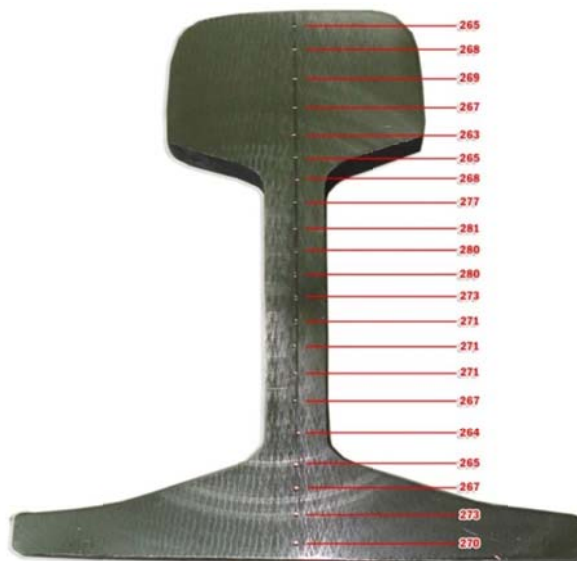


Fig. 9. Result of hardness test, (numbers in HB)

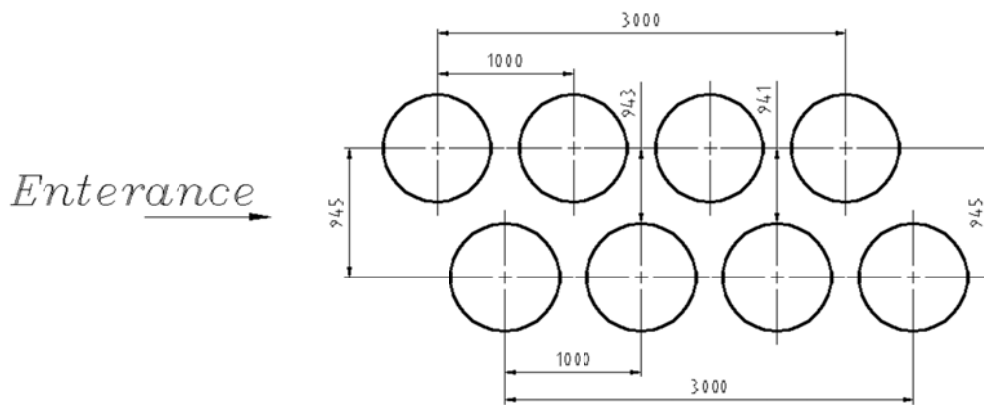


Fig. 10. Roller straightening machine and vertical distance of the rollers (unit is mm).

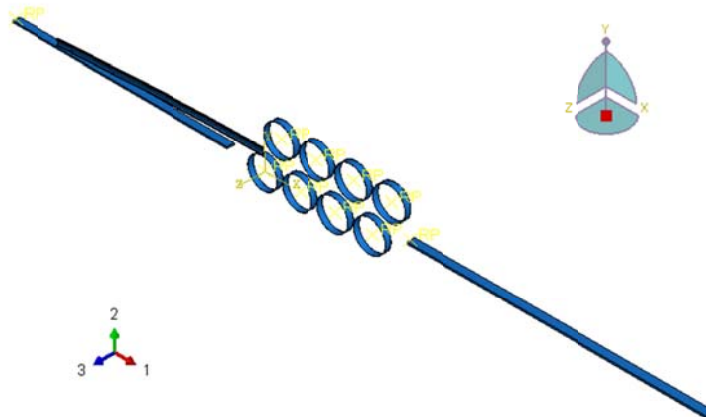


Fig. 11. Assembly of straightening segments.

Regarding the tests results, it is obvious that mechanical properties in all portion of the rail are approximately the same; therefore the material has been considered homogenous and isotropic.

The distance between the rollers in vertical direction is a very important parameter in roller straightening. This distance sets the pressure force on the rail. According to experimental tests results carried by the authors, the proposed vertical distance of rollers are indicated in Fig. 10. FEM model has been made using the information that obtained from the tests. Based on the symmetry of the rail cross section and the camber, only half of the cross section and length have been modeled. Rollers are modeled

as rigid and also the beads are simplified as a friction less sheet. The contact between the rail and the rollers are surface to surface by friction coefficient of 0.2 and the assembled segments are indicated in Fig. 11. Rail has been meshed by 8802 C3DAR elements and whole model contain 147194 elements. Nodes in the cross section of the rail have been determined and then extracted in length of the rail illustrated in Fig. 12.

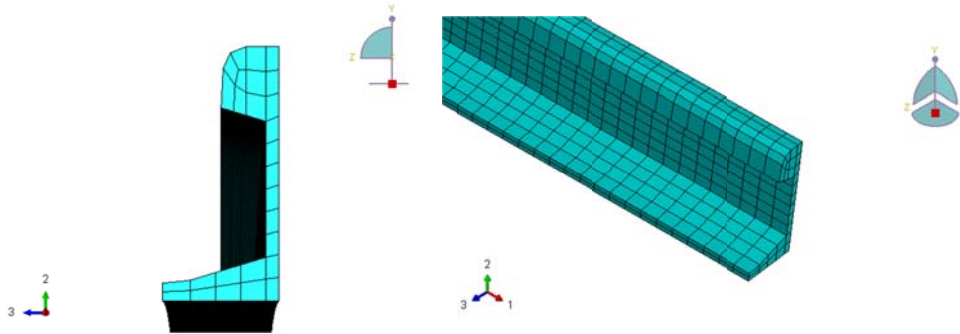


Fig. 12. Mesh in the cross section and length of the rail.

In roller straightening machine, just bending stresses are induced, therefore just calculation of longitudinal stresses ( $\sigma_x$ ) are important. The process residual stresses in several sections then measured and it was observed that the amount of the residual stresses change in each section but the pattern in most of the sections are the same. The results in a cross section are indicated in Fig. 13. Pattern of residual stresses in the middle of the model is graphically indicated in Fig. 14.

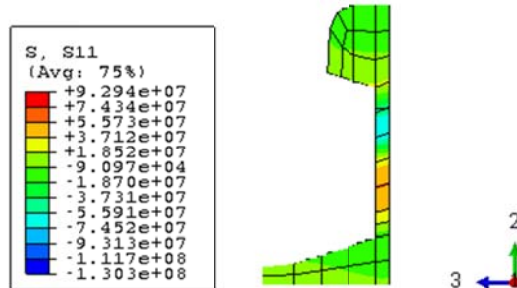


Fig.13- Cross section of the rail after straightening (stress in Pa).

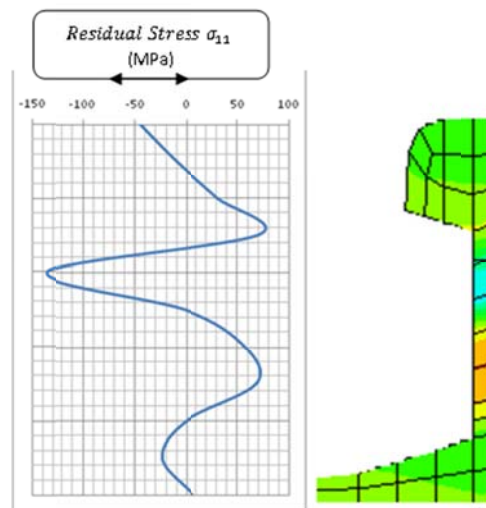


Fig.14- Residual stresses in middle of the rail length model (stress in MPa).

These results indicate 44.7 MPa compressive residual stresses in head, 75.58 MPa tension residual stress in underneath, 135.2 MPa compressive residual stresses in middle of web, 72.2 MPa tension residual stresses in lower portion of the web and 6.9 MPa tension residual stresses in foot of the rail.

### 3. Strain Gage Sectioning Technique Procedure

Sectioning technique is a kind of stress-relaxing method which analyze residual stresses through measuring the deformation caused by relaxation of the present residual stresses. The strains released during the cutting process are generally measured using electrical or mechanical strain gauges. In this research, residual stresses have been measured by strain gage sectioning technique according to the rail manufacturing standard [12]. In the present investigation, three strain gages have been used for determining the pattern of longitudinal residual stresses and the strain gages were installed according to Fig. 15. Specification of the used strain gages are indicated in Table 3. Actual resistances of the strain gages before any deformation have been measured as  $349 \Omega$ .

Table 3. Strain gage specification

Specification	Unit
Type of cover	Kapton
Foil thickness	$15 \mu m$
Cover thickness	$9 \mu m$
Nominal resistance	$350 \Omega \pm 1 \Omega$
Gage factor	$2.1 \pm 10\%$
Working temperature	$-20 \sim 100^\circ C$
Hysteresis	Negligible

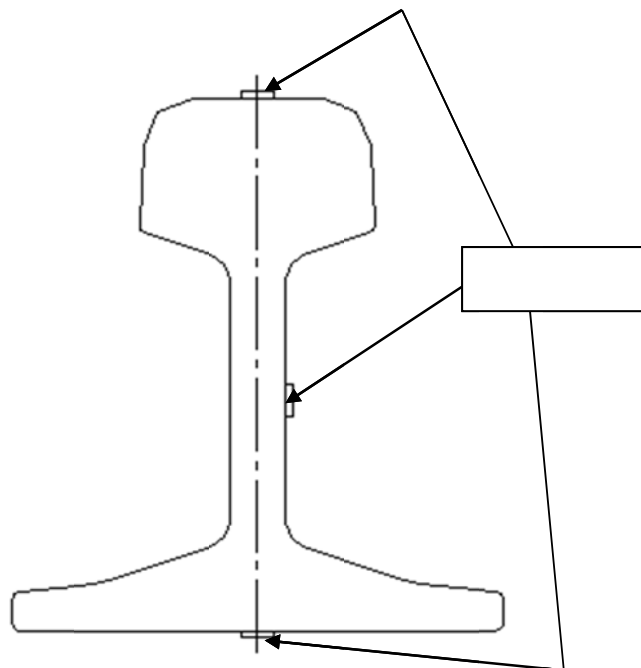


Fig. 15. Position of strain gages.

After installing the strain gages, two saw cuts have been made on the rail according to Fig. 16. Saw cuts made stress relaxation and therefore deformation occurs in the specimen. The effect of this deformation is changed in strain gage resistance. Residual stresses can be calculated by measuring the resistance change. Resistance of the strain gages have been measured by calibrator and the result are indicated in Table 4.

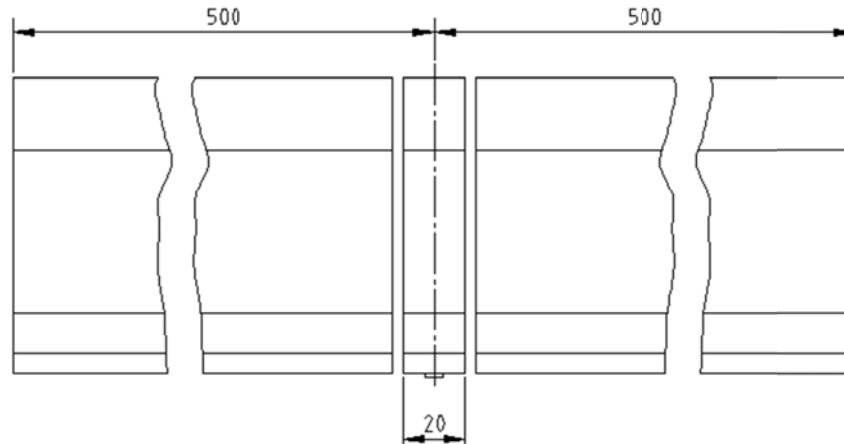


Fig. 16. Position of saw cuts (unit is mm) [12].

Table 4. Resistance of strain gages after saw cut.

Position	Resistance ( $\Omega$ )
Head	349.085
Web	349.371
Foot	348.891

Calculated stresses by means of strain gages are indicated in Table 5 and show compressive residual stress in the rail head and web, and tension residual stress in the rail foot.

Table 5. Calculated residual stress by means of strain gage

Position	Residual stress $\sigma_{11}$ (MPa)
Head	-23.54
Web	-102.76
Foot	30.19

#### 4. Results and Discussion

In straightening process, various kinds of tension and compression stresses induced on the rail and boundary conditions are continually changed, therefore it is very difficult to introduce a comprehensive theory which states all the process. When rail enters to the straightening machine, the head of the rail is under the tension and the foot is under the compression stress. After a while and by passing the rail from the rollers, the position of tension and compression stresses will be changed and these conditions will be repeated several times during the process, Fig. 17.

The amount and position of these tension and compression stresses during the process controls the final residual stresses. In straightening machine, bending stresses induced on the rail and the lower rollers act as a support and the pressure induced by upper rollers. Therefore, one of the most important parameters in straightening process is the distance between the rollers. The distance between the rollers also depends on several other factors, such as the initial camber. Vertical distance adjusts the pressure and high pressure could make a fracture in the rail. Another parameter is straightness of the rail after straightening process. According to rail manufacturing standard, the maximum deflection in straightened rail in each 1500 mm is 0.7 mm indicated in Fig. 18, [12]. Straightness after straightening process is measured and results are indicated in Fig. 19. Considering the results of the residual stress measurement and straightness of the rail after straightening process and comparing the results with the similar research, it is concluded that the level of the residual stresses reduced using new arrangement of the rollers introducing in the presented paper.



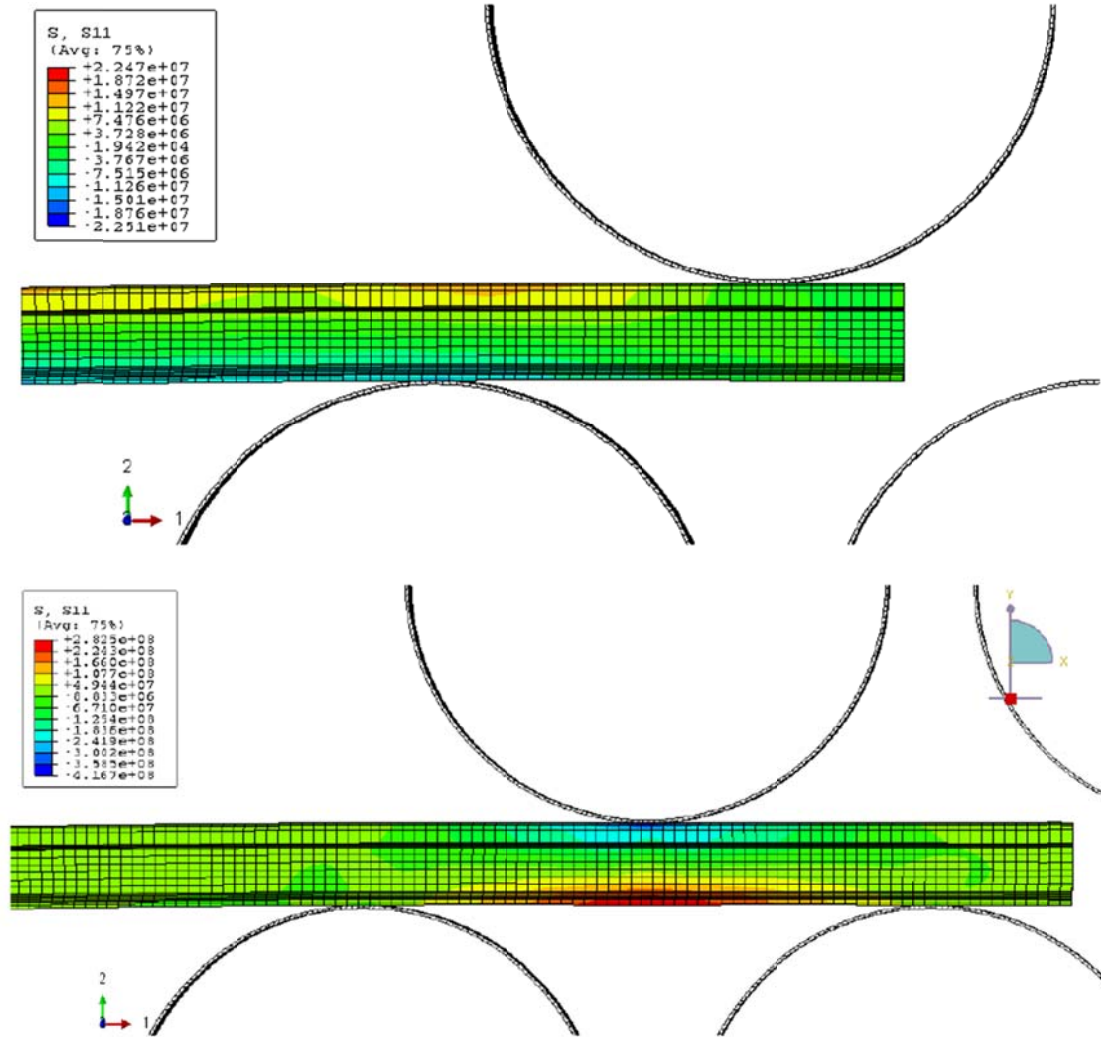


Fig. 17. Change the position of tension and compression stresses during the straightening process.

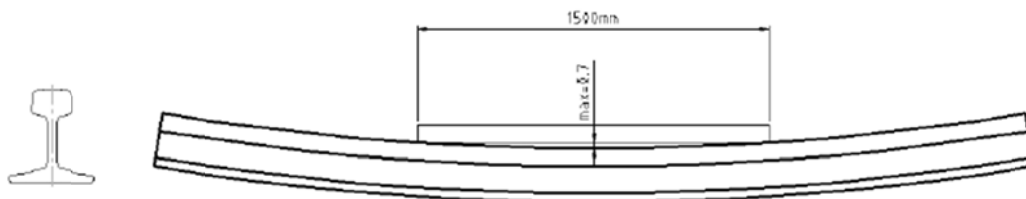


Fig. 18. Acceptable deflection after straightening process [12].

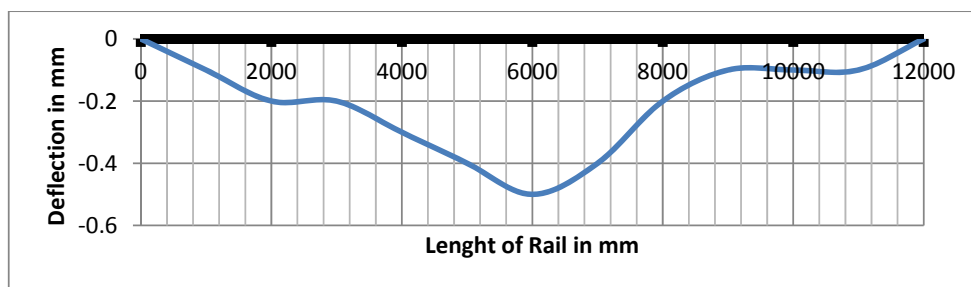


Fig. 19. Straightness of the rail after straightening process.

## 5. Conclusion

FEM analysis indicated compressive residual stresses in the rail head and web and tension residual stresses in the rail foot. Moreover, the experimental sectioning test results indicated the same pattern, hence, its results confirm the results of FEM model. Vertical distance between the rollers in roller straightening machine is a very important parameter in the development of residual stresses and the proposed arrangement of the rollers could be reduced to the level of the residual stresses comparing with the previous practices. FEM model and experimental sectioning technique both indicated compressive residual stress in the rail head and web and tension residual stresses in the rail foot. Therefore, the model is confirmed and it can be used for more investigation.

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