The Influence of Residual Stresses on the Fatigue Resistance of Axles Used in the Construction of Railway Equipment

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ABSTRACT. *The paper is focused on the fracture mechanism of railway axles due to the fatigue of material. The purpose is to numerically predict the number of cycles (or kilometres) to fracture in various theoretical conditions. The stresses in the axles were calculated by finite element methods. The number of cycles to fracture was calculated using closed form solution of NASGRO equation for fatigue crack development starting from an initial crack detectable by means of non-destructive testing. In order to demonstrate the deep negative impact of forbidden thermal treatments and operations applied to railway axles, residual stresses of this treatments were calculated and new numerical predictions of number of cycles to fracture were made.*

INTRODUCTION

During of one-month period from 15.07.2004 to 15.08.2004 an unprecedented series of 4 major railway axle fractures with many similarities has occurred in Romania. All broken axles were from gasoline tank wagons with a relatively massive load compared to passengers wagons. All broken axles were fractured due to the fatigue of material as seen in "Fig. 1" and were manufactured by the same company in the same month January 2004.

Figure 1. Broken tank wagon axle from a severe derailment, Romania, 15.08.2004 [1].

The purpose of this article is to numerically simulate the loads, stresses and predict the number of cycles (or kilometres) to fracture in various theoretical conditions. This article does not substitute in any way the legal inquiries (still pending at the time of this article being written) and does not make any assumption or statement regarding the accidents.

METHODS

An accurate 3D model of the axle has been created using mechanical design software as in “Fig. 2”. To this model restraints and static loads has been applied, in order to numerically calculate von Mises stresses. “No translation” type restraints have been applied to cylindrical surfaces that connect the railway axle to the wheels. The maximum load of 100 kN has been applied on both ends of the axle. After meshing of the 3D model, a static analysis has been performed and von Mises stresses were calculated. Maximum von Mises stresses were 86.27 MPa that is very low in comparison with yield strength of the A1N steel. The deformation scale in Fig. 3 is 1416.9. The mechanical properties of the material are shown in Table 1.

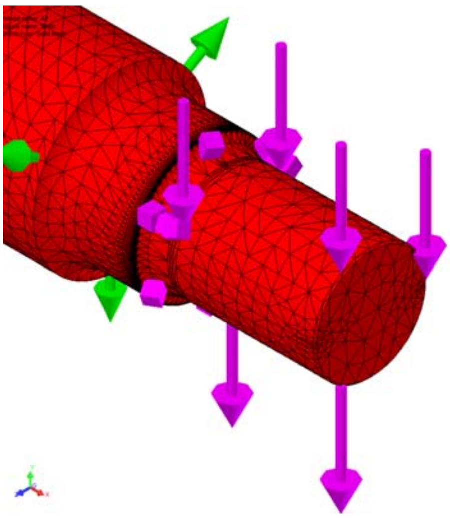

Figure 2. 3D CAD model of the tank wagon railway axle.

Table 1. Mechanical properties of A1N steel

Mechanical Properties of A1N steel	Value
Elastic Modulus	210000 N/m
Poisson’s Ratio	0.26
Shear Modulus	78000 N/m2
Density	7300 kg/m3

Mechanical Properties of A1N steel	Value
Ultimate Tensile Strength	550 N/mm2
Compression Strength	550 N/mm2
Yield Strength	350 N/mm2
Thermal Expansion Coefficient	$1.5 \cdot 10^{-5}$/Kelvin
Thermal Conductivity	38 W/(m.K)
Specific Heat	440 J/(kg.K)

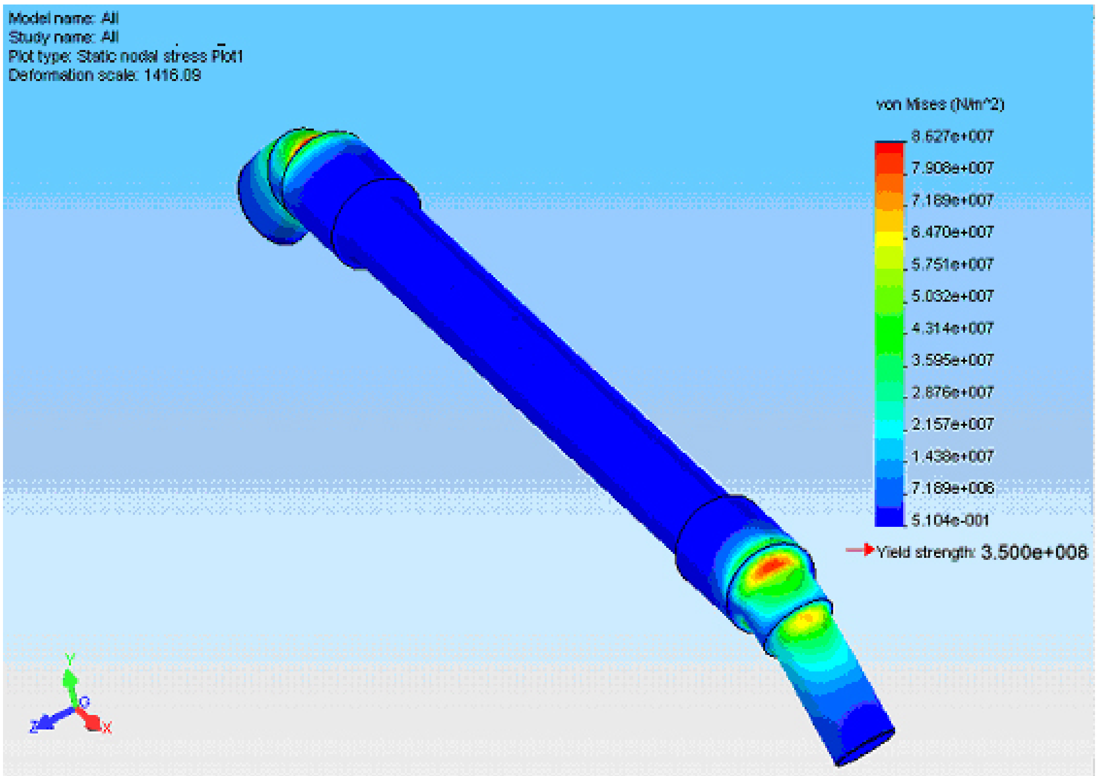

Figure 3. Von Mises stresses and deformations for a tank wagon railway axle model.

In order to ensure a much more realistic estimation of stresses in the axle, the dynamic loads have been taken into consideration as a static model [2]. We have found the maximum von Mises stresses to be 110.7 MPa, a value that is three times lower than the yield strength.

In order to apply the worse case scenario further fracture analyses have been completed right in the section of the axle with maximum von Mises stresses. In addition, other simulations are proposed using residual stresses from a theoretical 5 mm depth welded layer (even such mechanical operations are strictly prohibited by railway regulation. In fact, in railway industry, if a structural moving part does not meet the required dimensions or has material defects (like scratches or cracks) it is strictly forbidden to cover or repair the part using welding or any other heat treatment). These additional simulations were made in order to highlight the real risks of such a procedure. Fracture analyses were completed using NASGRO equation "Eq. 1" expression (also called Forman–Newman–de Koning equation) jointly introduced by NASA and ESA [3], which is now common in aerospace applications. "Equation 1" was numerically solved using AFGROW software.

$$\frac{da}{dN} = C \cdot (\Delta K_{eff})^n \cdot \frac{\left[1 - \frac{\Delta K_0}{\Delta K_{eff}}\right]^p}{\left[1 - \frac{K_{\max}}{K_{Jc}}\right]^q} \tag{1}$$

The numerical issues involved in crack propagation were further discussed in recent article [4].

The method used by AFGROW is closed form solution, in this particular case; classic model of rod standard solution has been used.

The methods in this paper are following the guidelines in recent articles [5] and [6].

RESULTS

During AFGROW crack growth simulation the following constants and mechanical material properties were used:
Young's Modulus =206843
Poisson's Ratio =0.33
Coeff. of Thermal Expan. =1.26e-005
The Forman-Newman-de Koning- Henriksen (NASGRO) crack growth relation is being used
No crack growth retardation is being considered
For Reff < 0.0, Delta K = Kmax
Material: A1N
Plane strain fracture toughness: 76.919
Plane stress fracture toughness: 115.379
Effective fracture toughness for surface/elliptically shaped crack: 109.884
Fit parameters (KC versus Thickness Equation): Ak= 0.75, Bk=0.5
Yield stress: 350
Lower 'R' value boundary: -0.3
Upper 'R' value boundary: 0.8
Exponents in NASGRO Equation: n=3.6, p=0.5, q=0.5
Paris crack growth rate constant: 1.4473e-012
Threshold stress intensity factor range at R = 0: 8.791
Threshold coefficient: 2
Plane stress/strain constraint factor: 2.5
Ratio of the maximum applied stress to the flow stress: 0.5

Failure is based on the current load in the applied spectrum
Vroman integration at 1% crack length

A normalised spectrum was used "Fig. 4" statistically reproducing the track with straight and curved segments of railway. The spectrum was repeated until fracture has occurred. The load and the initial crack were applied in the section of the axle with maximum stresses.

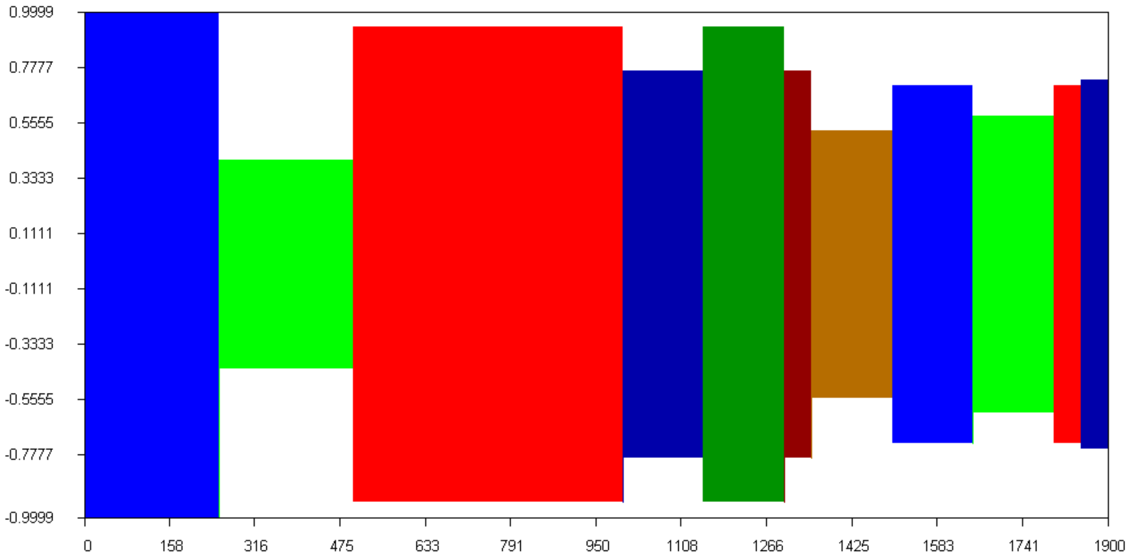

Figure 4. Statistically determined normalized load spectrum.

The following results have been obtained after running the prediction of crack propagation as in Table 2 and "Fig. 5":

Table 2. Prediction as number of cycles and kilometres to failure for a tank wagon railway axle fracture with no residual stresses

Initial crack size ***c*** [mm]	4.5	6	7.5
Cycles to fracture (no residual stress)	-	$6.1 \cdot 10^7$	$1.8 \cdot 10^7$
Kilometres to fracture (no residual stress)	-	354000	109000

Let assumes that a 5 mm welded layer is laid on external surface of the axle including the section with most elevated stresses. Due to the thermal contraction some residual stresses will appear after the welded layer will cool down. As we previously calculated in [7], the residual stresses can be calculated with "Eq. 2" and are plotted in "Fig. 6".

$$\sigma(x_{amb}) = \frac{E \cdot x_{amb} \cdot \alpha \cdot \Delta T}{R \cdot (1 - \alpha \cdot \Delta T) + x_{amb}} \quad (2)$$

In table 3 are shown residual stresses values for ΔT = 200, 400, 600, 800, 1000 K, at diferent x_{amb} values or equivalent depth of the new layer. Using residual stresses calculated for ΔT = 200, 400, 600, 800, 1000 K (Table 3), new predictions regarding crack propagation were made (Table 4). As expected, the number of cycles to failure dramatically decreases with the increase of residual stresses (ΔT increases).

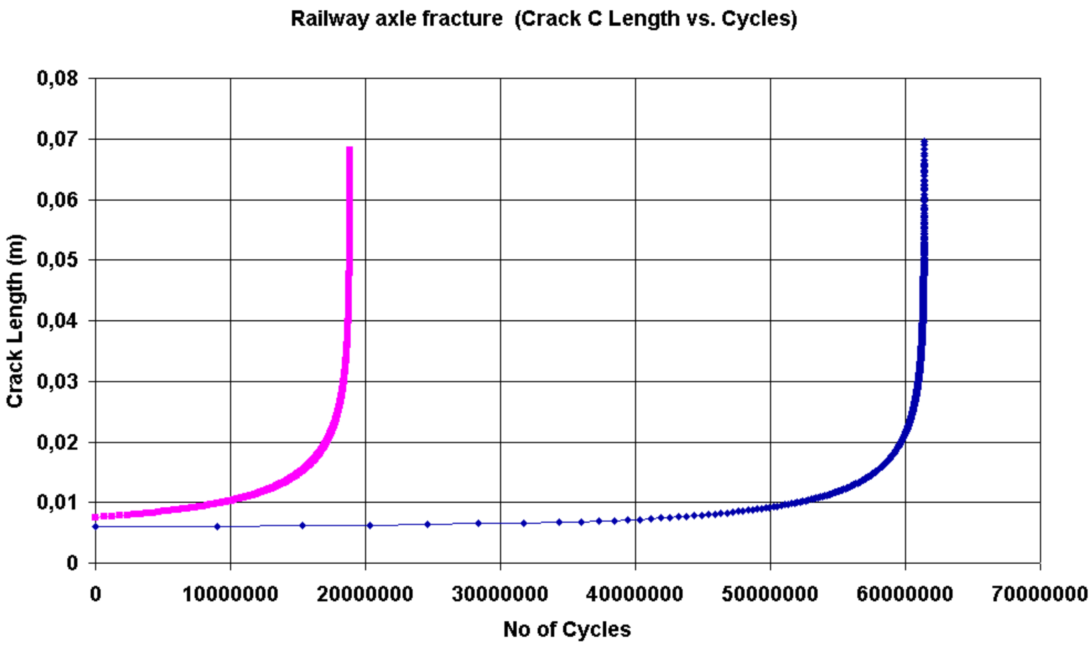

Figure 5. Predictions of crack ***c*** lengths [m] against number of cycles for a tank wagon railway axle with no residual stresses starting from different initial crack sizes.

Table 3. Calculated residual stresses values

x_{amb}	σ[MPa] at ΔT = 400K	σ[MPa] at ΔT = 600K	σ[MPa] at ΔT = 800K	σ[MPa] at ΔT = 1000K
0.000	80.57	121.13	161.74	200.48
0.001	65.43	98.38	131.64	165.01
0.002	48.89	75.02	100.24	125.35
0.003	33.77	50.77	67.86	84.79
0.004	17.19	25.85	34.73	43.10
0.005	0.00	0.00	0.00	0.00

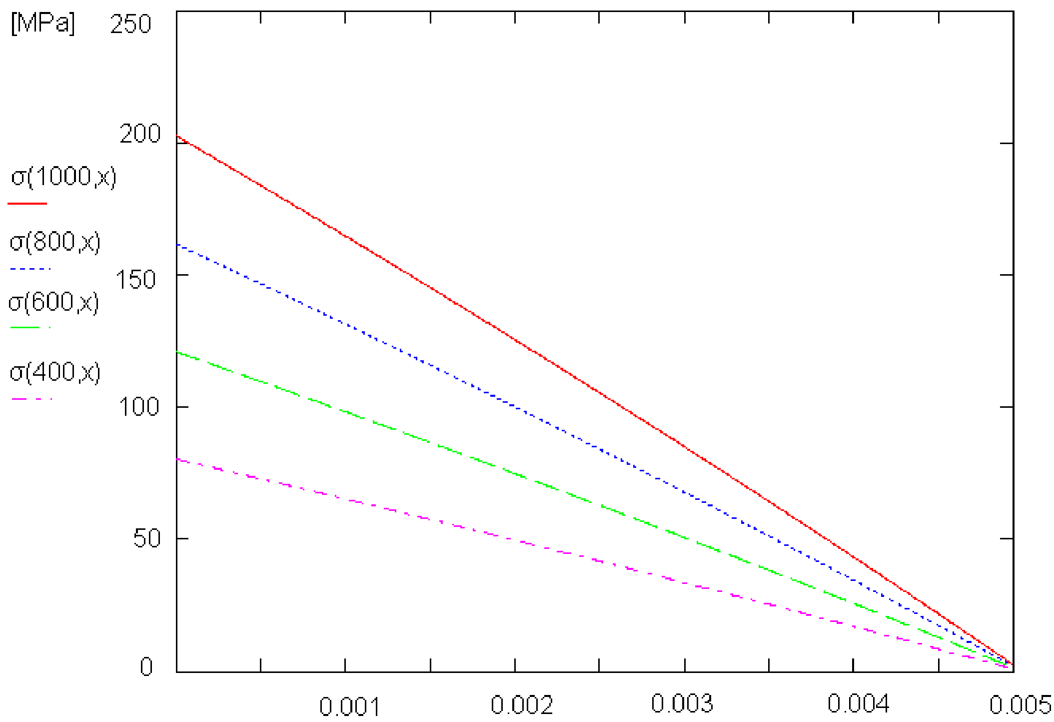

Figure 6. Residual stresses σ [MPa], theoretically calculated, against x [m] and ΔT [K].

Table 4. Prediction as number of cycles and kilometers to failure for a tank wagon railway axle fracture with residual stresses

Initial crack size ***c*** [mm]	4.5	6	7.5
Cycles (kilometers) to fracture with residual stresses due to a welded layer of d = 5 mm at ΔT = 400K	$2.4 \cdot 10^7$ (139600)	$1.4 \cdot 10^7$ (81600)	$9.3 \cdot 10^6$ (53900)
Cycles (kilometers) to fracture (with residual stresses due to a welded layer of d = 5 mm at ΔT = 600K)	$1.5 \cdot 10^7$ (86250)	$9.9 \cdot 10^6$ (57150)	$7.0 \cdot 10^6$ (40450)
Cycles (kilometers) to fracture (with residual stresses due to a welded layer of d = 5 mm at ΔT = 800K)	$1.0 \cdot 10^7$ (59500)	$7.3 \cdot 10^6$ (42400)	$5.4 \cdot 10^6$ (31350)
Cycles (kilometers) to fracture (with residual stresses due to a welded layer of d = 5 mm at ΔT = 1000K)	$7.8 \cdot 10^6$ (45250)	$5.7 \cdot 10^6$ (33200)	$4.4 \cdot 10^6$ (25200)

CONCLUSIONS

Any residual stresses in a railway axle will dramatically reduce the number of cycles (kilometres) to failure. In real life the railway axle will not fracture as soon as predicted in this paper for a few reasons:

- the wagons will not always be filled (sometimes they have to be emptied);

- if there is no residual stress, a corrosion crack will grow very slowly to a depth that will propagate through fatigue, in a longer period than the time needed to fracture the axle through fatigue propagation. But, it is probable and plausible that a crack will develop in a welded layer right from the beginning;
- a worse case scenario was used, the crack was supposed to be right in the section of the maximum stresses.

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