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STUDY OF THE RUBBER METAL SPRINGS FATIGUE OF PRIMARY SPRING SUSPENSION OF ELECTRIC LOCOMOTIVES

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Abstract. *Rubber-metal springs (RMS) that are widely used in both primary and secondary spring suspension of rail vehicles are reliable elastic-damping elements. They are compact since they combine elastic and damping properties and do not require operational maintenance. But their significant disadvantage is the process of characteristics' changes taking place on RMS known as rubber "aging". It has been found that the average lifecycle of RMS of locomotives series 46-000 in the operational practice of the Bulgarian State Railways since 1986 does not exceed 60% of the one guaranteed by manufacturers. Most probably the explanation for this is related both to poor features of the rail network in the country and the operation of locomotives without balancing the static load on their wheels. The study presented includes a simulation analysis carried out by the finite element method in order to predict the distribution of stress and evaluate the behavior of fatigue. Based on the nonlinear quasi-static modeling and analysis, residual stresses have been registered and superimposed and a methodology considering material fatigue has been developed to help predict RMS resource exhaustion. The results obtained in the study can be used to optimize the basic RMS design parameters and features.*

Key words: *Electric Locomotive, Rubber-metal Springs, Failure Analysis, Life-cycle Prediction*

1. INTRODUCTION

A significant part of the rail vehicles are with bogies. The calculation, design and testing of springs suspension as an important component of the bogie represent a complex and highly comprehensive engineering task [1, 2, 3].

The use of RMS in spring degree (most often in the axle once) has important advantages since RMS which have both elastic and damping properties can be used instead to mount cylindrical coil springs and hydraulic dampers. The structure of locomotives of series 46-000 is of such a type.

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The bogie of the electric locomotive of series 46-000 that are operated in the system of Bulgarian railways (Fig. 1) uses rubber-metal springs in their primary (axle) suspension (Fig. 2).

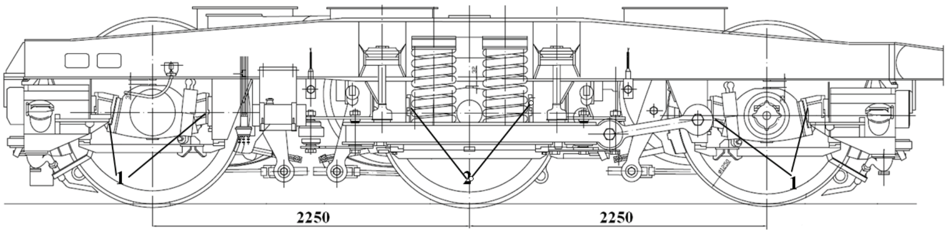


Fig. 1 Bogie of an electric locomotive of series 46-000
1- RMS in wheelsets no.1 and 3; 2- RMS in wheelsets no.2

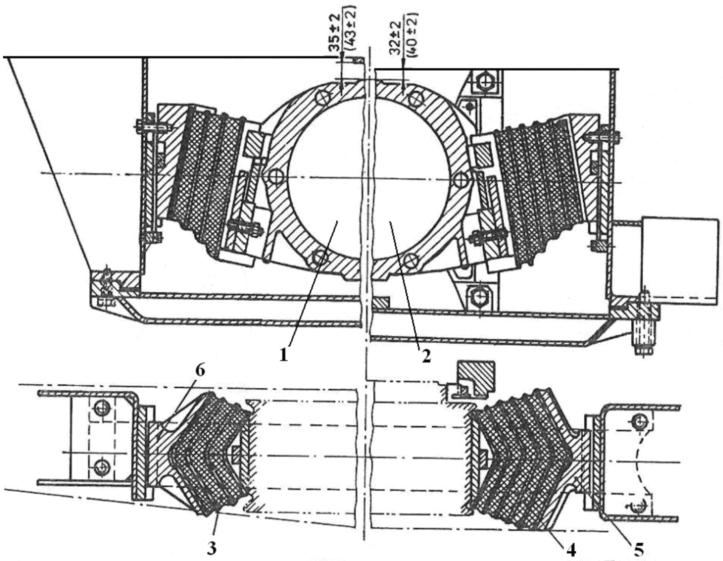


Fig. 2 Primary suspension of the bogie of an electric locomotive series 46-000
(1- axlebox in wheelsets no.1 and 3; 2 - axlebox in wheelsets no.2;
3 - RMS with 3 rubber springs; 4 - RMS with 5 rubber springs; 5, 6 - supporting elements)

A RMS consists of V-shaped metal plates (four or six) interspersed with vulcanized rubber (in three or five layers). The rubber parameters are appropriately chosen to ensure the required properties. The operational position of the RMS in a locomotive is set at an angle to the vertical axis, which determines the existence of loading on the rubber layers with shear and compression.

Paper [4] contains a list of the main parameters of rubber-metal elements (e.g. values of residual deformation, elastic and damping properties, etc.).The results of RMS testing for similar locomotives operated by the Serbian Railways (named series 461) are given in [5].

Some studies of foreign authors [6, 7] have confirmed that the life cycle of a RMS reaches about **0,8** million cycles with **1,5** million cycles set at the stage of design and construction, as the probable explanation is related to the material's integral fatigue and the presence of residual stresses in the V-shaped metal plates.

Other studies (e.g. [8]) present an attempt made on the basis of an effective three-dimensional analysis of stress and strain state of metal plates and rubber layers to predict the timing of cracks caused by fatigue and tearing of the rubber layers.

2. MATERIAL PROPERTIES

To investigate and analyze the distribution of stresses and evaluate fatigue behavior, the finite element method has been applied.

2.1. Metal material properties

The metal part (plate) is made of steel with maximum permissible stresses of 355 MPa. The British standard code for design, calculation of fatigue and assessment of steel structures BS7608 gives the ratios between stress and number of load cycles (S/N) established by statistical analysis of experimental data [9].

The dependency below (with constant amplitudes) is in force:

$$\log N = \log Co - d/\sigma - m\cdot\log Sr \tag{1}$$

where: N – number of cycles, S_r – stresses, C_o is a constant related to the mean value of dependency S_r-N; d – standard deviation from the mean one; σ is the standard deviation of log N; m is the inverse slope of log S_r *versus* log N curve.

To determine the constant with real loading, the equation below is used:

$$\log C_d = \log C_o - d\sigma \tag{2}$$

After substitution and transformation it is obtained that:

$$S_r^m N = C_d \tag{3}$$

2.2. Rubber material properties

The elastic models proposed in [9] and applicable to rubber and other elastomeric materials (based on the potential strain energy of deformation or the density or strain energy) have been used.

Synthetic polyisoprene (IR), which has similar properties to those of natural rubber, is used in the new generation of RMSs. Despite its slightly higher price it has significant advantages such as slow hardening, better mixing, extrusion, molding in RMS manufacturing.

For an isotropic, incompressible material the dependency between the Young's Modulus and the modulus of shear is E = 3G.

Dependency E = 2G (1 + v) is well-known from classical mechanics, where v –Poisson's coefficient (Poisson's ratio = normal stress/lateral stress). For small levels of stresses, the coefficient takes the value of 0,5; i.e.: E = 2G (1 + 0,5)

The dependencies given above are valid for pure rubber but according to [10] the dependency (e.g. for material 65IRHD) takes the type of E = 4,2G when adding solid carbon (soot).

In [10], the following values are recommended for natural rubber: E = 1,5 MPa and G = 0,49 MPa and for material 65IRHD G = 1,3 MPa, respectively.

The method used to evaluate fatigue and RMS life cycle duration is based on predefined data of the material and effective stress (σ_f). The stress sensor can be easily integrated with finite elements (e.g. by using Solid Works 2010 [11].

The rubber crack initiation is a result of the cumulative damage when visual cracks appeared [9, 12]. Sample of main text.

3. FINITE ELEMENT MODELS

An analysis by the finite element method is made to forecast the distribution of stresses and evaluate the behavior of fatigue. With the study of fatigue the RMS is examined as a single unit. Based on the locomotive weight distribution among its wheels, the nominal load of 50 kN is chosen.

The models in Figs. 3 and 4 show the maximum tensile stress. Fig. 5 shows the strain profile of the modified part.

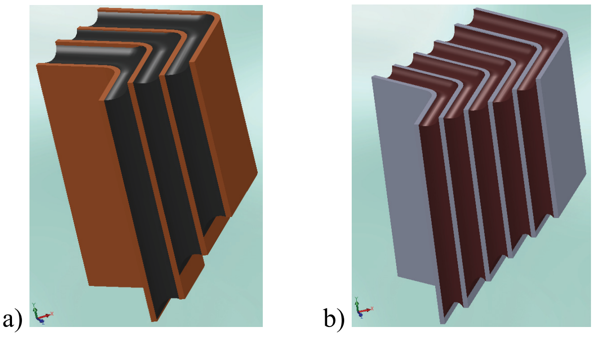


Fig. 3 The models of RMS. a) With 3 packages; b) With 5 packages

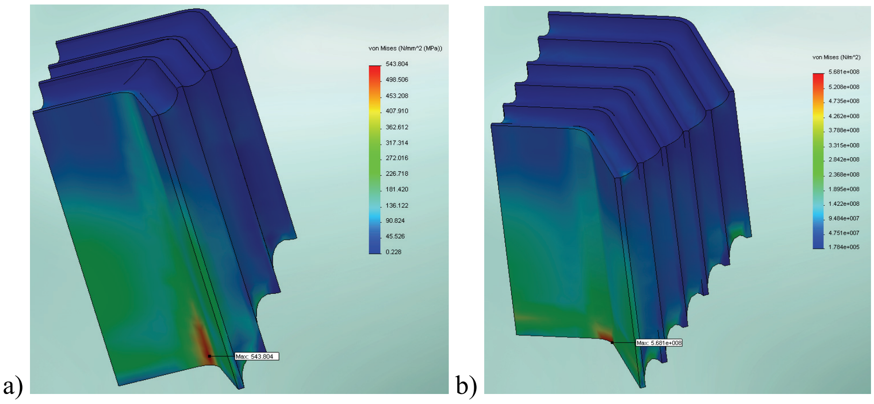
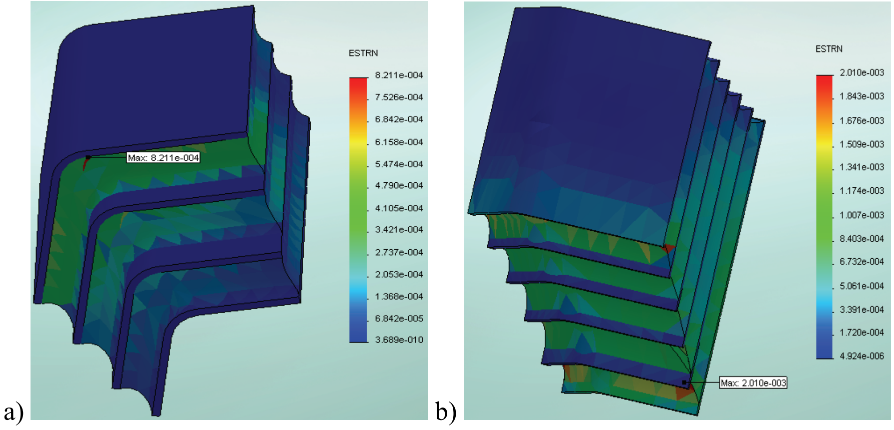


Fig. 4 Stress profile of the modified part. a) With 3 packages (max **543,8MPa**). b) With 5 packages (max **568,1MPa**).



a) b)

Fig. 5 Strain profile of the modified part. a) With 3 packages (max **$0,82 \cdot 10^{-3}$**)
b) With 5 packages (max **$2,01 \cdot 10^{-3}$**).

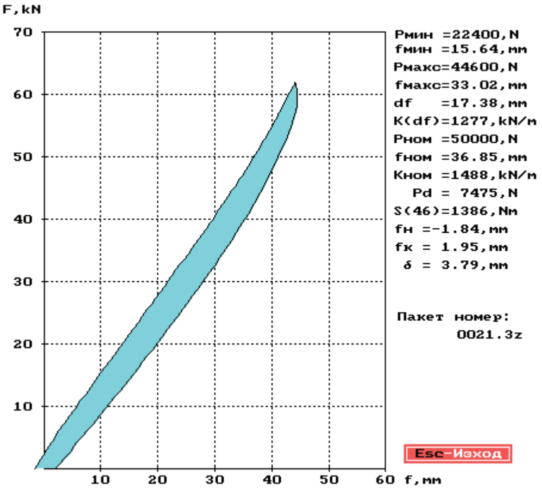
The survey results have justified the statement that the excessive bending moment can cause fatigue damage. Therefore, the RMS life of operation can be extended by reducing stresses.

4. STIFFNESS VERIFICATION

To evaluate the results obtained, it is crucial to test and validate the developed models.

For the needs of the Bulgarian railways a number of devices to test RMSs have been developed and one of them is shown in Fig. 6 [13]. The results of laboratory tests for 3-layer and 5-layer RMSs carried out on this device are used to validate the models (Fig. 7 shows the parameters obtained and a diagram of 3-layer RMS).

Fig. 6 Stand for testing.



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Pмин =22400,N
fмин =15.64,мм
Pмакс=44600,N
fмакс=33.02,мм
df    =17.38,мм
K(df)=1277,kN/м
Pном =50000,N
fном =36.85,мм
Kном =1488,kN/м
  Pd = 7475,N
S(46)=1386,Nм
fн =-1.84,мм
fк = 1.95,мм
 δ = 3.79,мм

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Fig. 7 The stiffness and histerezis of RMS models.

5. METAL FATIGUE VERIFICATION

The verification for both RMS models is performed with a nominal load (50 kN). The maximum values of stresses in the first metal layer with a 3-layer package are 543,8 MPa and with a 5-layer one they are 568,1 MPa, respectively.

The check-up determination of the fatigue cycle has been carried out on the basis of the requirements of regulations [14] and [15]. The life cycle specified in these standards depends not only on the stress changes and the number of loading cycles, but also on the probability parameter of fail-safe operation.

For class B the probability of failure of 2,3% is used to validate the analysis of fatigue. Steel for metal plates has a limit of 355 MPa.

After cold forming of RMS plates, with stress of above 355 MPa, residual stresses are created on the inner surface. Therefore, the stresses have to be reduced to 189 MPa for a RMS with 3 elements and to 213 MPa for a RMS with 5 elements. Based on the fatigue curve [14], the life cycle of a three-layer RMS is approximately $0{,}6\cdot10^6$ cycles instead of $2\cdot10^6$ cycles and the life cycle of a five-layer RMS is approximately $0{,}8\cdot10^6$ cycles instead of 3.10^6. The estimated life cycle of the order of $1{,}5\cdot10^6$ cycles shows good alignment between simulation research and practical testing of RMSs.

6. RUBBER FATIGUE VERIFICATION

The assessment of fatigue for the rubber components of RMSs is based on a three-dimensional method of stress assessment. The effective values of stresses σ_f are 3,57 - 4 MPa for both types of RMSs. From the curve of fatigue of the rubber component, approximately $75\text{-}90\cdot10^3$ cycles correspond to the stresses of 3,57 - 4 MPa. Cracks due to fatigue occur after approximately $170\cdot10^3$ cycles.

7. DISCUSSION

An integrated evaluation of the fatigue of RMS components (rubber layers and V-shaped metal plates) has been made and validated. The nonlinear quasi-static variable stresses are superimposed with residual stresses and the lifecycle of the metal plates is forecasted. The prediction of life cycle of the rubber layers considering the strength fatigue is more complex due to the specific material characteristics of material. Using the three-dimensional effective method for stress evaluation the beginning of crack appearance due to fatigue can be predicted. This study on RMSs can be used in the processes of design, modeling and analysis of RMSs and optimization of their parameters in terms of material (rubber and metal).

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ISTRAŽIVANJE ZAMORA KOD GUMENO-METALNIH OPRUGA PRIMARNOG OGIBLJENJA ELEKTRIČNIH LOKOMOTIVA

Dobrinka Atmadzhova, Nencho Nenov

Gumeno-metalne opruge ili, skraćeno, GMO, uveliko se koriste i kod primarnog i kod sekundarnog ogibljenja železničkih vozila kao pouzdani elastično-prigušni elementi. Oni su kompaktni budući da kombinuju elastične i prigušne osobine a ne zahtevaju operativno održavanje. Ali je njihov značajan nedostatak proces promena karakteristika poznat kao "starenje" gume. Utvrđeno je da prosečni radni vek GMO-a kod lokomotiva serije 46-000 u operativnoj praksi Bugarske državne železnice od 1986. ne prelazi 60% garancije koju daje proizvođač. Objašnjenje ove činjenice se odnosi i na slabe odlike železničke mreže u zemlji kao i na rad lokomotiva bez uravnoteženja statičkog opterećenja na točkovima. Ovo istraživanje obuhvata simulacionu analizu metodom konačnih elemenata radi predviđanja raspodele napona i procene ponašanja zamora. Na osnovu nelinearnog kvazi-statičkog modeliranja i analize, utvrđeni su rezidualni naponi a razvijena je i metodologija razmatranja zamora materijala kako bi se pomoglo pri predviđanju istrošenja GMO resursa. Rezultati dobijeni u ovom istraživanju mogu se koristiti za optimizaciju osnovnih GMO konstrukcionih parametara i njegovih svojstava.

Ključne reči: *električna lokomotiva, gumeno-metalne opruge, analiza otkaza, predviđanje radnog veka*