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HEAT GENERATION PREDICTION IN THE RAILWAY DRAW GEAR RUBBER-METAL SPRING [*]

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Abstract. *The temperature of rubber or rubber-metal springs is liable to increase under cyclic loading, due to hysteresis losses and low rubber thermal conductivity. This well-known phenomenon, called a heat build-up, is the primary reason for rubber aging. A temperature increase within the rubber compound leads to degradation of its physical and chemical properties, its stiffness increase and its damping capability loss. An extensive heat build-up can be a major concern during the accelerated fatigue testing of rubber-metal springs as it alters the spring properties during the testing procedure and can cause permanent damage leading to the testing results unreliability. The paper presents a case study of the heat generation prediction in the rubber-metal spring of railway draw gear during dynamic testing in accordance with UIC Code 827-1.*

Key Words: *Draw Gear, Rubber-metal Spring, Hysteresis Heat Generation, Finite Elements Analysis*

1. INTRODUCTION

The draw gear is a basic and extremely important subsystem of railway vehicles whose primary task is to connect vehicles in trains, i.e. wagons and locomotive, and to transfer the traction force from locomotive to other train wagons. Moreover, their absorption properties have crucial influence upon transferring and reducing impact loads between the locomotive and the rest of the wagons, namely those that affect the stability and safety of running and maneuvering. The draw gear malfunction may be the cause of unstable running and, in the worst case, of derailment of a vehicle.

Absorbing elements in the draw gear are usually implemented as elastomer springs. Fig. 1 shows an assembly of the draw gear with haul hook.

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Rubber or rubber-metal springs have several advantages with respect to metal springs (lower price, easier installation, lower mass, reduced corrosion, no risk of fracture and no need for lubrication) [1]. However, they have one major disadvantage reflected in an insufficiently reliable service life caused by rubber fatigue.

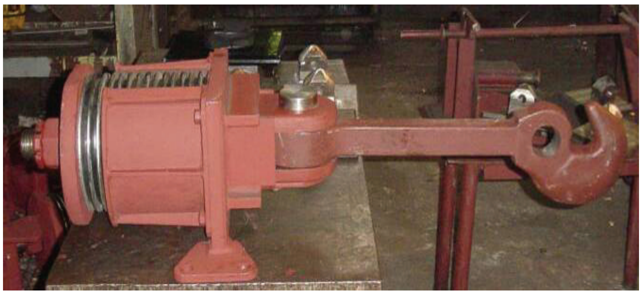

Fig. 1 The draw gear assembly filled with the rubber-metal spring

When rubber is used for a long period of time it ages, becomes stiffer and loses its damping capability. This aging process results mainly from the heat generated within the rubber due to hysteresis loss, and it affects the rubber's material properties as well as its useful lifetime [2].

Due to the viscoelastic response of the rubber compounds, the rubber's stress-strain curve creates a hysteretic loop during the full load-unload cycle. The area in hysteresis loop corresponds to dissipated energy which is primarily converted into heat [3, 4]. Since the heat generation occurs within the material and it is not easily conducted away, due to the rubber's thermal properties, it induces an increase of temperature inside the rubber compound which can even lead to melting of the material or to an explosive rupture (blowout). The heat generation in rubber compounds is affected by the nature of polymers, the physical and chemical properties of the compounding ingredients, their interaction with rubber, operating parameters, and the environment [5]. The decrease in the heat generation of rubber or rubber-metal springs leads to their longer service life.

Although the heat build-up has a primary effect on rubber fatigue, in engineering practice it is very difficult to monitor the inside temperature during operation or mechanical tests. It is important to know an appropriate dynamic frequency range and time duration, both in the service environment and in the laboratory fatigue testing programs in order to keep the inside temperature within a reasonable range [6]. In the accelerated fatigue testing defined by the railway standards it is necessary to ensure that any temperature rise inside the rubber-metal spring should not exceed the design requirements. Furthermore, a severe heat build-up can even lead to devulcanization of the component (Fig. 2) if the temperature rise is not within the suitable range.

As heat generation is a major concern to rubber lifetime, numerous authors have investigated the processes of heat generation due to hysteresis loss in rubber compounds, as well as the effect of heat generation on rubber lifetime and its thermo-mechanical properties. With recent development of viscoelastic/viscoplastic rubber constitutive models, several authors have applied the numerical approach to predict hysteresis heat generation. The referential researchers can be divided into two categories based on the approach used by the authors to predicting heat build-up, either by direct coupling of mechanical and thermal field [3, 4], or by experimental determination of hysteresis losses i.e. dissipated energy as an input in thermal analysis [6, 7].

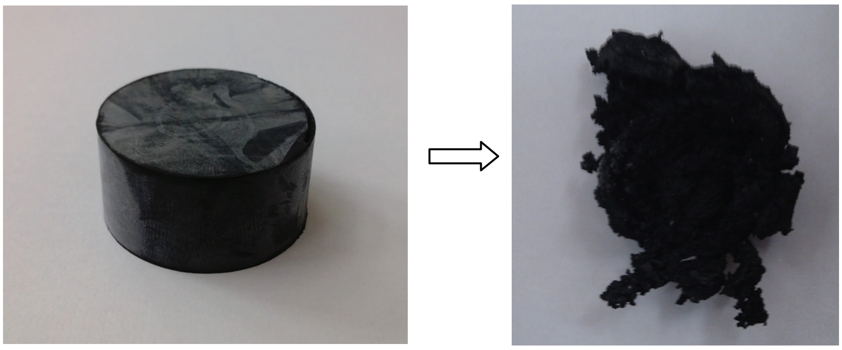

Fig. 2 De-vulcanization of the rubber specimen during the accelerated fatigue testing

The direct coupling of mechanical and thermal fields is performed on the basis of equality of heat energy density and dissipation energy density. Although such approach is purely numerical, the prediction accuracy radically decreases as strain and frequency increase. Such approach addresses only moderate temperature changes and cannot take into account time-temperature superposition.

The second approach requires the experimentally obtained static hysteresis loop in order to calculate energy loss per cycle. Luo et al. [6] have determined that energy loss per cycle of the rubber spring loading, under fixed dynamic amplitude, does depend on the loading frequency. Although prediction accuracy issues are solved thus enabling time integration, the second approach requires experimental determination of hysteresis loss at all amplitudes, i.e. strain values at which the spring operates which can be quite problematic and time consuming.

The aim of this paper is to apply an efficient procedure [8] for prediction of heat generation in the railway draw gear filled with rubber-metal spring in order to ensure that any temperature rise inside a rubber metal spring does not exceed the design requirements in the accelerated fatigue tests. The proposed procedure encompasses the prediction of dissipated energy during the cycling loading by FEM. The dissipated energy is then used as an input for the transient thermal analysis in which the draw gear assembly temperature distribution is obtained. The proposed approach is verified by comparing the simulation results with the experimentally obtained temperature distribution.

2. Heat Generation Prediction Procedure

As previously mentioned, both testing and simulation have shown that energy loss per cycle of the rubber spring, under the fixed dynamic amplitude, does not depend on the loading frequency. Therefore, the energy loss per cycle can be more easily obtained by using a conventional quasi-static loading procedure, to reduce the cost and the time, than by conducting more complicated dynamic tests [6].

A schematic (algorithm) of the new procedure for predicting heat generation due to hysteresis loss in rubber or rubber-metal springs is shown in Fig. 3 [8]. The proposed procedure is completely computation-based and does not require determination of static hysteresis experimentally as proposed by other authors [6, 7], as static hysteresis it is determined by computer simulation (FEM).

If assumed that dissipated energy (E_D) is primarily converted into heat, heat generation rate (H_G) can be derived over time (t) from static hysteresis (I) and total mechanical energy (E_T) or total mechanical energy and returned energy (E_R) as:

$$H_G = \frac{E_D}{t} = \frac{I \cdot E_T}{t} = \frac{E_T - E_R}{t} \qquad (1)$$

Due to relatively low computational demands, the proposed approach enables the time integration, thus enabling the prediction of spring heat emission during prolonged operation time i.e. establishing of thermal equilibrium.

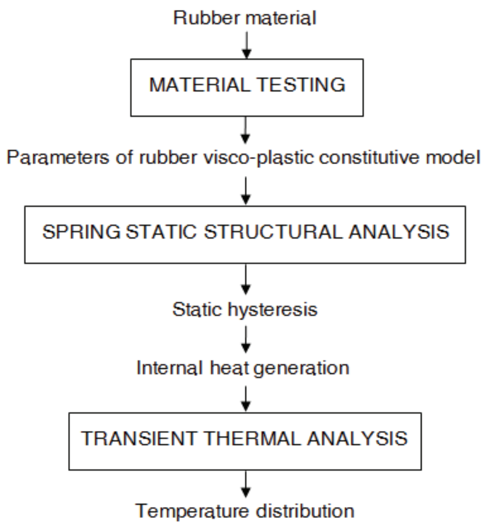

Fig. 3 Scheme of a new procedure for predicting temperature distribution in rubber and rubber-metal springs with FEA

The determination of static hysteresis is enabled by application of the Bergström-Boyce visco-plastic rubber constitutive model. The high accuracy across different elastomer compounds of Bergström-Boyce material model is a primary reason for adaptation of the noted material model during investigation of heat generation in the draw gear rubber-metal spring. The Bergström-Boyce material model is a phenomenologically based and highly-nonlinear model used for modeling visco-plastic behavior of elastomers. The model allows for a nonlinear stress-strain relationship, strain rate dependence and can capture the hysteresis effect of elastomers.

3. Prediction of Static Hysteresis

In order to predict heat generation due to hysteresis losses in the draw gear rubber metal spring a case study is defined. The goal of the case study is to obtain temperature of the rubber metal spring during the accelerated fatigue test according to the UIC Code 827-1. UIC Code 827-1 defines the fatigue testing conditions which replace the exploitation investigation of buffer and draw gear [9].

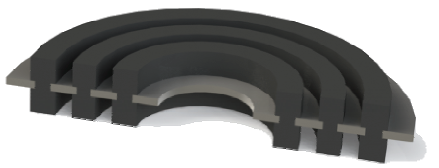

Fig. 4 Basic rubber metal spring element of the draw gear

The rubber-metal spring of the draw gear by manufacturer *MIN Svrljig* from Serbia is subjected to accelerated fatigue testing. The noted rubber metal spring consists of 5 elements shown in Fig. 4, serially connected into a draw gear assembly. The elements are made with rubber mixture TG-B-712 by manufacturer *TIGAR Technical Rubber* from Serbia. TG-B-712 is a caoutchouc-butyl rubber with vol40% carbon black particles. Mechanical properties of TG-B-712 are given in Table 1.

Table 1 Mechanical properties of rubber compound TG-B-712 [10]

Test	
Hardness in Sh-A according to ISO/48	80
Strength in MPa according to ISO/37	15.3
Elongation at rupture in % according to ISO/37	379
200% Modulus of elasticity in MPa according to ISO/37	9
Compression set after 25% compression for 24 hours at 70 ºC in % according to ISO/815	12.1

The parameters of rubber constitutive model (Bergström-Boyce) are determined by uniaxial compression at different strain rates and stress relaxation test on the samples of the TG-B-712 rubber compound (∅35.7 × 17.8 mm) in a research project conducted at Faculty of Mechanical Engineering, University of Niš [8]. The samples are compressed between hardened steel plates lubricated with machine oil in order to prevent the barreling of samples. Based on the performed experiments, the model parameters for the rubber compound TG-B-712 are obtained during the optimization procedure in MCalibration software. The following material parameters are obtained: μ_A^0 = 0.8, λ_A^{lock} = 5.23, μ_B^0 = 9.87, λ_B^{lock} = 5.23, K = 565, ξ = 2.47, C = -0.9, m = 12.64.

The next step in procedure given on Fig. 3 is to determine the static hysteresis by the static structural analysis. To lower the computational demands, due to symmetry of the spring assembly and the load, only one quarter of the model is considered. The finite element model (Fig. 5) is meshed with 3D solid hex mesh.

Finite element model consists of 128167 nodes which form 93209 3D SOLID 185 [11] finite elements. During static structural simulation value of coefficient of friction 0.5 is assumed to have value of 0.5 [12]. The spring load is defined based on UIC Code 827-1. The draw gear assembly is compressed from stroke of 6 mm to final stroke of 36 mm at 0.75 Hz.

The simulation prediction of static hysteresis follows exactly the experimental procedure with regard to the loading and boundary conditions. Furthermore, the force-displacement data is recorded during the experimental investigation in order to verify the accuracy of prediction of static hysteresis.

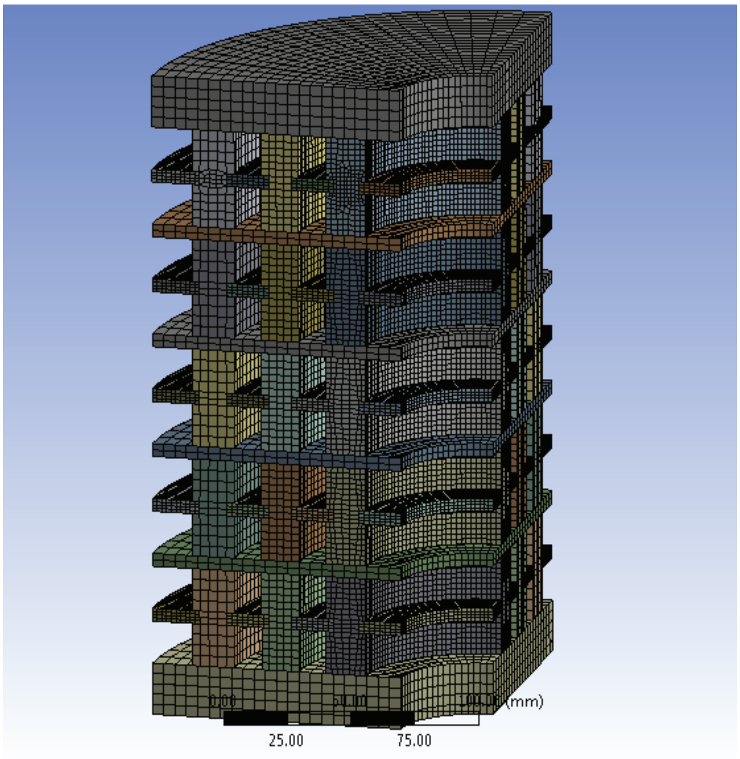

Fig. 5 FE model of the draw gear rubber metal spring

Fig. 6 shows the comparison of the load-deflection curves obtained by simulation and experimentally. It is clear that the predicted behaviour has a very good resemblance with the experimental results. Table 2 gives the comparison of the values of stored energy and hysteresis obtained, both experimentally and by simulation.

Table 2 Results of the static hysteresis test

	E_T, kJ	E_D, kJ	I, %
Experiment	2.865	0.765	26.71
Simulation	2.745	0.721	26.25

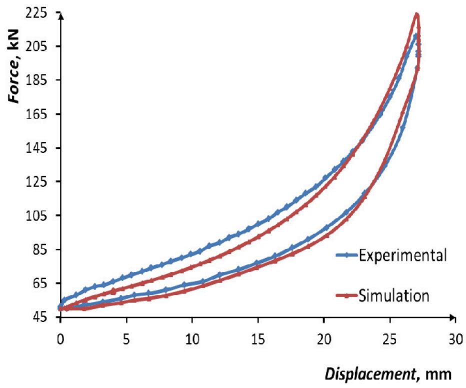

Fig. 6 Comparison between the experimentally obtained and the predicted behavior during the accelerated fatigue testing

The difference between the simulated and the experimentally obtained static hysteresis values is in the frame of 2 % (Table 2), which is rather high accuracy.

4. PREDICTION OF TEMPERATURE DISTRIBUTION

The predicted hysteresis values are used to determine heat generation rate (H_G) according to equation 1. Heat obtained generation rate (H_G) is applied as the major heat source via the internal heat generation load case. Furthermore, convection and radiation from the rubber and steel outer surfaces are also taken into consideration. The values of the parameters used in the transient thermal analysis are listed in Table 3. The parameter values are either obtained from the relevant literature or predicted based on data extrapolation from literature.

The internal heat generation is applied to all basic rubber metal elements in the draw gear assembly. The results of the transient thermal simulation are shown in Fig. 7. From the temperature profile the highest value is in the central rubber ring confined between the outer and inner rubber ring. Such temperature distribution is expected because the heat exchange is much quicker near the inner and outer draw gear assembly surface.

Table 3 Parameters used for thermal analysis [6, 1]

Parameter	Value
Rubber density (kg/m^3)	1000
Stefan–Boltzmann constant (W/m^{2}K^4)	5.67×10^{-8}
Steel specific heat capacity (J/kgK)	434
Rubber specific heat capacity (J/kgK)	1700
Steel conductivity coefficient (W/mK)	60.5
Rubber conductivity coefficient (W/mK)	0.238
Convective heat transfer coefficient from steel to air (W/m^{2}K)	6
Convective heat transfer coefficient from rubber to air (W/m^{2}K)	8
Steel emissivity	0.2
Rubber emissivity	0.95

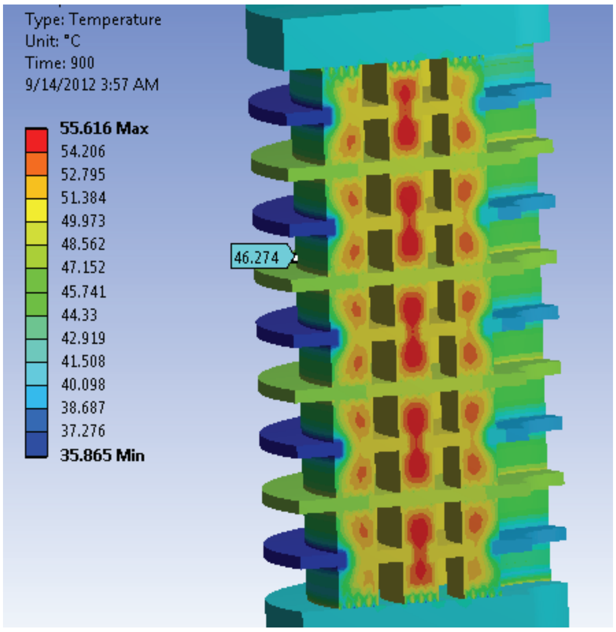

Fig. 7 Temperature distribution of the draw gear assembly obtained by simulation

The predicted temperature is compared to the experimentally obtained one, at cycle 700, which corresponds to a time range 15 min from the test onset. At that moment the measured temperature of the rubber surface is 44 °C. The predicted temperature in the same spot is 46.2 °C which is a very good agreement.

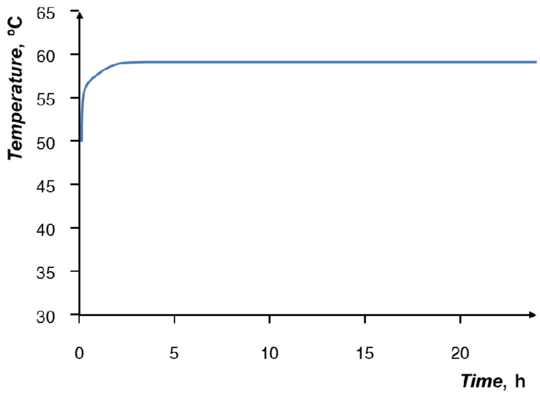

Fig. 8 Maximal temperature of the draw gear assembly over time of 24 h

It is clear from the obtained results that the new procedure for temperature distribution prediction in rubber and rubber-metal springs with FEA gives very good results in case of the object of a complex geometry such as draw gear assembly. Furthermore, as maximal predicted temperature after 24 h does not surpass 60 °C (Fig. 8), it can be concluded that during the accelerated fatigue tests, the rubber design requirement will not be exceeded i.e. no additional cooling of the rubber metal spring during fatigue test will be required.

5. Conclusion

By application of the new procedure for predicting heat generation in rubber or rubber-metal springs it is possible to predict the spring temperature during the fatigue testing which is of uttermost importance for reliability of testing results.

As the parameters of the rubber constitutive model are usually known the procedure encompasses the following steps for the heat generation prediction:

1. Performing of the static structural analysis over the required loading range;
2. Calculating the energy loss per cycle;
3. Carrying out the transient thermal simulation and evaluating the results.

The presented procedure is used for predicting heat generation in rubber-metal spring of the railway draw gear subjected to fatigue testing in accordance with UIC Code 827-1. As obtained results are in a very good agreement with the experimental results and the procedure is completely computation-based, it can be concluded that the presented procedure is a valuable tool for predicting and controlling the rubber metal spring temperature during fatigue tests.

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PREDVIĐANJE GENERISANJA TOPLOTE U GUMENO METALNOJ OPRUZI VUČNE OPREME ŽELEZNIČKIH VOZILA

Milan Banić, Vojislav Miltenović, Miloš Milošević, Aleksandar Miltenović, Nataša Jovanović

Temperatura gumenih ili gumeno metalnih opruga se povećava pri cikličnom opterećenju zbog histerezisnih gubitaka energije i niske toplotne konduktivnosti gume. Ovaj dobro poznati fenomen zagrevanja gume pri cikličnom opterećenju je osnovni uzrok njenog starenja. Povećanje temperature gumene smeše dovodi do pogoršanja njenih fizičkih i hemijskih svojstava, povećanja krutosti i gubitka prigušne sposobnosti. Pregrevanje gumene smeše može predstavljati veliki problem pri ubrzanom ispitivanju zamora gumeno metalnih opruga jer se menjaju karakteristike opruge tokom ispitivanja, a može izazvati i trajno oštećenje opruge čime rezultati ispitivanja postaju nepouzdani. U radu je prikazana procedura predviđanja generisanja toplote u gumeno metalnoj opruzi vučne opreme železničkog vozila prilikom dinamičkog ispitivanja prema UIC Objavi 827-1.

Ključne reči: *vučna oprema, gumeno metalna opruga, generisanje toplote usled histerezisnih gubitaka, analiza metodom konačnih elemenata*