Temperature and Stress State of the Block-Braked Solid Wheel in Operation on Yugoslav Railways

Dušan Milutinović
Railway Transport Company Belgrade

Aleksandar Radosavljević
Traffic Institute CIP, Belgrade

Vojkan Lučanin
Associate professor

University of Belgrade
Faculty of Mechanical Engineering

Thermal load of the block-braked solid wheel railway vehicles is dominant on the other types of loads. This load, which is mainly consequence of long-term braking on downgrades for maintaining the defined constant speed purpose, is the main cause of occurrence of cracks on treads of wheel and finally fractures of wheel. The paper gives the analysis calculation results of the thermal load of the railway vehicle block-braked solid wheel on characteristic selected line on Yugoslav Railways network. Thermal analysis was done using the finite elements method, which was also used for obtaining wheel temperature and stress states in the simulated operation conditions.

Keywords: *railway, thermal load, residual stresses, block-brake, braking, FEM, temperature and stress state.*

1. INTRODUCTION

Occurrence of fractures on block-braked solid wheels railway vehicles, caused by thermal load, has been researched in Europe for more than 15 years. Researching is mostly performed in Rail Research Institute (ERRI) [1-7] with the basic aim was to define new design of solid wheel which is as little as possible sensitive to thermal overloads [8].

Previous results confirmed dominant influence of thermal loads in regard to mechanical loads [1,3,8, 9,10] but in [11] and [12] regulated residual stresses measurement appeared because of high thermal loads in block-braked solid wheel. It means that the problem prevention damages of solid wheels fractures are still very actual [9]. It is necessary to emphasis that high thermal loads, in other words overloads, of wheel very often occur as a result of long-term braking for the maintenance constant train speed on down-grade or unwanted locking of wheels purposes.

The paper presents results of estimated analysis of solid wheel thermal loads on selected characteristic line part on the network of Yugoslav Railways (JŽ). Calculations of temperature and stress states are made by finite element method (FEM), and characteristic line part is chosen as a line with maximum thermal loads of braking on the basis of detailed analysis of all lines on the JŽ network. Result of this analysis is thermal loads collective of braking on chosen line Belgrade - Bar (port on Adriatic coast), which is characterize by referent slope of 25‰ in both directions of train running. Final calculation results show changes of temperature in chosen wheel points during train running and pictures of stress states in periods of highest temperatures. On the basis of obtained results we can confirm hypothesis that thermal loads are the main cause of cracks occurrence on wheel rim on the JŽ network.

Received: November 2002, accepted: April 2003.
Correspondence to: Vojkan Lučanin,
Faculty of Mechanical Engineering,
27. marta 80, 11000 Belgrade, Serbia and Montenegro
E-mail: vlucanin@mas.bg.ac.yu

2. CALCULATION OF BRAKING POWER DISTRIBUTION

Numerous high up-grades and downgrades lead to an increase of both train traction consumed energy and thermal load as a result of intensive braking. All this results in motive power cost increase. In addition to increased consumed train traction energy to overcome rolling resistance in curves and gradient forces, very important costs are from frequent use of brakes for stopping as well as for maintenance issued train speed on down-grades. However, we are not asking a question of increased operation costs but increased maintenance costs is of great significance.

For calculation of power breaking distribution on Belgrade (Resnik) - Podgorica line it was necessary to simulate train traction in both directions. Train traction simulation is performed for longitudinal rail profile divided by train traction simulation software, which is shown in [13].

Electric brake diagram of locomotive series JŽ 461 for determination power braking distribution to maintenance-regulated speed on downgrades is used [14]. On the diagram basis are determined: braking effort, braking current and excitation current of traction motor for every train (locomotive) speed value, and finally braking power. Since train-running simulation is executed in function of time as a result we obtain dissipated train energy applying electric brake. In that way by train, running simulation, for each concrete case, is obtained brake energy distribution in function of passed route and running time. Therefore, brake energy is calculated in this way, which is developed during maintenance assigned constant speed on downgrades.

For simulation in direction Resnik - Podgorica, freight train with the mass of Q=1000 t and brake percentage of p=60%, is chosen hauled by electric locomotive series JŽ 461. In opposite direction freight train with the mass of Q=1060 t and brake percentage of p=61% is chosen with the same locomotive.

Considering obtained power braking distribution values, characteristic intervals with intensive braking and average values of brake power, are established. All of this is done to prepare input data for thermal load calculation of block-braked solid wheel by finite element method. Brake power diagram of freight train in Resnik-Podgorica direction is shown in Fig. 1.

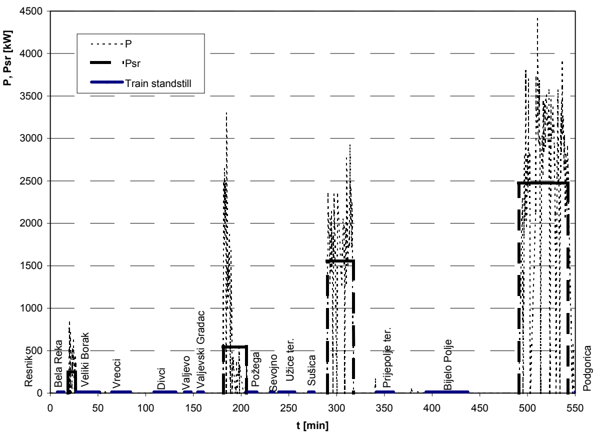

Figure 1. Brake power diagram (Resnik-Podgorica).

Average brake power value in Resnik-Podgorica direction on an energy maximum load point is 2.473 kW and in opposite direction 2.031 kW.

3. CALCULATION OF TEMPERATURE AND STRESS STATES CHANGES OF BLOCK-BRAKED SOLID WHEEL ON BELGRADE - PODGORICA LINE

Influence of thermal load from block braking on temperature and stress states of solid wheel is analysed by finite element method. Inside this analysis calculations for chosen line part, in both directions, and freight trains (train data are given in previous item) are conducted. Two groups of calculations are carried out: temperature states calculation of solid wheel during train running and stress states calculation which is result of temperature states, in other words thermal loads. Calculations are repeated for load case with allowable block-brake positions on the wheel tread during braking when the block-brakes are moved in relation to wheel tread for 10 mm. This case during operation is relatively often. All thermal loads, as input data, are defined on the basis of brake power diagram for chosen characteristic line part, which is shown in Fig.1.

Performed calculation of temperature and stress states of block-braked solid wheel presented simulation of more consecutive long-term braking, which happen on high down-grades for the maintenance constant train speed purposes, with separate periods of train running in traction regime and by coasting or time periods when train stop in station and there was no braking. In this cases wheels are exposed to process of cooling.

3.1. Models and loads

Wheel model created for calculation of temperature and appropriate stress condition, in other words corresponding finite element mesh, is shown in Fig. 2.

For calculation is used model of solid wheel, shown in [10], which presents dominate influence of thermal loads on stress condition and probability of occurrence cracks on wheel rim. Marked numbers of nodes are shown on presented net for which will be later given temperature change in function of time. Model is taken as axisymmetric because the processes of convection and conduction on wheel surface, during high wheel revolution, may be considered as uniform.

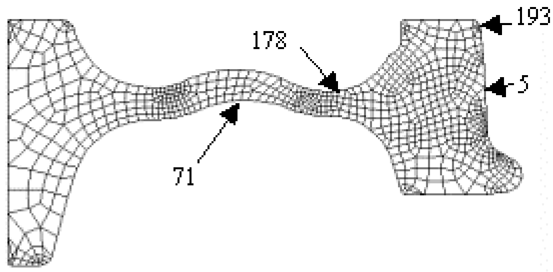

Figure 2. Solid wheel model (acc. FEM).

One of more significant phases of temperature states calculation was determination of thermal wheel balance, in other words determination wheel areas where thermal energy exchange with environment is in positive and negative direction. Input and output characteristics of thermal energy are obtained on the basis results of researches performed in ERRI reports [1,8] and shown in Fig.3 and Table 1.

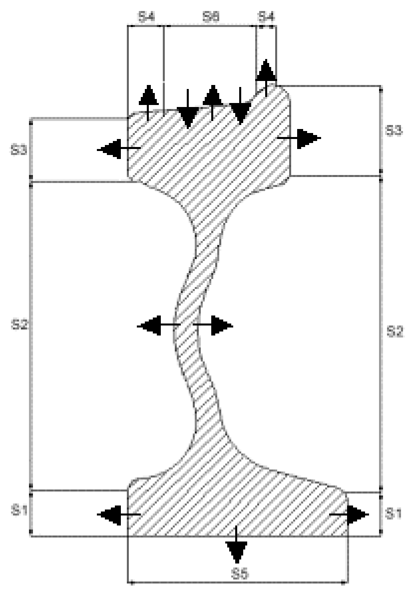

Figure 3. Wheel areas where thermal energy exchange is performed.

In Table 1, characteristic heat transition on environment from wheel surfaces, marked S1-S4 (in other words corresponding heat-transition coefficients), which depends on temperature are shown. In that way, thermal load change during braking is taken into consideration and simulated nonstationary process. On the surface S5, which is in firm contact with axle (pressed fit), thermal energy transfer is defined like heat conduction with constant thermal energy flux.

Table 1. Heat-transition coefficients [W/mm^2].

Area label	Temperature [^{o}C]			
	0	200	400	600
S1	17e-6	27e-6	43e-6	68e-6
S2	17e-6	27e-6	43e-6	78e-6
S3	37e-6	50e-6	70e-6	95e-6
S4	31e-6	43e-6	62e-6	84e-6
S5	Heat conduction Q_5 = - 6.6e-3 W/mm^2			
S6	Generation of thermal energy dependence on load step and heat-transition with coefficients:			
	28e-6	39e-6	57e-6	77e-6

Surface S6, representing a part of tread wheel upon which slide the friction parts of the block-brake, has been somewhat more complicated problem for modelling the heat exchange. Because of the adopted axisymmetric model, at that surface it was necessary to simulate the simultaneous heat inflow from friction (a part of heat transferred to the wheel rim) and heat outflow due to cooling at the segments of the surface, which are not in contact with block-brakes. The problem of simultaneous heat inflow and outflow is solved by introducing into the model at the surface S6 special surface elements serving solely for heat generation. Simultaneously, the heat-transition coefficients at the surface S6 are reduced compared with the corresponding coefficients at the surface S4 for the ratio of areas of block-brake contact surface and S6 shoe sliding surface. The reason is simulation of reduced heat removal surface caused by permanently present block-brake at the surface (defined axisymmetric model assumes heat removal from the complete surface S6).

The computation included using the wheel material characteristics dependent upon temperature [1] shown in Fig. 4, so the *nonlinearity* of the process was included.

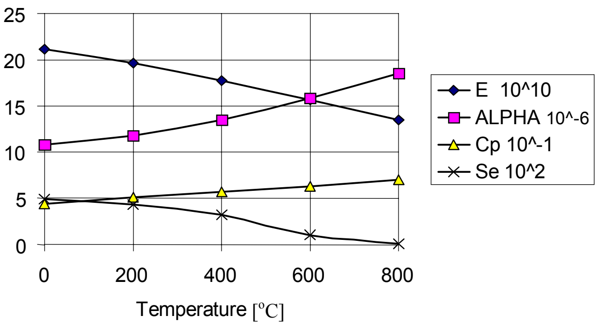

Figure 4. Dependence of the material characteristics upon temperature: modulus of elasticity *E* [N/mm^2], extension coefficient ALPHA [1/°C], specific heat *Cp* [kJ/kgK] and yield stress *Se* [N/mm^2].

Presented dependencies, especially the dependence of material yield stress upon temperature, were used for explaining the obtained results of computation that follows.

Variable thermal load of the wheel, occurring as the result of braking with shoes during the train running at the given line, was simulated in the form of the so-called load steps. Each of the load steps represents a constant thermal load with respect to input data for the temperature state computation. That means that characteristics of heat inflow and outflow through defined outer surfaces of the wheel are constant for each load step, i.e.: dependencies of heat-transition coefficients on temperature, dependencies of material characteristics on temperature and quantity of heat flux generated during the simulated long-lasting braking are constant for each load step.

The load steps are defined on the basis of braking power distribution diagrams, at which have been clearly marked the segments of the line with braking of the train with the aim of keeping the constant speed of motion when going downhill. In order to speed up the computation realisation, and with no significant influence upon the accuracy of the results, several consecutive brakings have been unified and defined are the mean braking powers for chosen periods of downhill braking. In that manner, determined are the load steps shown in Fig. 1 (thicker dashed lines marked with P_{sr}), which simulate long lasting downhill braking and load steps without thermal load from braking (periods when the train is in traction regime, coasting or standing at the station).

For computation of the change of temperature state in the braked wheel of the train, performed in table, used are the data on time of start and duration of load and data on heat input for each load step. With the aim of analysing critical load cases, data on heat input are defined also for the case of wheel with irregularly placed shoes at the tread wheel, when the width of the contact surface is reduced from 80 to 70 mm. It should be mentioned that the quantities of the heat input obtained on the basis of braking powers reduced by the part of heat transferred onto the shoe during the braking process (about 30% according to ERRI data [1]). On the other hand, these data were, when simulating the braking with irregularly placed shoes, increased proportionally to reduction of contact surface with aim of keeping the same braking energy in both cases.

Mean braking power per wheel, computed based upon data on the mean train braking power, indicates that the largest mean power of 24.72 kW lasting 51.54 min is realised at line Belgrade-Podgorica (line part Kos-Podgorica). At that line part the largest braking energy per wheel of 76.44 MJ is realised, so it is realistic to expect largest values of temperature and strain load of the wheel at that section.

In direction towards Belgrade, the largest mean braking power per wheel is 15.82 kW lasting 36.36 min, so the total braking energy per wheel is 34.52 MJ.

3.2 Results of computation of temperature and stress states of the wheel

Results of computation of temperature are presented in the form of diagrams of time dependence of temperature in the critical point at the tread of wheel and in the form of distribution of temperatures in the cross section of the wheel in the moment of its maximal thermal load, while the results of calculation stress states are given in the form of stress distributions at the wheel cross section at the moment of occurrence of maximal thermal load. Computations were performed for both directions of train running and for two shoe positions at the tread of wheel when braking - for the regular allowable position and for the unallowable (irregular) position. Presentation of temperature change in time is given only for the more critical case of the unallowable shoe position, because for the allowable shoe position curves of the same character of change are obtained; however with somewhat lower general temperature level.

Computational results of temperature change are by its character very similar to the results obtained by measuring during investigations performed at the same railroad section in both directions [15]. Namely, comparison of curves obtained by computation and curves obtained by measurements shows that the computational curves represent approximately the curves of mean values around which dissipate the values measured in exploitation. That and comparison with results of computation and measurements, realised within the investigations performed by ERRI [1,8], confirm the satisfactory accuracy of the results of own computations.

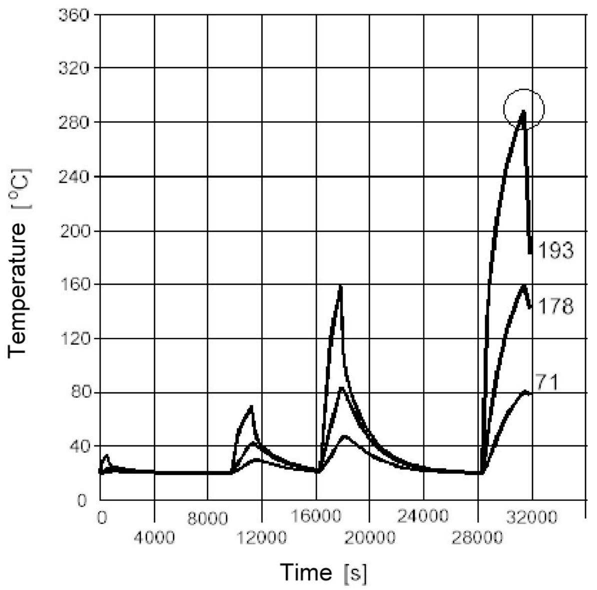

Figure 5. Wheel temperature change with the unallowable placement of block-brakes.

In Fig. 5 we have the computationally obtained diagram of temperature change depending upon the time of train running for the line part from Belgrade to Podgorica with unallowable placement of shoes at the tread of wheel. Numbers by which the curves in the picture are marked are the numbers of model nodes for computation by the finite element method.

It can be seen from the given diagram, that the maximum temperatures on wheel are attained immediately before arrival of the train to Podgorica at the downhill Kos-Podgorica part of line.

For the time moment with the highest temperatures in the wheel (circled maximum of the curve in Fig. 5) in Fig. 6 and 7 are shown temperature and stress states in cross section of the wheel for the allowable and the unallowable position of block-brake at the tread of wheel.

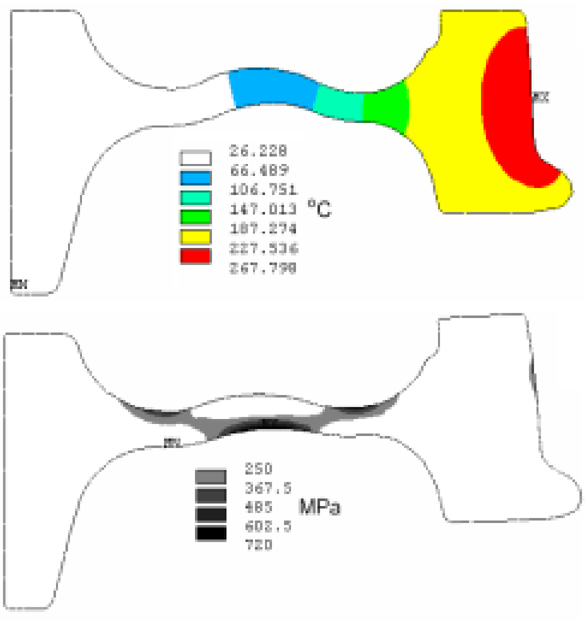

Figure 6. Wheel temperature and stress states with the allowable position of block-brake at maximum thermal load.

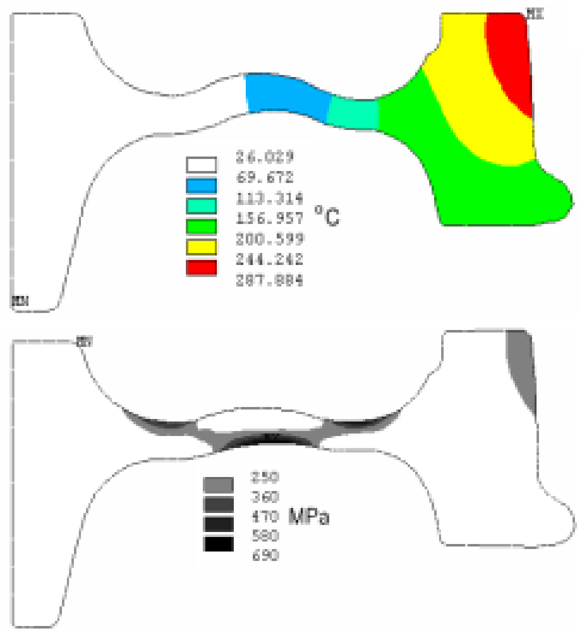

Figure 7. Wheel temperature and stress states with the unallowable position of block-brake at maximum thermal load.

From the display of the temperature state of the wheel for maximum thermal load at the Belgrade-Podgorica line it can be seen that computation has yielded maximum temperature of 288°C in the case with the unallowable position of block-brake (Fig. 7), i.e. 268°C in the case with the allowable position of block-brake. So, with the unallowable position of block-brake the maximum temperature was increased for about 20°C and logical shift of the place of maximum temperature to the edge of tread wheel (marks MX in Fig. 6 and 7).

The reviews of stress states, which are formed because of the calculated temperature states under the maximal thermal load conditions, show slightly lower maximal stresses in case of unallowable brake blocks position (690 MPa in case of unallowable and 720 MPa in case of allowable brake blocks position). The maximal stresses are formed on the middle curve of the wheel disc and they are higher than the wheel material yield stress. However, in order to explain the appearance of the wheel rim cracks which are formed as a consequence of the wheel thermal loads we have to watch the more interesting appearance of the wheel rim region with stresses above 250 MPa in the case of the unallowable brake blocks position (Fig. 7). In this region of maximal temperatures, thermal cracks appear during usage. The explanation of the causes that make cracks to appear in this region and not in the region of maximal stresses lies in the fact that material yield stress is significantly lower in the region of maximal temperatures (Fig. 4).

When it comes to the opposite direction, the maximal temperature on the first downgrade at the beginning of the Podgorica-Belgrade line is not higher than 180^{o}C.

The maximal stress of 390 MPa is formed on the wheel disc central curve and this is the same thing that happened during running in the Belgrade-Podgorica direction. The stresses in the region where thermal cracks appear are also significantly lower (slightly higher than 150 MPa).

Wheel temperature and the corresponding stress states in case of the allowable brake block position and the maximal thermal load are slightly lower for this direction. Calculated maximal temperature is 165^{o}C and the maximal stress at the centre of the disc central curve is 410 MPa (the rim stresses are lower than 150 MPa).

Considering the complete results of the block-braked wheel temperature and stress state analysis for the Belgrade - Podgorica and Podgorica - Belgrade directions we can conclude that the conditions which cause thermal cracks to appear (which can lead to wheel fracture) are present during this usage. These conditions appear on the Kos - Podgorica down-grade in the direction towards Podgorica in the cases of both unallowable and allowable brake blocks position. 11 wheel fractures formed because of thermal overloads in current usage on this line can be explained by this fact.

4. CONCLUSION

The JŽ network is versatile considering both the allowable axle load and quality and the cross-section and the longitudinal section characteristics. This network is rich in slopes, and therefore causes significant thermal loads of the railway vehicle wheels. Performed analyses showed that (considering the wheel thermal load during down-grade running) on the JŽ network key line-part was Belgrade-Podgorica and for this line part, the calculation of the time dependence of wheel temperature and stress state was carried using the finite elements method. The significance of the carried calculation of the thermal load of the solid wheel being braked by brake blocks on the JŽ increases if we consider the fact that JŽ has almost 17.000 wagons and over 4.000 coaches with brake blocks [16].

The calculation results both for allowable and unallowable brake block positions on the wheel tread during braking showed that high thermal loads appeared on the biggest down-grade of the Belgrade-Podgorica line (Kos-Podgorica line part). On that line part, the calculated wheel rim maximal temperature was 288^{o}C for unallowable and 268^{o}C for allowable brake-block position. The calculation of stress states, as consequence of thermal loads, shows that maximal stresses appeare in the middle of the wheel disc central curve, and that they are 720 MPa in the case of allowable and 690 MPa in the case of unallowable brake blocks position. The obtained stress values are higher than material yield stress, therefore obtained conditions for the plastic deformations, and initial cracks can lead to wheel fracture.

In order to prevent fracture of the solid wheels being braked by the brake-blocks caused by the thermal overloading we have to take some measures during usage. These measures consist of consistent wheel monitoring process and examination of the residual stresses in the wheel rim in order to prevent fracture of solid wheel with high tensile residual stresses. As a part of wheel monitoring, we have to carry out the following processes:

- to determine paint burns and therefore to choose the paint sensitive to high temperatures (burning is the consequence of high thermal loads),
- to determine the increase of distance of the internal side surfaces of the wheels,
- to determinate the brake-blocks positions on the tread and
- to note and additionally make the slots those were formed because of the tightening on the lathe for wheel profile making.

All mentioned measures, providing they are carried out consistently, could significantly decrease the probability of appearing of cracks caused by the thermal loads. These measures can also help these cracks to be discovered on time.

Analysing the amount of energy obtained during braking on the whole Belgrade-Bar line and comparing it with the spent electrical energy for train traction we can conclude that this line is ideal for the regenerative brakes to be applied. However, the existing electric locomotives on the JŽ network do not have regenerative brakes and, what's more, the electrodynamics rheostat brakes are out of order. Only 30% of the leading electro-locomotives series JŽ 441 have the electric brakes, which have many technical flaws, and therefore their appliance is insecure. The same thing goes for the locomotives from the JŽ 461 series. Although all these locomotives have electric brakes, only few are in function. This approach on electric braking significantly increases the probability of cracking caused by the railway vehicle wheel thermal loads.

The last and probably the most important measure for preventing the solid wheel fractures to appear which was prescribed by the newest changes of the UIC leaflets 510-2 and 812-3 is the test of the residual stresses in the wheel rim made of R2, R3, R8 and R9 materials in order to determine the possible exceed of the allowable level. This measure (supported by the large researches) represents the final part of the process of solving problems concerning the solid wheel fracture because of thermal loads.

REFERENCES

[1] ORE B 169/RP1 Limites thermiques des roues et des sabots, Choix des paramètres pour l`étude des limites thermiques des roues et des sabots, Utrecht, 1987.

[2] ORE B 169/RP 2 Limites thermiques des roues et des sabots, Effet du cumul des freinages sur le champ des contraintes résiduelles dans la jante des roues,Utrecht,1989.

[3] ORE B 169/RP 3 Limites thermiques des roues et des sabots, Recherche du seuil de rupture, Utrecht, 1991.

[4] ERRI B 169/RP 4 Standardization of coach wheelsets, Standardization of a block-braked solid wheel (rim diameter 920 mm) for coaches with a maximum speed of 160 km/h, Standard wheelsets for block brakes, Utrecht, 1993.

[5] ERRI B 169/RP 5 Standardisation des essieux, Méthodes de surveillance des roues monoblocs (mesures immédiates contre les ruptures des roues), Utrecht, 1993.

[6] ERRI B 169/RP 6 Standardisation des essieux, Méthodes de surveillance des roues monoblocs en service, Méthode aux ultrasons pour la détermination non destructive des contraintes résiduelles dans les jantes de roues monobloc, Utrecht, 1995.

[7] ERRI B 169/RP 8 Standardisation des essieux, Détermination de la ténacité des roues monobloc en R7, Définition d`une méthode d`essai et d`un critère d`acceptation, Utrecht, 1995.

[8] ORE B 106/RP 12 Standardization of coaches, Standardization of a block-braked solid wheel (tread diameter 920 mm) for coaches with a top speed of 160 km/h, Basic calculations, Utrecht 1989.

[9] Jovanović R., Milutinović D., Modern Ways for Preventing the Domages Caused by the Railway Vehicle Solid Wheel Fractures (in Serbian), VI International Scientific Conference of Railway Experts - JUŽEL, Vrnjačka Banja 1999.

[10] Milutinović D., Tasić M., Jovanović R., Thermal Load as a Primary Cause for the Fracture of the Block-Braked Solid Wheel (in Serbian), Železnice, br. 11-12, Belgrade 1999.

[11] UIC 510-2 Matériel remorqué, Roues et essieux montés, Conditions concernant l`utilisation des roues de différents diamètres, 3e édition, 1.1.1998.

[12] UIC 812-3 Technical specification for the supply of solid (monobloc) wheels in rolled non-alloy steel for tractive and trailing stock, 5th edition, 1.1.1984.

[13] Radosavljević A. et al., Consumption rationalization and decrease of electric energy costs during railway train traction – optimization of the electric locomotive 441 series control (in Serbian), Institute of transportation CIP, Belgrade, 1992.

[14] Radosavljević A., Milutinović D, Bečejac Lj., Simulation of Electric Locomotives Running for the Driving Energy Savings Purposes, Fourth International Conference "Drives and Supply Systems for Modern Electric Traction in Integrated XXIst Century Europe", Warsaw, Poland, 23-25 September 1999.

[15] Milovanović M., (PhD thesis), Addition to the research of the maximal railway vehicle braking possibilities (in Serbian), Faculty of Mechanical Engineering, Belgrade, 1991.

[16] Milutinović D. et al., Study of the feasability of the researches and development of the sinter brake blocks and pads for railway vehicles (in Serbian), Institute of transportation CIP, Belgrade, 1999.

ТЕМПЕРАТУРНО И НАПОНСКО СТАЊЕ МОНОБЛОК ТОЧКА КОЧЕНОГ ПАПУЧАМА У ЕКСПЛОАТАЦИЈИ НА ЈУГОСЛОВЕНСКИМ ПРУГАМА

Д. Милутиновић, А. Радосављевић, В. Лучанин

Термичко оптерећење моноблок точка железничког возила коченог папучама је доминантно у односу на остале врсте оптерећења. То оптерећење, које је углавном последица дуготрајног кочења на падовима у циљу одржавања брзине, је основни узрок појаве пукотина на површини котрљања точка и, као крајња последица, лома точка. У раду су дати резултати прорачунске анализе термичког оптерећења моноблок точка на одабраној карактеристичној деоници пруге Југословенских железница. Прорачуни температурних и напонских стања точка рађени су помоћу методе коначних елемената.