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The Influence of the Change of the Fatigue Strength Distribution Parameters on the Railway Vehicle Solid Wheel Reliability

This paper analyzes the influence of the material limit fatigue strength mathematical expectation and standard squaring deviation (as a critical stress) on the railway vehicle solid wheel reliability under the affect of the mechanical loads. Reliability calculation was conducted using the methodology which includes the determination of the ideal working stresses in the critical area of the wheel according to the load distributions obtained during operation and the reliability calculation according to the defined working and critical stresses distributions.

***Keywords**: Railway vehicle, solid wheel, reliability, fatigue strength, distribution, calculation.*

1. INTRODUCTION

Reliability research is related to the random appearance of the unwanted events, that is to the technical system failures. Bearing in mind that there are several different reliability definitions in literature, we should emphasize here that in this paper reliability represents a probability for the system which works in the given conditions to do the given task in a satisfactory way in a given time. Reliability is the system internal feature and its level is determined at the design stage. Dealing with the complex technical systems such as railway vehicle systems, the failure of only one element can cause very serious conse-quences.

The factors that have the influence on the railway vehicles solid wheel reliability under the mechanical loads can be divided into two basic groups:

- first one is related to the realization of the operating load regimes and eventually to the working stresses distribution on the critical spot of the wheel, and
- the second one is related to the material strength characteristics and eventually to the distribution of the material critical stress which is responsible for the appearance of failures (cracks) and, at the end, wheel fractures.

The influence of the first group of factors can be determined with the satisfying accuracy only by carrying out large and complex tests of the wheel load regimes in the real operating conditions, [1]. In those tests vertical and lateral force on the wheel are measured during vehicle operation. The values of those forces obtained by measurement are then statistically analyzed and they represented the base for the reliability calculations of the fatigue strength and reliability.

This paper investigates the second group of the factors which is related to the material strength characteristics and their influence on the solid wheel reliability. Keeping the working stresses distributions of the wheel obtained by research constant, we tried to analyze the influence of the change of the critical stresses distribution parameters (fatigue strength limits) on the railway vehicle solid wheel reliability. At the same time, the paper further investigates the influence of the different material categories. This paper also presents the shorter analysis of the possibilities of the material fatigue strength different probability characteristics use for the reliability calculation and defines the procedure for the selection of the critical stresses distributions parameters used in this calculation.

The whole reliability analysis was carried out using only the mechanical loads (vertical and lateral force on the wheel). The stress state which is the consequence of the thermal loads caused by the long-time braking of the block-braked wheels was not taken into consideration though it represents the dominant cause of cracks appearance during operation [2, 3, 4]. This was done because we wanted to determine the degreee of the solid wheel overdimension in the operating conditions without block brakes/without thermal loads (that is when only mechanical loads were present/vehicles with disc or block brakes operating on the tracks with small down-grades, that is without long-time braking with high power).

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2. THE PROCEDURE FOR THE CALCULATION BASED ON THE WORKING LOADS AND CRITICAL STRESSES DISTRIBUTIONS AND LOAD REGIMES USED IN THIS CALCULATION

For the reliability calculation we used a methodology developed in [5] and given in detail in [6] which uses the empirical working stresses and theoretical critical stresses distributions. A part of that methodology is the software POUZD.M [7] specifically developed for this purpose which can carry out the reliability calculation and also has the following features: enables easy manipulation of the data from the database of the empiric distributions of loads; carries out the equivalent stresses calculation using the stress coefficients of the working loads relation; and enables easy input of the critical stresses distributions.

A special routine for data preparation was developed as a part of the POUZD.M software in order to obtain the working stresses distribution based on the working loads distribution. This routine is used to calculate the equivalent stresses based on the sum of the direct and shear stresses components for two loads (vertical and lateral force on the wheel) using the Huber-Mises-Henky's hypothesis about material destruction, that is the hypothesis about the highest deformation work for shape changes (3-D stress state). Component direct and shear stresses are based on the load size and so-called stress coefficients which represent the relation between the component stresses direct ratio and load.

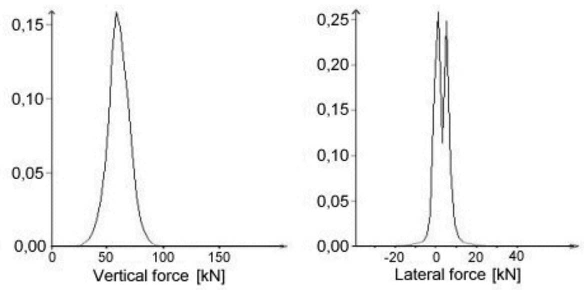

Figure 1. Vertical and lateral force empirical distributions on the wheel in the first operating regime [1].

The calculation methodology proposed in this paper uses the characteristic features within the given reliability in order to calculate the complex constructions stresses based on the known loads. Considering the fact that there is almost no possibility to measure the stress directly on the critical spots of the elements or constructions and therefore to obtain the corresponding distributions and considering the limited possibilities of the standard calculation methods of stresses in complex constructions, finite elements method today often represents the only option for the stress state analysis.

POUZD.M's main part is the reliability calculation procedure based on the working and critical stresses distributions obtained earlier in the process. The calculation is based on the slightly changed so-called graphical method which is used to obtain the value of the probability for the work without failure using the empirical working and critical stresses distributions [8].

Load regimes in the form of the railway vehicle solid wheel dominant loads distributions can be obtained only by carrying out large and complex tests which involve the measurement of the vertical and lateral force at the wheel-track contact. Although such tests are very useful as a base for design and reliability check, so far they have not been conducted under the operating conditions on our lines. On the European lines, on the other hand, the solid wheel load regimes tests were conducted as a part of the European Rail Research Institute's ORE B 106.1 project [1] in order to form the standard for the solid wheel being braked with brake blocks on the passenger coaches with maximum speed of 160 km/h. Wheel stresses and vertical and lateral forces in the real operating conditions on the selected sections with total length of 450 km were measured. During the operating conditions two basic regimes were defined: operation with lower speeds (first regime) and operation with high speeds (second regime). Measurements in both operating regimes were conducted using a number of selected sections for different conditions: track maintaining state (superstructure quality), layout of the line (directions, curves, points, crossings and passageways) and speeds.

To calculate the solid wheel reliability in order to analyze the influence of the material fatigue strength distribution parameters on the reliability we used the load distributions obtained for the first operating regime which are shown in Fig. 1.

The solid wheel reliability calculation was carried out using the working stresses distribution based on the given load distributions (vertical and lateral force) on the wheel. The procedure which is used to obtain the ideal working stresses distribution on the critical spot (in the critical area) using the wheel vertical and lateral force distributions is given in detail in [6]. Within this procedure the calculation of the wheel stress state was done using the finite elements method in order to determine the stress coefficients for the calculation of the ideal stresses and the critical spot on the wheel for which the further calculation would be carried out. Figure 2 shows the stress image obtained by the calculation using the finite elements method in case when vertical and lateral force are present at the same time as well as the critical area C.

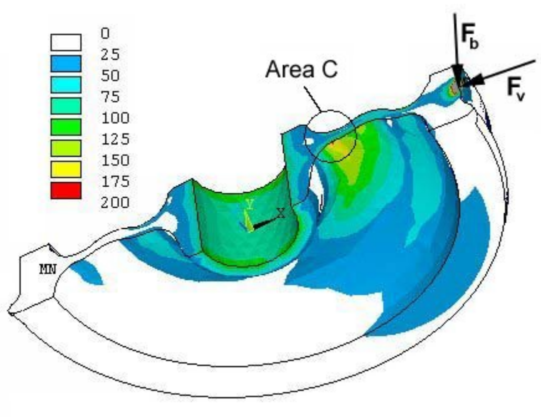

Figure 2. Wheel stress state under the effect of the vertical and lateral force (stresses are in MPa).

3. FATIGUE STRENGTH PROBABILITY CHARACTERISTICS AND CRITICAL STRESSES DISTRIBUTIONS USED DURING ANALYSIS

Above all the critical stresses distribution selection depends on the selected critical failure, that is on the failure criterion. Concerning the mechanical elements strength these failures include static fracture in case of loads invariable in time and the fracture caused by the material fatigue in case of variable loads. It is undesrstood that the same failure criterion must be the base during the determination of the working and critical stresses distributions and corresponding stresses.

It is relatively simple to determine the critical stresses distribution related to the static fracture by conducting the corresponding tests of the specimens made from the given material. However, things get complicated when we want to determine the critical stresses distribution when the critical failure is material fatigue caused by the long-time effect of the variable load (so-called multicycle fatigue) especially if the variability is random [9, 10, 11]. The complexity of this problem is the consequence of a number of factors, which more or less determine the distribution form. All these factors have an influence on the shape and position of the so-called curved fatigues with the same fracture probability [11]. These curves are related to the long term laboratory researches with the number of specimens with different variable stress values.

Most of the data about fatigue in laboratory conditions were obtained for the alternate variable load, that is for the alternate variable load with zero mean value. However, operating loads are often variable and have non zero mean value. Therefore, it is very important to know how the cycle mean stress affects the material behaviour during fatigue. This can be determined by the elements calculation (whose alternate variable load has some mean stress) based on the results of the laboratory researches of specimens with symmetrically variable load.

Designer seldom has the results of the material fatigue strength research, which were obtained for the different cycle mean stress values and for the number of cycles needed for the appearance of fracture. Therefore, the influence of the mean stress is usually evaluated using one of the several known empirical ratios between fracture characteristics at a given number of cycles needed for the appearance of fracture with the non zero cycle mean stress value and fracture characteristics with the same number of cycles but with the zero mean stress. In most of the published reports a number of empirical dependencies of the cycle stress is usually evaluated using one of the several known empirical ratios between fracture characteristics at a given number of cycles needed for the appearance of fracture with the non zero cycle mean stress value and fracture characteristics with the same number of cycles but with the zero mean stress. Concerning the results of many reseaches, a number of empirical dependencies of the cycle stress amplitude on the cycle mean stress were defined (Smith's or Goodman's, Gerber's, Zoderberg's, etc.).

All these mentioned explanations about the definition of elements critical stresses distributions whose reliability is based on the material fatigue as a critical failure are related to the harmonically variable loads. However, the loads of almost all railway vehicle elements are extremely random (especially the loads of the wheelset elements). These random loads are very often simulated by the definition of the corresponding load blocks which consist of several different levels of harmonic loads based on which the corresponding fatigue curves (and even the curves with the same fracture probability) can be formed [10]. These tests are seldom conducted because they last long and therefore are expensive.

The results of these program tests (defined program load blocks) show that the life values obtained at the same mean stress value σ_{sr} during testing with the random load order are lower than the values obtained during testing with precisely defined program load order.

Critical stresses distributions (fatigue strengths) for the R7 material of the solid wheel in this paper were obtained using the data from the available literature. We presumed that the normal distribution law could be successfully applied to the fatigue strength distribution [8, 9, 10, 11, 13] so the problem has been reduced to determination of the mathematical expectation and standard deviation as parameters of the normal distribution.

Mathematical expectation was determined from the Smith's diagram [14] based on the data near wheel material yield point and the data near mean stress determined from the critical stresses distribution (calculation bases were load regimes obtained within tests conducted by the ERRI [1]). Obtained mathematical expectation was corrected because of the object size influence and the state of the external surface [14] so the final value was 112 MPa.

Standard deviation was determined using the empirical expression which represents the dependence of the fracture probability on the given number of cycles for the appearance of fracture N and the amplitude stress ratio (fatigue strength for the alternate variable load) σ_a and tensile strength σ_m: Using this expression we can determine the material fatigue strength distribution for every N. In addition, when N equals 10^7 we can determine the limit fatigue strength. When we put the distribution obtained in this case into the probability paper we can determine the variation (the ratio between the standard deviation and the mathematical expectation) of about 0.095. This value which corresponds the similar values form the literature (in [10] the values are 0.08 – 0.1) and the value of the mathematical expectation are used to calculate the critical stress standard deviation for the R7 material of the solid wheel (obtained value is 10.54 MPa).

4. THE ANALYSIS RESULTS OF THE INFLUENCE OF THE CRITICAL STRESSES DISTRIBUTION PARAMETERS ON THE RELIABILITY

In order to analyze the influence of the critical stresses distribution parameters (limit fatigue strengths) on the solid wheel reliability we formed a number of normal distributions with different parameters according to the model mentioned in the previous section. The analysis consisted of two parts:

- the first part was the analysis of the influence of the wheel material limit fatigue strength *mathematical expectation* on the reliability using the distributions with the same standard deviations and different mathematical expectations, and
- the second one was the analysis of the influence of the wheel material limit fatigue strength *standard deviation* on the reliability using the distributions with the same mathematical expectation and the different standard deviations.

The complete analysis consisted of 20 normal distributions of the limit fatigue strengths. The results of the reliability calculations conducted in order to analyze the influence of the wheel material limit fatigue strength mathematical expectation on the wheel reliability are shown in Fig. 3. The influence of the mathematical expectation is significant in the analyzed area change (decrease in mathematical expectation from 100 MPa to 75 MPa caused the decrease of the reliability of 0.0033). Diagram shows the nonlinear dependence of the reliability and the limit fatigue strength mathematical expectation and also the fact that under the operating conditions adpoted during calculation there was no sense to use the wheel material with the value of the limit fatigue strength mathematical expectation higher than 100 MPa.

Thicker vertical lines in Fig. 3 show the limit fatigue strength mathematical expectation levels of the known wheel materials with steel grades R1, R2 and R7 (the values for the steel grades R1 and R2 were obtained using the procedure explained in section 3 for the steel grade R7). The results show that in the given operating conditions without thermal loads we can use wheels with steel grade R2 instead of the R7 without the significant decrease of high level of the reliability.

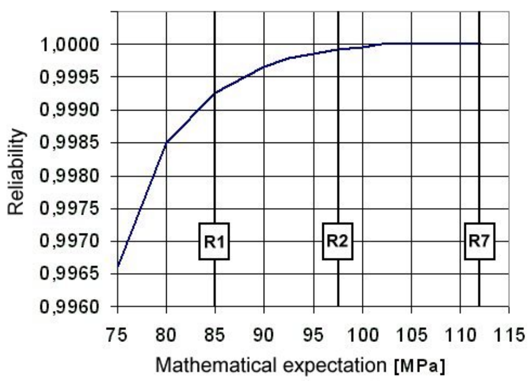

Figure 3. The influence of the wheel material limit fatigue strength mathematical expectation on the wheel reliability.

However, if we already think about the reconstruction of the "overdimensioned" wheel made from material R7, selection of the lower level material is not a good solution. Materials with lower limit fatigue strength or tensile strength also have unfavorable wear characteristics so the better solution would be to keep the high quality material and reconstruct the wheel by decreasing the disc and hub dimensions which means to develop a new lower mass wheel construction which will be used only in conditions without the dominant influence of the thermal loads. The advantages of the lower mass wheels appliance are very well known and they include the decrease of the non-suspended masses and fatigue strengths and costs. The greater appliance of disc-brakes on the passenger and freight cars in the future (especially on the higher speed trains) should lead to the necessity of development of the new lower mass wheel construction for the operating conditions without thermal loads.

The analysis of the influence of the wheel material limit fatigue strength standard deviation on the wheel reliability was realized using the distributions with the same mathematical expectation of 75 MPa (the lowest value was taken because of the clearer understanding of the influence character) and different standard squaring deviations from 4 MPa to 10.64 MPa. The analysis results are shown in Fig. 4 where we can see that reliability decrease because of the limit fatigue strength standard deviation increase in the given interval. However, if the limit fatigue strength dissipation characteristics are within the intervals known from the literature (variation change between 0.08 and 0.1 – gray field in the diagram), reliability change caused by the standard squaring deviation change is not so significant but it is still obvious. Therefore, if the material (wheel) production quality control maintains the requested level of the material dissipation characteristics the influence on the reliability decrease will not be big (especially if we have in mind that the diagram in Fig. 4 was formed for the material with the lowest value of the mathematical expectation which means that the difference is even smaller for the high quality materials).

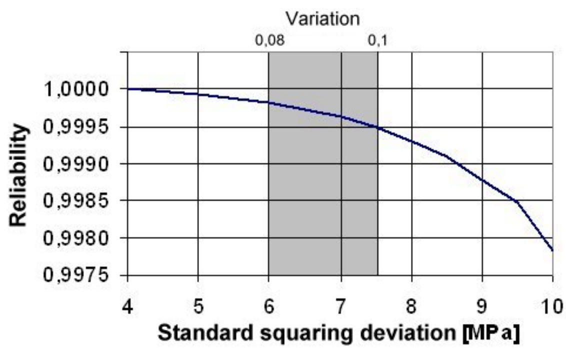

Figure 4. The influence of the wheel material limit fatigue strength standard squaring deviation on the wheel reliability

5. CONCLUSIONS

a) Great number of factors affect the fatigue strength and therefore the railway vehicle solid wheels existing materials fatigue strength probability characteristics. Therefore, during the solid wheel reliability calculation it is important to determine the material limit fatigue strength distribution as critical stresses with the satisfying accuracy. Based on the adpoted theoretically and experimentally proved assumptions this paper defines the limit fatigue strength normal distribution for the solid wheel steel grade R7 and the distributions with lower mathematical expectation and lower and higher dissipation which were used to analyze the influence of the critical stresses distributin parameters change on the reliability in the conditions with mechanical loads.

b) Conducted calculation showed the high level of agreement between the solid wheel reliability affected only by mechanical loads in the operating conditions obtained in this paper and defined by the tests conducted by ERRI [1]. Obtained results show that the existing solid wheel standard construction under the adopted operating conditions is overdimensioned if it is used without thermal loads, that is without braking with brake blocks.

c) There is a significant influence of the wheel material limit fatigue strength mathematical expectation decrease on the wheel reliability. Obtained dependence of the wheel reliability change on the wheel material limit fatigue strength mathematical expectation showed that in the defined operating conditions we can use lower quality materials (steel grade R2 instead of R7) if the wheels operate without thermal loads.

d) The calculation results show that it is rightminded to consider new solid wheel construction which will be used in the operating conditions without thermal loads, that is on the vehicles with disc-brakes or only in the operating conditions without long term braking on large down-grades. The greater appliance of the vehicles with disc-brakes in the relatively near future should probably arise the question of development of the new construction of the cheaper solid wheel with lower weight.

e) The analysis of the influence of the solid wheel material limit fatigue strength standard deviation change on the reliability shows that the we can maintain the requested high level of the wheel reliability by conducting the process of the control of material characteristics and their maintaining within the given limitations.

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УТИЦАЈ ПРОМЕНЕ ПАРАМЕТАРА РАСПОДЕЛЕ ДИНАМИЧКЕ ЧВРСТОЋЕ МАТЕРИЈАЛА НА ПОУЗДАНОСТ МОНОБЛОК ТОЧКА ЖЕЛЕЗНИЧКОГ ВОЗИЛА

Д. Милутиновић, В. Лучанин

У раду је извршена анализа утицаја математичког очекивања и стандардног квадратног

одступања трајне динамичке чврстоће материјала (као критичног напона) на поузданост моноблок точка железничког возила под дејством механичких оптерећења. За прорачун поузданости коришћена је методологија која подразумева одређивање идеалних радних напона у критичној области точка на основу расподела оптерећења добијених у експлоатацији и израчунавање поузданости на основу дефинисаних расподела радних и критичних напона.