ANALYSIS OF STRENGTH AND DEFORMATION OF PARABOLIC LEAF SPRINGS FOR TRANSPORT EQUIPMENT

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ABSTRACT: Modelling and comparative strength analysis of different structures of parabolic leaf springs are carried out in this paper. They are used in the suspension structures of transport equipment. For example, it includes wagons for transport of ore, coal and other bulk cargo as well as many trucks. Statistical results of many operational observations of the suspension elements of railway wagons and trucks up to their failure status are reflected. The loads and strength characteristics of different types of parabolic leaf springs are described. They were modelled by the Finite Element Method (FEM) and after that a comparative strength analysis using modern software packages is performed.

Keywords: transport equipment, spring suspension, leaf springs, failures in parabolic leaf springs, strength analysis, Finite Element Method

ЯКОСТНО-ДЕФОРМАЦИОНЕН АНАЛИЗ НА КОНСТРУКЦИИ ПАРАБОЛИЧНИ ЛИСТОВИ РЕСОРИ ЗА ТРАНСПОРТНА ТЕХНИКА

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РЕЗЮМЕ: В доклада е извършено моделиране и сравнителен якостен анализ на различни конструкции параболични листови ресори. Те се използват в конструкцията на ресорното окачване на транспортна техника. Например, това са вагони за превоз на руда и други насипни товари, както и много товарни автомобили. Отразени са статистически резултати от експлоатационни наблюдения на елементи от ресорното окачване на железопътни вагони и товарни автомобили, до състоянието им на отказ. Описани са натоварванията и якостните характеристики на различни видове параболични листови ресори. Същите са моделирани по метода на крайните елементи, след което е извършен сравнителен якостен анализ с помощта на съвременни програмни продукти.

Ключови думи: транспортна техника, ресорно окачване, листови ресори, откази в параболични листови ресори, якостен анализ, метод на крайните елементи

Introduction

One of the most important parameters determining the reliability and safety of land vehicles running is the functionality of spring system (SS). The SS failure causes very serious consequences and in many cases leads to derailment. For this reason, the design and reliability of the vehicle SS are subjects of many documents including those related to fault detection and analysis of failures (Mateev, 1971; Fan et al., 2010; Yusuke et al., 2008; Kumbhalkar et al., 2011). The purpose of the above-mentioned studies is to identify potential problems and define constructive and technological solutions for improvement of existing or newly developed types of suspension (Kocev et al., 2018).

Fig. 1. A derailed wagon of Fbd type with spring suspension (leaf springs) owned by Nikola Tesla TPP in Obrenovac, Serbia and used for coal transportation

For example, such a system is the system used for rail coal transportation from Kolubara mining basin to Nikola Tesla Thermal Power Plant (TPP) in Obrenovac, Serbia. The transportation based on Fbd wagons is performed along one of the busiest industrial railway lines in Europe. Due to that and some peculiarities of the SS design based on leaf springs, this type of fractures often leads to derailment (Petrovic et al., 2012; 2014) (Fig. 1).

The consequences of derailments are with huge material damage and considerably reduce railway transport efficiency. Such problems are often encountered along many busy freight rail lines.

Each accident is followed by extensive measures and detailed expert examinations carried out to determine the causes of incident. Based on the results of these studies, relevant regulations are set up to give guidelines for further development of railways and establish relevant measures to prevent incidents and accidents. SS failures, which may be of different nature, are among the dominant causes of rail derailments, especially in freight transportation. The modern approach to avoid any possible risks is based on research to obtain both theoretical and experimental identification of reasons leading to rail vehicle suspension failures (Skrobanski, 2019), such as the quality of leaves used in leaf springs (LS), operation conditions, uniformity of loading, etc. (Nikolov, 2019). Such faults are also observed in the leaf springs of automotive freight vehicles.

Examining the reasons of the Fbd wagon derailment, the following data about fractures of SS components as reflected in Pareto diagram (Fig. 2) have been noticed: fracture of a leaf of leaf spring (1), spring eye (2), spring shackle (3) and centring bushing (4).

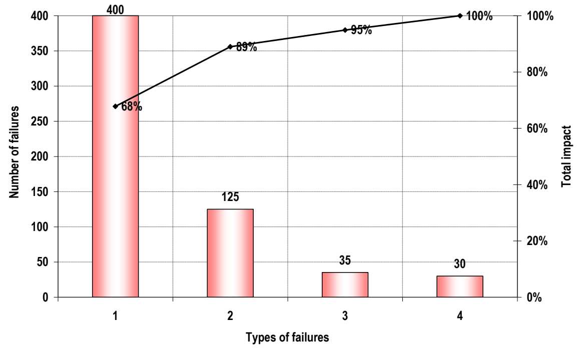


Fig. 2. Pareto diagram of failures of Fbd wagon spring system components

The analysis of the graph in Figure 2 shows that the failures of: leafs of leaf spring are 68%; spring eye – 21%; spring shackle – 6% and centring bushing – of 5%.

The most frequent fractures occur due to destruction of the main leaf and leaves of the multiple packages. In approximately 70% of cases, leaves have been broken in the centre, which is closer to the spring shackle, but in approximately 30% of cases the fracture has appeared in the eye area.

Many conceptual ideas how to reduce failures of leaf springs have been examined (Petrovic et al., 2012). The main idea of solving this problem is to apply parabolic leaf springs (PLS) in SSs (spring systems) of railway wagons and trucks.

Failures of leaf spring structures

Failures or damage of leaf springs include: a crack or breaking of the eye, breaking of the main leaf; breaking of a leaf of the multiple package; corrosion on leaves; a loose U-bolt or loose shackle, a fallen wedge.

The study has been conducted based on statistical data obtained from reports made on repairs or prevention of failures of individual truck suspension elements and the suspension of two-axle freight wagons in a year's period of monitoring.

Concerning the leaf springs of trucks, there are 100 failures registered, distributed in 6 types (groups) while the failures of leaf springs in spring suspension of two-axle freight wagons are distributed into 7 types (groups).

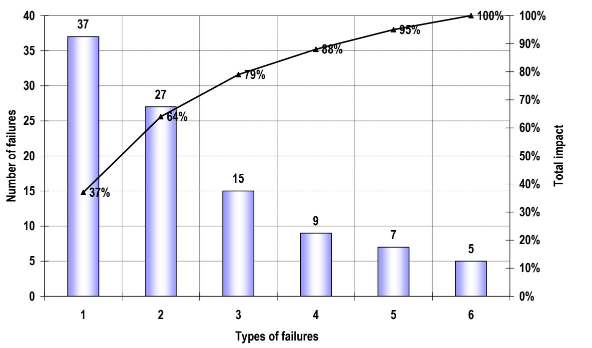


Fig. 3. Pareto diagram of failures of leaf springs for truck spring system

From the Pareto diagram (Fig. 3) it can be determined that the truck leaf springs are characterised with the following six faults (repairs): the main leaf eye (1); the main leaf (2); a leaf of the multiple package (3); a spring suspension component (4); a U-bolt (5); corrosion on leaves (6).

In conclusion, the analysis of failure types shows that the above-mentioned components are the main systems defining (limiting) the reliability of truck suspension. These systems account for 100% of failures. The graph of analysis in Figure 3 shows that failures are due to: the main leaf eye – 37%; the main leaf – 27%; a leaf of the multiple packages – 15%; a U-bolt – 9%; a spring suspension component – 7% and corrosion on leaves – 5%.

From the Pareto diagram (Fig. 4) it can be determined that the leaf springs in spring suspension of two-axle freight wagons include the following seven characteristic faults (repairs): the main leaf eye (1); the main leaf (2); a leaf of the multiple package; (3); a spring suspension component (4); a spring shackle (5); a wedge (6); a spring bushing (7)

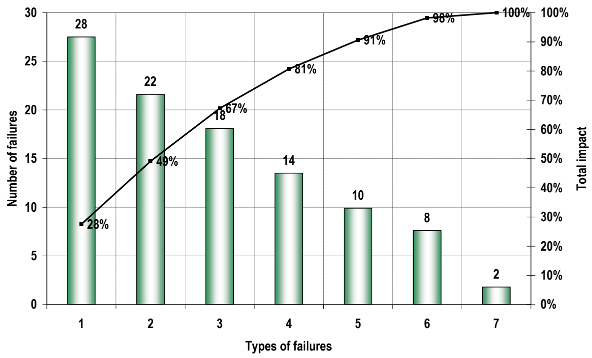


Fig. 4. Pareto diagram of leaf spring failures in spring suspension of two-axle freight wagons

In conclusion, the analysis of failure types shows that the above-listed components are the main systems defining (limiting) reliability of spring suspension of two-axle freight wagons. These systems account for 100% of failures. The graph of analysis in Figure 4 shows that failures are due to: the main leaf eye – 28%; the main leaf – 21%; a leaf of the multiple package – 18%; a spring suspension component – 14%; a spring shackle – 10%; a wedge – 7% and a spring bushing – 2%.

Structures of parabolic leaf springs

PLS of suspension for automotive equipment

Leaf springs are used in suspension of trucks (Tsvetkov, 2011, BDS 2505:1985). Parabolic leaf springs of HST type have been introduced since 1997: for the first time in suspension of Land Rover, Land Cruiser, Suzuki, Daihatsu, etc.

Parabolic springs have leaves of varying profile. Each leaf of parabolic shape has a full multi-leaf spring function - thick in the centre and thinner towards the outer edges.

All springs of HST parabolic type are manufactured according to ISO 9000 standards. The ideal parabolic spring requires only one leaf, but for safety reasons it is necessary to use at least two leaves. The second leaf is of expanded style and it serves as a precautionary measure in case of breaking. Fig. 5-6 shows the computational diagram of a two-leaf parabolic sheet spring.

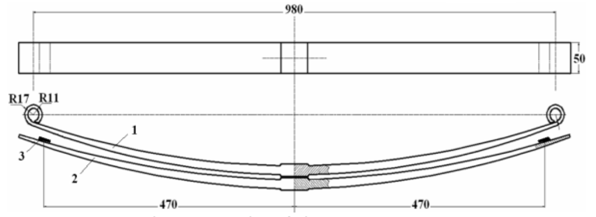


Fig. 5. Diagram of a two-leaf PLS for automotive equipment. 1 – main leaf; 2 – additional leaf and 3 – silencer (limiter)

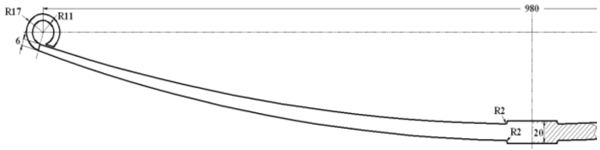


Fig. 6. Dimensions of the main leaf of a two-leaf PLS

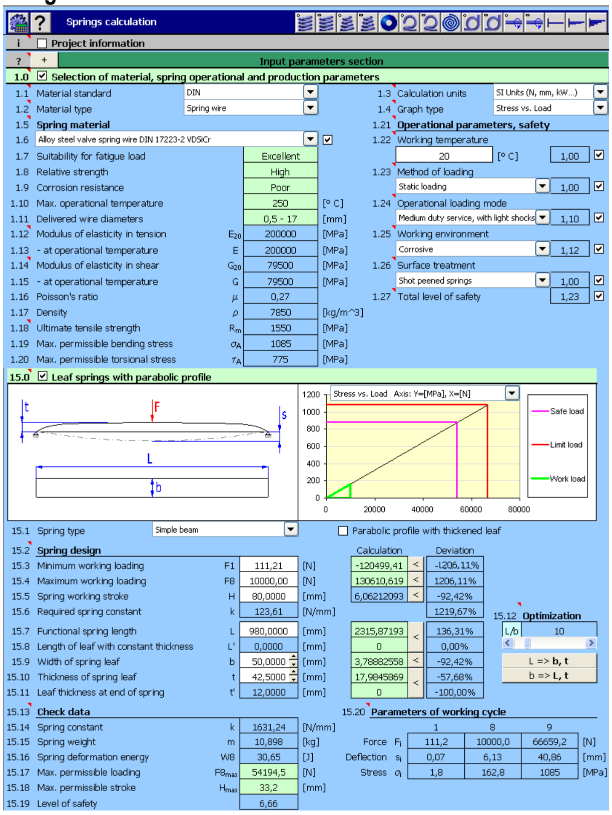
Westalia parabolic springs are designed to be 100% compatible with the standard suspension fittings.

The calculations of parabolic leaf springs can be made using MITCalc and simulations can be performed through Solid Works or another software.

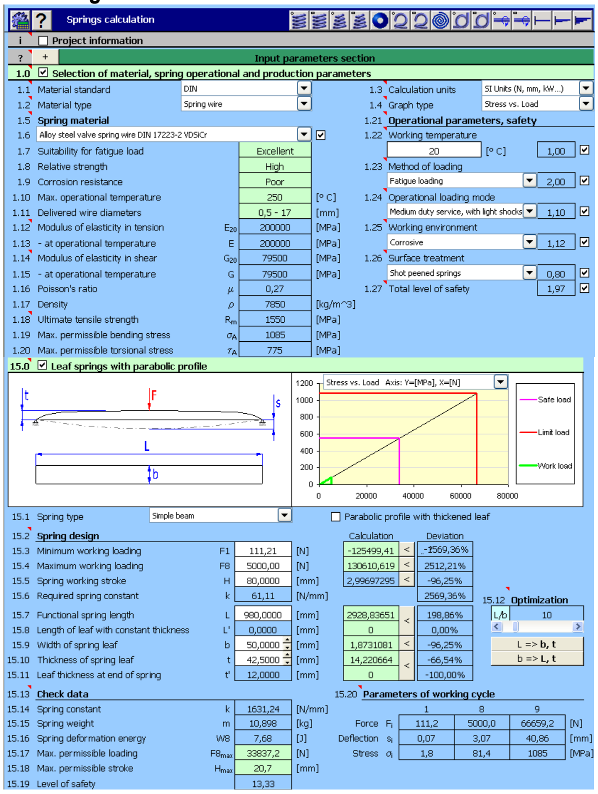
Determination of the strength and deformation state of two-leaf PLS using MITCalc software

The calculation of leaf springs using MITCalc software is based on the principle of calculating long rectangular-section beams subjected to bending. They are used as cantilevered beams fixed at one end, or as simple beams fixed at both ends. The leaves of leaf springs can be used independently or in packages (laminated leaf springs).

Results of calculations of a two-leaf PLS – with static load using MITCalc software



Results of calculations of a two-leaf PLS – with fatigue load using MITCalc software



Determination of the strength and deformation state of a two-leaf PLS using Solid Works software

Using SolidWorks software, a two-leaf PLS is modelled as in Figure 5 where the load is in the leaf eye and fixing is in the leaf spring centre. The model contacts are limited except for the contacts between rubber silencers and the main leaf, which are defined as non-friction joints. This type of connection describes the behaviour of a leaf spring in perfect condition where friction between leaves is not desired. The PLS leaf material is according to the manufacturer, SUP 9 (JIS). The standard comparison has shown that SUP 9 spring steel is equal to 55Cr3 by the European standards. Steel fatigue properties are defined in compliance with SAE using the database of Glyph Works material properties. The values for materials by SFS-EN 10089 standard for Glyp Work (SAE5160/SUP 9/55Cr3) materials are as follows: Elastic Modulus, E 207 GPa; Yield Strength, R_{eL} 1250 MPa; Ultimate tensile strength, R_m 1600 MPa; Work Hardening Coefficient, K 1940 MPa; Fatigue Strength Coefficient, Sf 2063 MPa; Cyclic Strength Coefficient K' 2432 MPa; Work Hardening Exponent, n 0.05; Fatigue Strength Exponent, b -0.08; Fatigue Ductility Exponent, c -1.05; Fatigue Ductility Coefficient E_f 9.56; Cyclic Strain-hardening Exponent, n' 0.13; Cut-off, Nc 2,00e+08 Reversals. Silicon material with the following parameters is used for the stops: Elastic Modulus 1.124e+011 N/m^2; Poisson's Ratio 0.28N/A; Shear Modulus 4.9e+010 N/m^2; Density 2330 kg/m^3; Yield Strength 120e+06 N/m^2; Thermal Conductivity 124W/(m·K). Mesh Type: Solid Mesh; Mesher Used: Standard mesh; Automatic Transition: Off; Smooth Surface: On; Jacobian Check: 4 Points; Element Size: 10.88 mm; Tolerance: 0.54402 mm; Quality: High; Number of elements: 11270; Number of nodes: 20763.

At a load of 10000 N in the eyes and fixing in the PLS centre, the maximum stresses equivalent to von-Mises are 439.06 MPa. The maximum stresses are in the area of weakening section in the centre (R2 – Fig. 6) and in the eyes of the main leaf as it can be seen in Figure 7.

With the increase of radius in the main leaf transition from R2 to R5 and the leaf thickness from 6 mm to 7 mm at the eye, it is obtained that the maximum stresses equivalent to von-Mises are175.6 MPa.

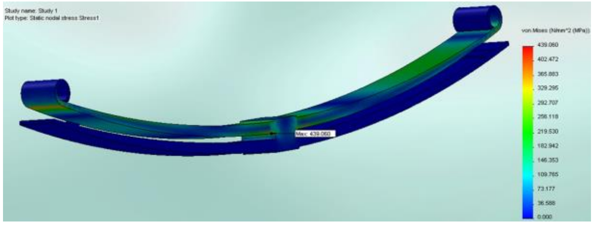


Fig. 7. Stresses in a two-leaf PLS

PLS for suspension of a rail wagon

The parabolic leaf spring (PLS) in compliance with UIC 517 (UIC 517: 2006) (Fig. 8), the main advantage of which is variable stiffness, consists of a main beam of 4 leaves (1 main leaf with eyes and 3 leaves of multiple package) and one additional leaf underneath. Each spring leaf has a section varying in height, which satisfies the condition of having one and the same strength and a line of bending on a vertical plane corresponding to a quadratic parabola. The leaves have equal length, they are connected in a package with a spring shackle. They lean on each other only in the central part and at both ends. A leaf of bigger thickness and a section of variable height is placed at the lower end of the package being mounted with a certain clearance in comparison to the basic package. The latter is calculated for the own mass of a wagon (an empty wagon), and the lower leaf is included in operation with wagon loading. As a result, the spring has a non-linear variable feature as a whole, which makes possible to achieve the necessary flexibility of both an empty and a loaded wagon.

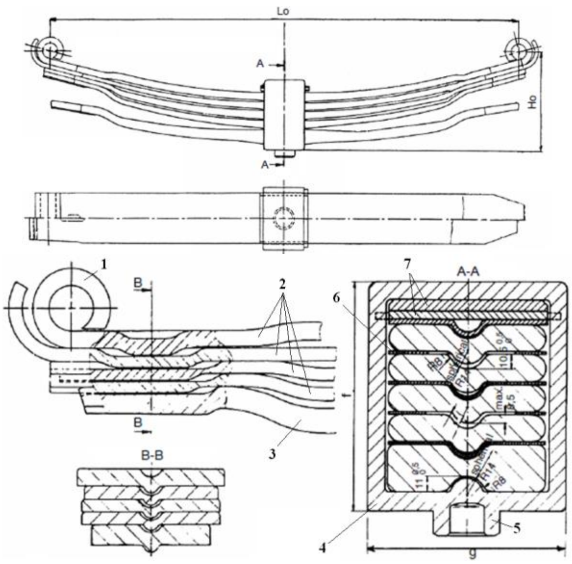


Fig. 8. Diagram of PLS for a railway wagon in compliance with UIC 517

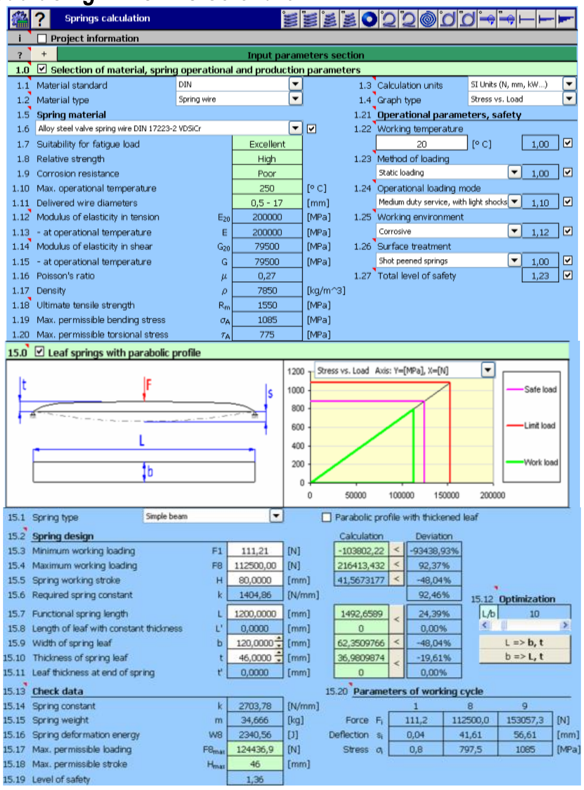
1 – eye; 2 – multiple leaves; 3 –additional leaf; 4 –spring shackle; 5 – a pin of shackle; 6 – metal plates; 7- wedges.

Dimensions: L_0 = 1200mm; H_0 = 227mm; f = 170mm; g = 100 mm. (bxh = 120x21 mm for multiple leaves and bxh = 120x36 mm for the additional leaf)

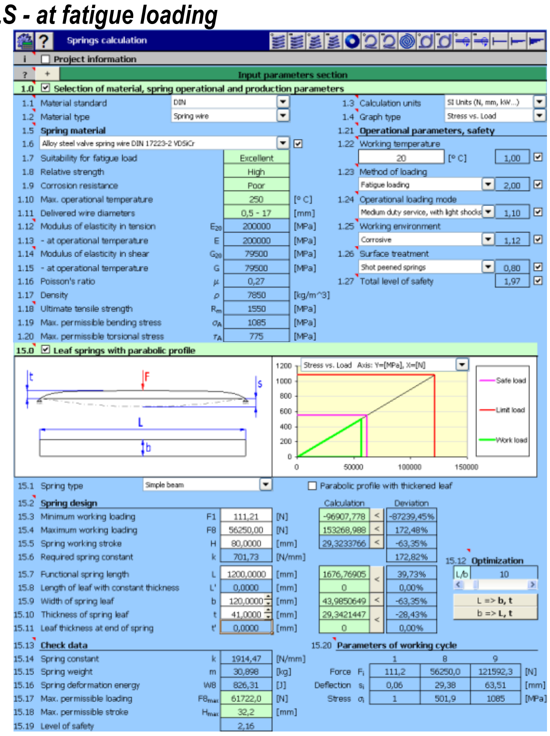
The spring leafs are made of steels – brands 55 C2 and 60 C2 (GOST 2052-53 and EN BDS 6742-73), 60si7 and 65si7 (DIN 17221) or others, equivalent to them in chemical composition and mechanical properties. The spring shackle is made of steel brand ВСт3 сп, and the spring wedge is made of steel brand АСт3 according to BDS 2592-71.

Determination of railway wagon PLS strength and deformation state using MITCALC software

Results of calculations of a railway wagon PLS – static load using MITCALC software



Results of calculations using MITCalc for a railway wagon PLS - at fatigue loading



Determination of strength and deformation state of railway wagon PLS using Solid Works software

Using Solid Works software, the PLS is modelled according to Figure 8, with loading in the spring eyes and fixing in the leaf spring centre in spring bushing. Model contacts are limited, except for the contacts of leaves in section B-B, which are defined as non-friction joints of leaves only in longitudinal direction. This type of connection describes the behaviour of a leaf spring in the ideal condition where friction of leaves is not desired. The leaf material of PLS is according to the manufacturer, SUP 11A (JIS).

The standard comparison according to the European standards has shown that UP 11A spring steel is equal to 65Si7 spring steel. The steel fatigue properties are determined according to SAE from the database of Glyph Works material properties. The values of Glyp Works materials (SAE5160 / SUP 11A / 65Si7) SFS-EN according to 10089 standard are as follows: Elastic Modulus, E 200 GPa; Yield Strength, R_{eL} 1196 MPa; Ultimate tensile strength, R_m 1495 MPa; Work Hardening Coefficient, K 1940 MPa; Fatigue Strength Coefficient, Sf 2063 MPa; Cyclic Strength Coefficient K' 2432 MPa; Work Hardening Exponent, n 0.05; Fatigue Strength Exponent, b -0.08; Fatigue Ductility Exponent, c -1.05; Fatigue Ductility Coefficient E_f 9.56; Cyclic Strain-hardening Exponent, n' 0.13; Cut-off, Nc 2.00E+08 Reversals.

Crosslinking is: Mesh Type: Solid Mesh; Mesher Used: Standard mesh; Automatic Transition: Off; Smooth Surface: On; Jacobian Check: 4 Points; Element Size: 7.0018 mm; Tolerance: 0.45726 mm; Quality: High; Number of elements: 303397; Number of nodes: 477934.

At a load of 112.5 kN in eyes (of 56.25 kN per eye) and fixing in the PLS centre, the maximum stresses are 634.7 MPa equivalent to von Mises stress. The maximum stresses are in the centre of the main leaf with eyes in the area of contact with the internal wedge (Fig. 9).

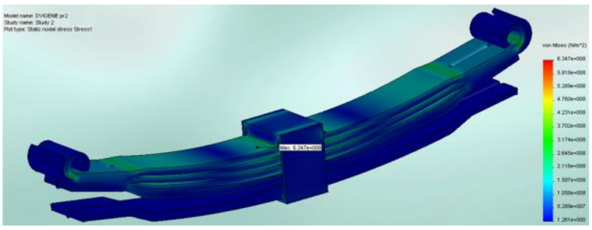


Fig. 9. Stress on a PLS in compliance with UIC 517

Strength analysis of parabolic leaf spring (PLS) structures for transport equipment

Strength analysis of PLS for automotive equipment

The results of modelling and determination of PLS strength and deformation state for automotive equipment using MITCalc and Solid Works software are given in Table 1.

From the results of PLS modelling for automotive equipment, it is established that when applying Solid Works software, stresses are significantly higher – 2.7 times. The maximum stresses are in the area of cross-section weakening in the main leaf centre and eyes. With the radius increase in the main leaf transition from R2 to R5 and the leaf thickness at the eye from 6 mm to 7 mm, the maximum stresses decrease twice and are closer to those obtained by MITCalc software.

Table 1. *Results of PLS modelling for automotive equipment*

MITCALC		
Material	**Stress, MPa**	
Modulus of elasticity, E = 200 GPa Ultimate tensile strength, R_m = 1550 MPa Max. permissible bending stress σ_a = 1085 MPa Max. permissible torsion stress τ_a = 775 MPa	**Static load 10000N**	**Cyclic load (of fatigue) 5000N**
	162,8	**81,4**
SolidWorks		
Material 55Cr3 for leaves	**Stress, MPa**	
Elastic Modulus, E = 207 GPa Yield Strength, R_{eL}=1250 MPa Ultimate tensile strength, R_m = 1600 MPa **Material Silicon for limiters** Elastic Modulus 1.124e+011 N/m²; Shear Modulus 4.9e+010 N/m²; Yield Strength 120e+06 N/m²	**Value**	**Area**
	439,06 **175,6***	The maximum stresses are in the area of cross-section weakening in the centre (R2 - Figure 6) and in the main leaf eyes.

* Maximum stresses equivalent to von-Mises stress with constructive adjustments.

Strength analysis of PLS for rail wagons

The results of modelling and determination of railway wagon PLS deformation state using MITCalc and SolidWorks software are given in Table 2.

Table 2. *Results of PLS modelling for a railway wagon*

MITCalc		
Materials of elasticity, E = 200 GPa Ultimate tensile strength, R_m = 1550 MPa Max. permissible bending stress σ_a = 1085 MPa Max. permissible torsion stress τ_a = 775 MPa	**Stress, MPa**	
	Static load 225kN	**Cyclic load (of fatigue) 56.25kN**
	797.5	**501.9**
SolidWorks		
Material 65Si7 Elastic Modulus, E = 200 GPa Yield Strength, R_{eL} = 1196 MPa Ultimate tensile strength, R_m = 1495 MPa	**Stress, MPa**	
	Value	**Area**
	634.7	Maximum stress in the main leaf centre in the area of contact with the internal wedge.

Based on the results of rail wagon PLS modelling, it is established that stresses are 25% greater with the application of MITCalc software in comparison to the values obtained by using SolidWorks. The maximum stresses most often occur in the main leaf centre in the area of contact with the internal wedge (Fig. 8).

The results of modelling vehicle and railway equipment for strength and deformation analysis have shown the necessity to apply both MITCalc and SolidWorks software packages. The determination of areas of maximum values gives a possibility for PLS constructive adjustments.

Conclusion

The occurrence of fractures in some spring suspension components of transport vehicle, such as leaf springs of wagons of Fbd type used for coal transportation from Kolubara mining basin to Nikola Tesla TPP in Obrenovac, Serbia, has imposed the necessity of strength and deformation analysis of new construction solutions. The statistical results of operation monitoring on the spring suspension components of railway wagons and trucks up to the state of their failures are considered. The obtained Pareto diagrams reflect the impact of damage types on the components of leaf springs in automotive and railway equipment. The calculations of selected structures of parabolic leaf springs made by the application of MITCalc and Solid Works software packages have confirmed the types of failures in the areas of maximum stresses.

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