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A NUMERICAL ANALYSIS OF A DOUBLE MULTI-LEAF SPRING MODEL

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Abstract

The use of a double spring in a vehicle suspension as a combination of elastic components of characteristics which are approximate to linear ones gives a nonlinear suspension nature, which should approximately meet the criterion of car motion smoothness connected with keeping the frequency of the free vibrations of the a motorcar body in the range of 1 – 2 Hz, in the whole range of load changes (cargo) [see references 8, 10].

The subject of considerations is a prototypical double spring that consists of a four-leaf main spring and a two-leaf auxiliary spring and is meant for the family of motor trucks (delivery trucks) of a total mass of about 3,5t. The presence of a clearance between the main spring and the auxiliary spring is the specificity of the aforementioned structural solution.

In the present study, there are presented different variants of FEM numerical models of a double spring as well as selected aspects of their applications at the stage of the research on the displacements and deformations of selected structural components. The structures of a two-dimensional beam model, a three-dimensional shell model and a solid model of a double spring are discussed. Moreover, the study discusses different approaches in the modelling of the effect of contact between particular leaves and their influence on analysis results. Selected model tests results were compared with experimental research results.

Keywords: *FEM, numerical models, double multi-leaf spring, suspension of a motor truck*

1. Introduction

In the work, there was investigated one of the typical structural solutions of a dependent rear suspension (see Figure 1) used in modern motor trucks of the total mass of up to 3,5 t., which are fitted with a double spring (see Figure 2).

Leading automotive companies (such as Mercedes – Benz, Volvo, Renault, Scania, Ford, MAN, Mitsubishi ,DAF, IVECO and others), depending on suspension type and the parameters, offer catalogued elastic components (springs, torsional bars, tilt stabilizers) and damping components according to the requirements of the vehicle being newly designed [see references 9,15]. The attempt to make a new suspension structure with the use of catalogued elastic and damping components must be preceded by a complex analysis connected with the dynamics of the vehicle being designed [see references 7, 8, 10]. The analysis is conducted with the use of mathematical models of different levels of complexity.

Tests presented in the work are the continuation of the strength analyses of double springs that were discussed in the works by the authors from the Military University of Technology [see references 1-4, 14]. Presented models and results were obtained thanks to applying more advanced modelling and analysis techniques accounting for contact issues which are possible to be realized by means of a MSC Software Corporation software package for engineering calculations [see references 11, 12].

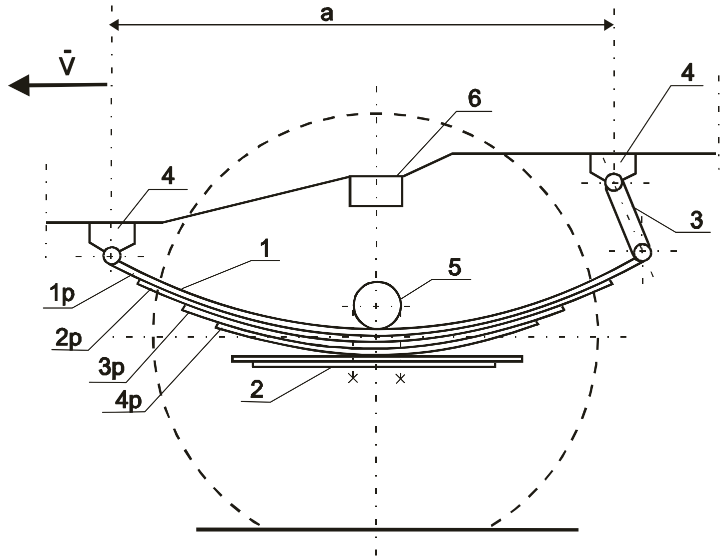

Fig. 1. Typical schematics of a dependent rear suspension of a motor truck fitted with a double spring (damping components and suspension stabilizing components were not accounted for); where: 1-main spring (1p,2p,3p,4p-leaf numbers); 2-auxiliary spring;3-shackle; 4-brackets; 5-driving axle; 6-spring stop

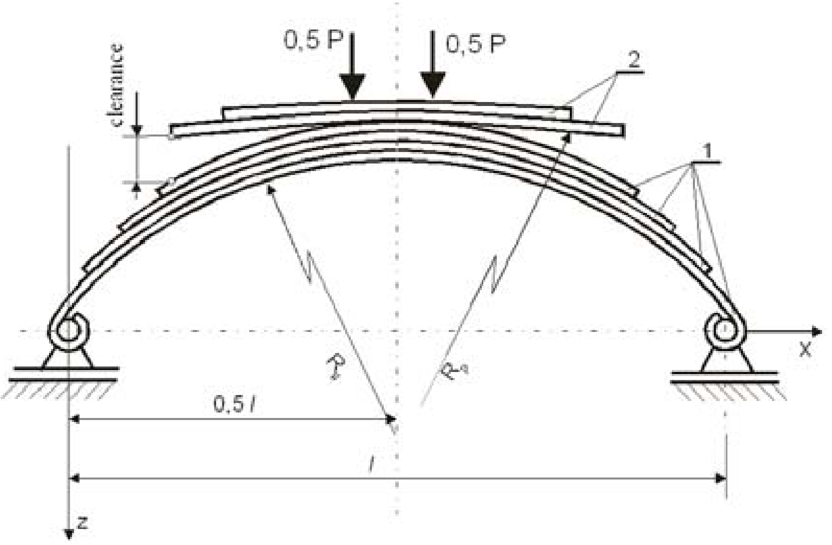

Fig. 2. A double spring schematic: 1-main spring leaves, 2-auxiliary spring leaves

2. FEM numerical models of a double spring

Tested numerical models that are discussed in the present chapter of the study were made as deformable discrete models meant for analysis by the finite element method (FEM). They reflect an identical prototypical version of a double spring. The models were built by means of a processor MSC.Patran [see reference 11].

2.1. A two-dimensional discrete model

In a two-dimensional discrete model of a double spring, particular main spring and auxiliary spring leaves were modelled by means of two-node beam elements of properly selected geometric characteristics. 114 BEAM-type elements with rectangular sections were used in order to represent spring leaves. The elements were connected by 125 nodes. The image of a beam model is presented in Figure 3.

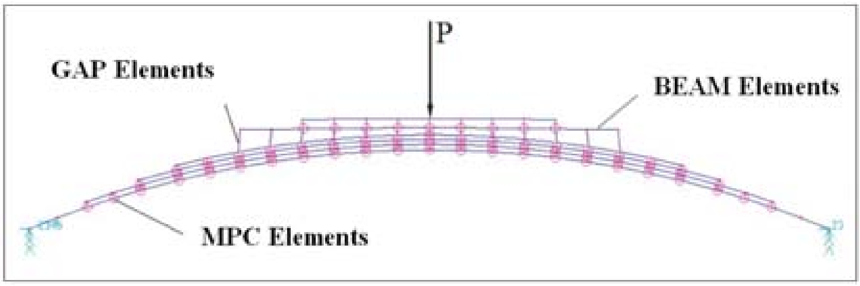

Fig. 3. A beam model of a double spring

There were defined different values of the flexural rigidity of elements in particular main spring leaves and they were as follows: EI_1 = 1129.39 Nm^2, EI_2 = 585.99 Nm^2, EI_3 = 382.52 Nm^2 and EI_4 = 398.119 Nm^2. For the elements which modelled two auxiliary spring leaves, an identical flexural rigidity, namely EI_5 = 28122.90 Nm^2, was accepted. In the two-dimensional model of the spring, no additional elements modelling a clamping screw were introduced. The effect of the element on the spring operation was guaranteed by accepting identical translational degrees of freedom for nodes that lay in the symmetry plane of the structure. It was realized by means of special MPC-type kinematical elements. Analogically, cooperation between adjacent leaves in both spring units wad defined, assuming, with certain simplification, that linear displacements of nodes are identical. 32 elements of this kind were defined between the proper nodes of beam elements which modelled adjacent spring leaves (see Figure 3).

Initial clearances between main spring leaves and auxiliary spring leaves were defined in a discrete manner by introducing two-node GAP-type elements between the two opposite nodes of extreme leaves in spring's units (see Figure 3). The values of clearances defined between the nodes of elements that modelled extreme leaves of the main spring and the auxiliary spring (see Figure 2) changed in the range of (34.12 – 0.0) mm. They were determined on the basis of the geometry of the prototypical spring in an unloaded state. In the extreme nodes of the first main spring leaf, there were introduced constraints that corresponded to the pivot bearing that was moved along the left and the right ends of the leaf model.

2.2. A three-dimensional shell model

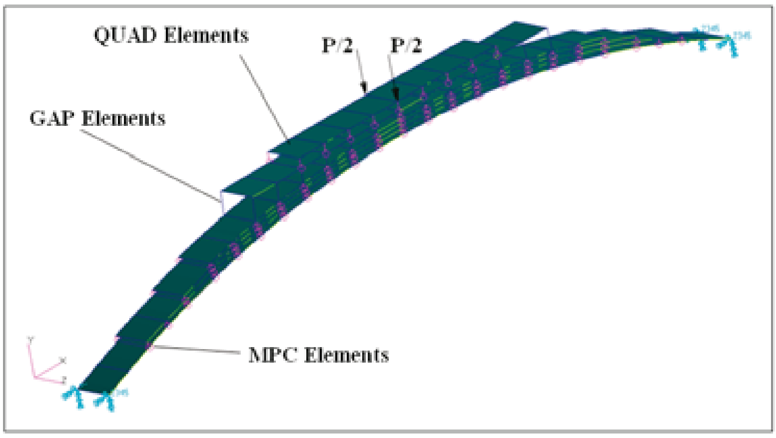

Fig. 4. A three-dimensional shell model of a spring

Three-dimensional discrete models of a spring were elaborated on the assumption that they would be comparable with the two-dimensional beam model described above as regards dimensions, physical characteristics of the used material, outer constraints, spring loading type and the value of load.

The three-dimensional model presented in Figure 4 was built as a shell model. QUAD4-type four-node shell elements, which are available in the MSC.Nastran software library [see reference 12], were used for the discretizaton of spring leaves.

Main spring and auxiliary spring leaves were represented by means of 1211 shell elements that were represented on a mesh of 251 nodes. Beam elements with properly selected substitute characteristics were used for representing clamping screw. They were spread on the nodes of extreme elements which modelled particular leaves in the symmetry plane of the spring. The components that modelled the clamping screw of the spring were accepted to be 10 times stiffer than the ones of the auxiliary spring. Clearances between main spring and auxiliary spring leaves (see Figure 4), which resulted from geometric and technological characteristics of the analyzed structure, were modelled by inserting two-node GAP-type elements between the nodes of adjacent spring leaves.

The conditions of mate between spring leaf terminals and adjacent leaves in both spring units were represented similarly as in the beam model, namely by special MPC-type kinematical elements. It was assumed that linear displacements (in the vertical direction) of the nodes of adjacent spring leaves connected by kinematical dependencies were identical.

2.3. Solid models

The analyzed double spring was also represented in the form of a solid model shown in Fig. 5.

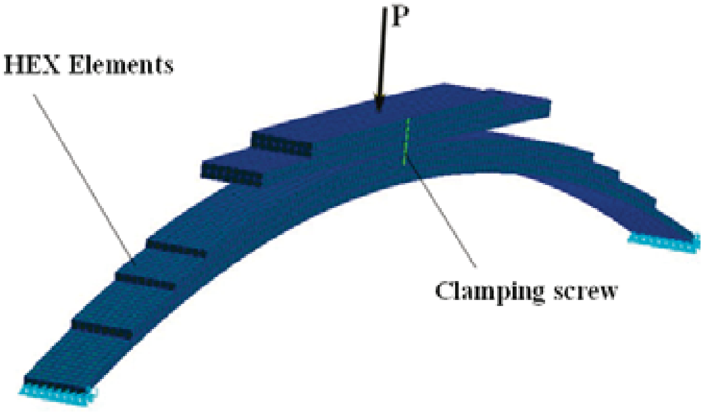

Fig. 5. A solid model of a spring – variant I

11310 eight-node HEX-type solid elements represented on a mesh of 91204 nodes were used for modelling main spring and auxiliary spring leaves. Clamping screw was represented by means of beam elements with properly selected substitute characteristics. They were spread similarly as in the case of the shell model, namely on the nodes of extreme elements that modelled particular leaves in the symmetry plane of the spring. Contact between particular spring leaves was modelled by determining the predicted contact surface of the walls of the elements of particular spring leaves and assigning proper physical parameters (such as friction) to them by means of the ‘master-slave’ function [see reference 12]. In the solid model, a continuous description of the phenomenon of contact was introduced as opposed to the discrete contact phenomenon representation used in the beam and the shell models.

In the solid model presented in Figure 5, a single clamping screw was represented. Beam elements with properly selected substitute characteristics were used for modelling the clamping screw. The beam elements were spread on the nodes of extreme elements that modelled particular leaves in the symmetry plane of the spring. The elements that modelled the clamping screw of the spring were accepted to be 10 times stiffer [see reference 14] than the auxiliary spring elements. In the discussed solid model, the conditions of mate between spring leaf terminals and adjacent leaves in the main and the auxiliary springs were represented by means of proper contact conditions without any additional MPC-type kinematical dependencies between the nodes of adjacent leaves. In order to guarantee the conditions of a continuous contact of the nodes of adjacent leaves that result from the initial spring tension, an additional variant of the solid model was built during the process of spring leaves assembly. The variant is presented in figure 6.

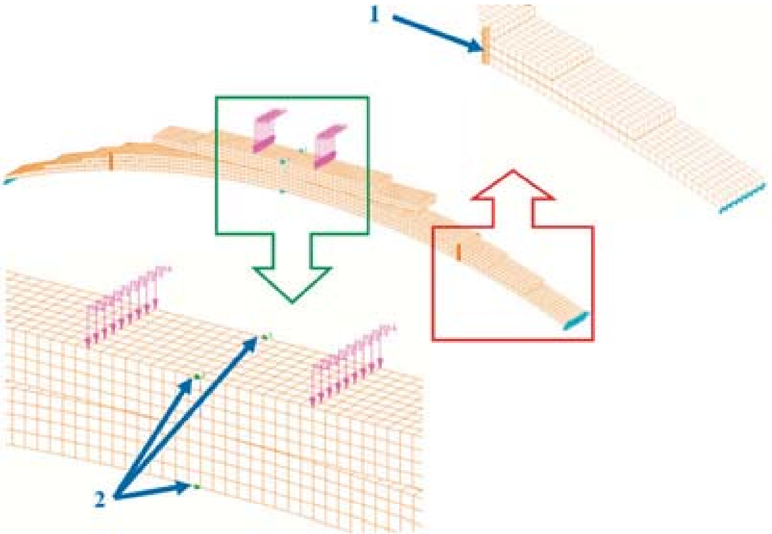

Fig. 6. A solid model of a spring- variant II; 1 – shackle, 2- clamping screw

The second variant of the solid model accounts for additional shackles of a main spring leaf in the section marked in Figure 6. In the model, additional shackles were modelled by beam elements (1), the extreme nodes of which were shared with the corresponding nodes of the shortest and the longest main leaves.

3. Numerical tests conducted on a double multi-leaf spring

Static tests on the spring of a bilinear spring rate are a nonlinear task even when the structure's material is linearly elastic and big displacements are not accounted for. Usually, the aforementioned problem boils down to the issue of searching for a feasible solution, which is determined on the basis of the solution of a system of a finite number of nonlinear algebraic equations. In the work, there was applied the approach of the finite element method. Solving the problem was boiled down to the repeated solving of a system of linear equations that were obtained on the basis of the principle of node balance [see references 5, 6, 13]. For an elastic structure of a spring loaded by a conservative force system, $P=\lambda\cdot p$, the FEM incremental balance equations in the updated Lagrange description have the following form (1):

$$\left[K_e^{(i)}+K_\sigma^{(i)}(\sigma)\right]\Delta q^{(i+1)}=\Delta P^{(i+1)}, \tag{1}$$

where: K_e is the stiffness matrix, $K_\sigma(\sigma)$ – the initial stress matrix, Δq – the displacement vector increment, $\Delta P=\Delta\lambda\cdot p$ - the load vector increment, p – the load vector, λ - the load multiplier.

The system of equations (1) is solved by a variable stiffness method. In a conventional concept, it is created at each increment step for the same discrete model. In the analyzed problem, the contact area change leads to the change of the static schematic of the analyzed spring. Accounting for variables in the loading process and the deformations of contact areas between particular spring leaves brings about a change in spring structure stiffness. It has a character of geometric nonlinearity. Additional equations which control the process of stiffness changes and which are solved at each step of the numerical analysis are also accounted for. Stiffness changes result from the presence of one-sided constraints and clearances between the main spring and the auxiliary spring leaves.

3.1. The range and conditions of the conducted numerical analyses

Numerical analysis of a double spring in beam and shell models was carried out in the range of linear statics by means of MSC.Nastran software [see references 12,18]. The analysis in solid models of the spring was conducted with the use of MSC.Dytran software [see reference 19].

Load in the two-dimensional beam model and the solid model was defined as a single force of the value of 14 kN applied to central nodes in the symmetry planes of the models (see Figures 3 and 5). In the three-dimensional shell model (see Figure 4), load was accepted in the form of two identical concentrated forces applied to the spring's transverse symmetry plane nodes of the values of 7 kN each. In variant I of the 3D spring model, load was modelled in the form of a concentrated force applied to the central node on the outer leaf of the auxiliary spring, as shown in Figure 5. In variant II of the solid model, load was applied as a force distributed between two node lines. Conformity with the conditions of load applied in stand tests was kept. The resultant value of the applied load was equal to 14 [kN]. Boundary conditions that correspond to fixing the spring on the test stand are presented in Figure 6. In the nodes of the model that correspond to the extreme edges of the longest spring leaf, the possibility of linear movement along Y and Z axes was prevented.

Therefore, the analyzed numerical models were loaded by a resultant force equal to 14 kN. The same maximum force was also applied to the spring in laboratory tests [see reference 3]. Numerical analysis carried out in the abovementioned load range makes it possible to compare the stiffness characteristics obtained by means of numerical and test stand analyses.

4. Laboratory tests conducted on a double multi-leaf spring

A test stand that allows recording experiment results by a discrete technique was used in laboratory tests [see reference 16]. Laboratory tests on springs are conducted in accordance with PN-90/S-47250(Polish standard). The measuring stand used in experimental tests is presented in Figure 7. The state of spring's strains under a maximum vertical load is illustrated in Figure 8. The obtained experimental results were used for verifying numerical calculations.

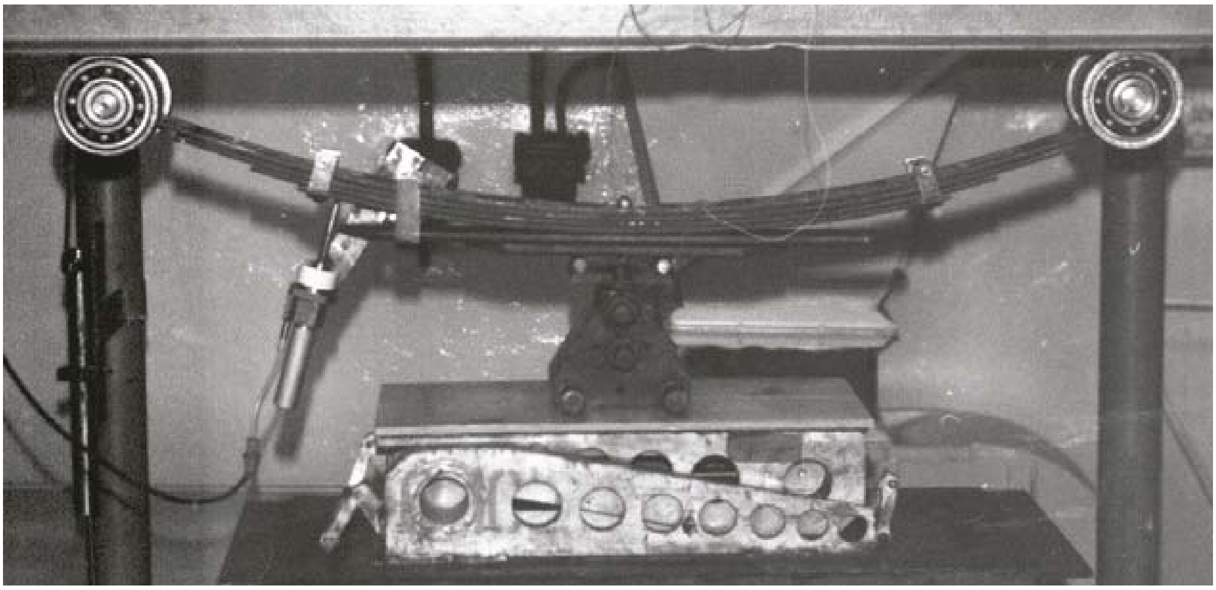

Fig. 7. An unloaded spring fixed on a test stand

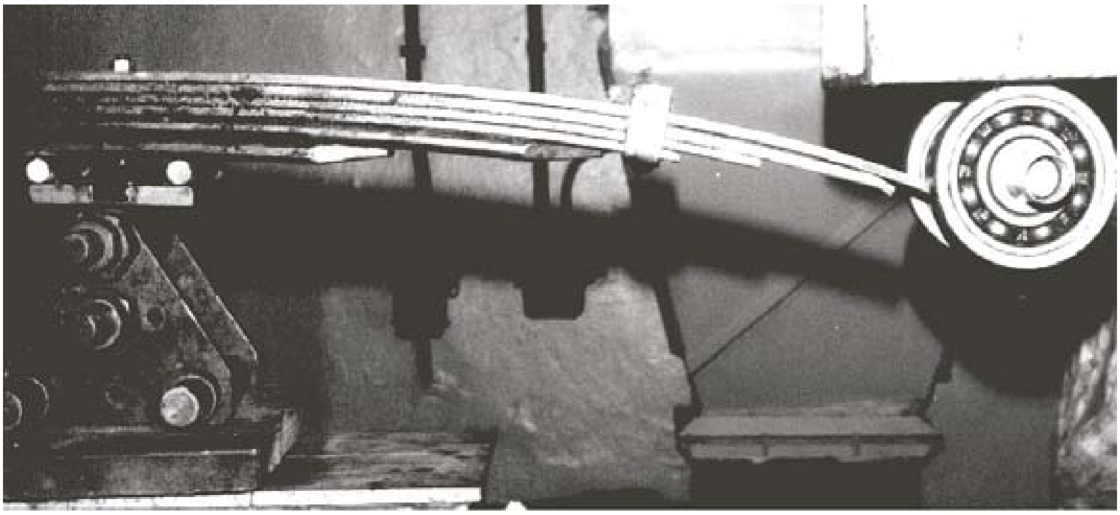

Fig. 8. A deformed spring on a test stand in the final phase of loading with a maximum force of approximately 14kN

5. Verifying the results of model tests and the experiment

5.1. An analysis of the deformations of the leaves of a double spring in a 3D model

3D models built in variants I and II were used in the numerical analysis of the multi-leaf spring of a bilinear nature.

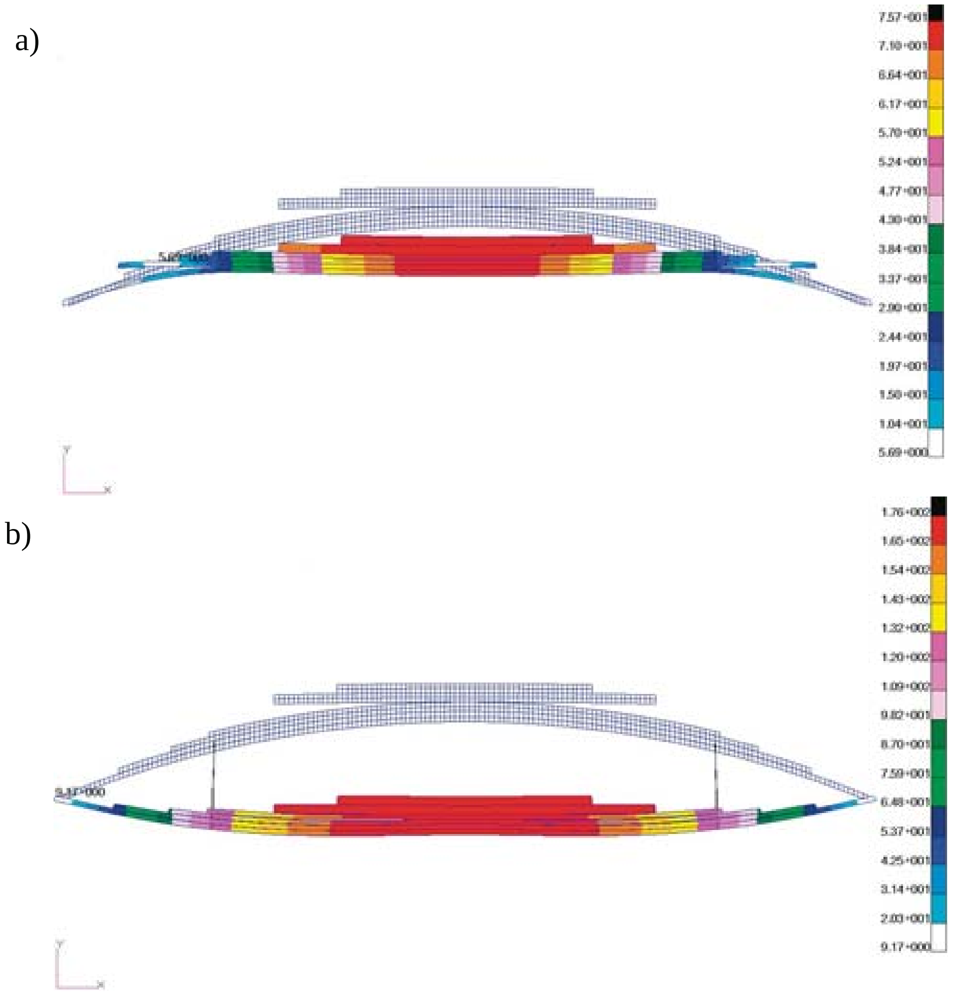

Fig. 9. Deformations of double spring leaves recorded during a numerically simulated load test in a solid model, variant I: a) initial load phase, f_{max}=75.7mm, b) final load phase, f_{max}=176mm

The deformation process of particular spring leaves of the aforementioned structure which took place with the increase of load was represented on the basis of the results of numerical simulations. Figures 9 and 10 illustrate double spring leaves' deformations recorded during a numerically simulated load test in the solid model, variants I and II respectively. The forms of spring deformations obtained for different variants of the discrete model differ mainly in the initial phase of the load process.

In variant I of the model, namely the one with one clamping screw, the deformation of the second leaf of the main spring draws attention (see Figure 9a). The leaf ends do not adhere to the first leaf of the main spring along a considerable length, therefore, they do not cooperate with the first leaf in the process of load transfer. The abovementioned phenomenon was not observed in the test stand analysis of the spring. Particular leaves of actual main and auxiliary springs were initially formed so that they had decreasing radii of curvatures. After the leaves had been assembled and bolted, they were pre-deformed and there were introduced stresses that produced a mutual pressure between the cooperating leaves.

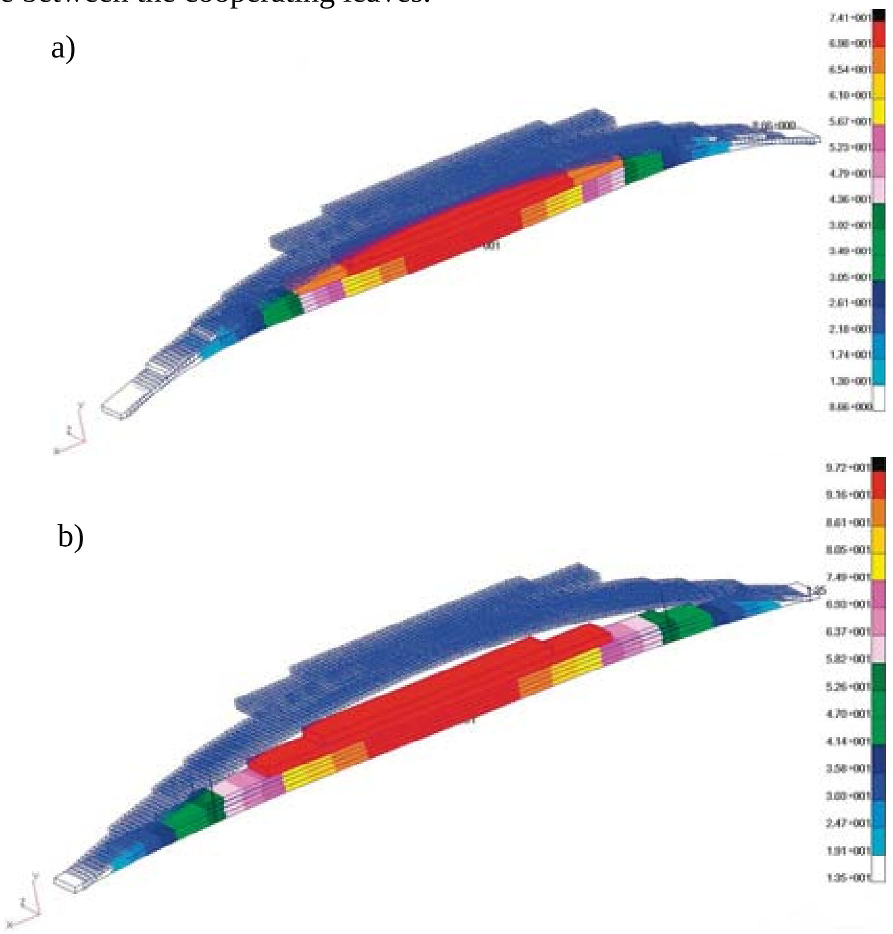

Fig. 10. Deformations of double spring leaves recorded during a numerically simulated load test in a solid model, variant II: a) initial load phase, f_{max}=74.1mm, b) final load phase, f_{max}=97.2mm

Initial stresses of leaves created as a result of the spring assembly process were not defined in the numerical models presented in the work. The lack of initial pressure between leaves in the solid model, in which particular leaves were given identical curvatures, brings about the effect of a non-physical deformation and a lack of cooperation of leaf ends in the simulation of the load test conducted with the use of model I. Figure 10 illustrates the deformations of double spring leaves recorded during the load test simulation of variant II of the solid model. In this case, proper cooperation between leaves is guaranteed by shackles that clamp the four leaves of the main spring (see Figures 6-8).

5.2. Comparing spring characteristics in the form of load force dependencies as a function of spring compression

Diagrams of load forces as a function of spring compression that were obtained with the use of beam, shell and solid numerical models as well as a curve obtained on the basis of laboratory tests conducted on a prototypical spring are presented in Figure 11. The results obtained for beam and shell models differ insignificantly, therefore, they are represented in the form of a single curve that is plotted as a broken line in Figure 11.

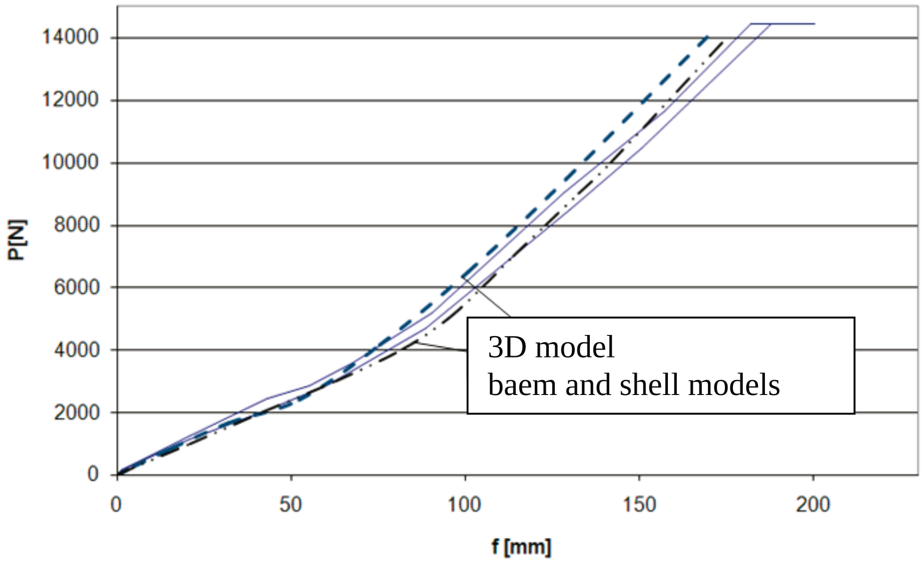

Fig. 11. A comparison of the diagrams of load forces as a function of spring compression obtained for beam, shell and solid models

In the diagrams, the curves recorded on a test stand are plotted by a solid line, whereas the dependencies obtained on the basis of numerical simulation results for different FEM models were plotted by a broken line. Maximum values of spring compression obtained in simulation tests by means of different numerical models differ by less than 5%.

Using even the simplest beam models of a spring that require little amount of work at the stage of preparations leads to obtaining satisfactory results.

Solid models provide a better consistency of numerically and experimentally determined curves at the points of curve bendings, that is, in the range that corresponds with the spring operation at the moment when the auxiliary spring is disengaged.

The solid model, which requires the most amount of work at the stage of preparing the numerical simulation and the longest calculation time, makes it possible to analyze the deformations and tensions of particular double spring leaves in detail. Moreover, using the MSC.Dytran program makes it possible to account for dynamic effects of the influence of load on the spring in numerical tests.

A detailed comparative analysis of the results of tests conducted on test stands and numerical simulations concerning the tension of particular leaves of a double spring, controlling the process of taking in the clearance between the leaves of main and auxiliary units or the effect of the crosshead speed on the recorded result will be the subject matter of future studies by the authors of the present work.

6. Conclusion

Tests presented in the work are the continuation of the strength analyses of double springs that were discussed in the works by the authors from the Military University of Technology.

Presented models and results were obtained thanks to applying more advanced modelling and analysis techniques accounting for contact issues which are possible to be realized by means of MSC.Software Corporation software package for engineering calculations.

Selected model tests results were compared with experimental research results. The differences between numerical and experimental results are about 5 %. An improving of the double multi-leaf spring numerical model is intended as well as taking into account the mate condition of spring with wheel vehicle suspension.

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