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NUMERICAL ANALYSIS AND EXPERIMENTAL INVESTIGATION OF DISK SPRING CONFIGURATIONS WITH REGARD TO LOAD CAPACITY OF SAFETY PROGRESSIVE GEARS

Abstract

The paper investigates the effect of various disk spring package configurations on brake load of safety progressive gears. The numerical analysis is performed using the Abaqus/CAE software and the designed 3D models. The numerical results are then verified in experimental tests. The tests also examine the effect of lubrication on brake load of spring packages. In addition, the paper investigates the work conditions of safety progressive gears at emergency braking. The experimental results show agreement with the numerical results.

1. STATE OF THE ART OF THE PROBLEM

The problem of selecting disk springs for technical objects is widely investigated in the field of metal forming. When it comes to the application of safety systems in traction lifts, however, the number of available studies devoted to this issue is very scarce. The authors of the study (Dharan & Bauman, 2007) examine composite disk springs. The results they report demonstrate that composites can satisfactorily replace steel in disk springs with mass savings of almost 80%. These authors also investigate the effects of different spring

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geometries on load deflection responses. In the studies (Dębski, Kubiak & Teter, 2012; Ozaki, Tsuda & Tominaga 2012), the authors apply the finite element method to predict load deflection curves based on the results of obtained using different friction factors. The authors of (Atxaga, Pelayo & Irisarri, 2006) discuss the effect of temperature and excessive environmental salinity on the life and reliability of stainless steel disk springs. In the study (Kayaoglu, Salman & Candas, 2011), the authors investigate stress and displacement of a lift safety gear brake block using the Abaqus/CAE software. They compare the numerical and experimental results. According to these authors, the numerical results agree with the results of the experimental tests. In the study (Taplak, Erkaya, Yildirim & Uzmay, 2014), the authors deal with the problem of using neural network predictors for the analysis of lift vibrations caused by variable load weight. The neural networks were applied to estimate vibration symptoms and, therefore, to identify failure of either one element of the lift or the entire lifting equipment. The authors of (Onur & Imrak, 2012) discuss the application of the reduction method to estimation of lift dynamics. In their analysis, the lift car model is reduced to a flat system with one vertical degree of freedom. This reduction-based methodology is then applied to describe a specific goods lift using analytical and finite element methods. Moreover, the above authors examine the effect of parameters of lift work on acceleration characteristics of the entire lift system. In the studies (Jong, 2004; Feng, Bao, Zhou & Wang, 2012), the authors discuss the application of the finite element method to estimation of rigidity and strength of a lift car frame in various types of lifts, focusing on the problem of safety gears, too. The FEM was applied to optimize the carrying frame design and thus to reduce both the sections of frame beams and frame weight as well as determine safety factors. Based on the results, they also undertake to determine failure-prone areas of the lift frame system. The problems of lift brake system dynamics, materials and safety gears are also investigated in the studies (Filas & Mudron, 2012; Lonkwic, Różyło & Dębski, 2015; Lonkwic & Różyło, 2016; Lonkwic & Szydło, 2014; Lonkwic & Gardyński, 2014; Lonkwic, Szydło & Molski, 2016). The authors of these publications analyze, among others, the lift brake system and compare the design and operation of safety gears produced by European manufacturers with a new developed solution. In the publication (Zhu & Ren, 2013), the authors raise the problem of the effect of weight of car lifting feeders and hoisting ropes on the operation of so-called tall lifts that are used in building above 40 stories tall. Due to the considerable lifting height, this type of lifts requires the application of an adjusting belt to compensate for the weight of hoisting ropes and feeders, so that other lift components are not excessively loaded. The authors describe the behavior of the adjusting belt and its effect on the linear model of lift operation. They examine the effect of horizontal displacements of the adjusting belt on free vibration frequency of the system. The above-mentioned studies provide information with regard to the methodology of disk spring package selection and the use of different materials for disk springs. Nonetheless, there is lack of studies reporting numerical results of the application of spring packages in safety gears. Given the above, it seems justified that this problem be investigated by both numerical modeling and experimental tests.

2. RESEARCH METHOD

The objective of the present study is to investigate the effect of different disk spring package configurations and lubrication on the brake load of a safety gear. The investigation of spring disk package deflection was performed following the configurations given in Table 1.

Tab. 1. Characteristics of tested spring packages [source: own study]

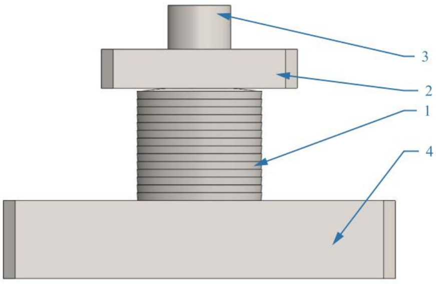
Pack	Package	Dry	Lubricated
I	14V_S	X	
II	7X7_S	X	
III	4V5X5_S	X	
IV	14V_Sm		X
V	7X7_Sm		X
VI	4V5X5_Sm		X

The denotation 14V stands for a configuration of 14 disk springs that are arranged in a parallel manner (Fig. 1a). The spring deflection load of this package is 14 times higher than the deflection load of a single spring. The denotation 7X7 (Fig. 1b) means that there are two packages, each containing seven springs, arranged in opposite directions. This configuration has the deflection load that is seven time higher than that of a single spring, while the deflection is two times higher than the deflection of one spring. The denotation 4V5X5 (Fig. 1c) stands for a mixed configuration of springs with the packages arranged in opposite directions, where deflection is three times higher than the deflection of a single spring and the deflection load is the multiplicity of load of one spring in the package. Given the design of the safety gear CHP 2000, the tested disk springs had the following dimensions:

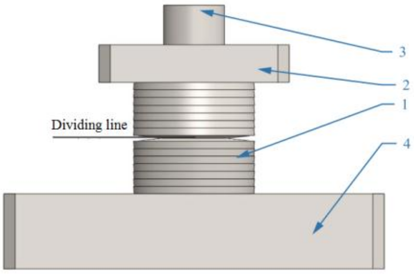
- outside diameter: 31.5 mm,
- inside diameter: 16.3 mm,
- thickness: 2 mm,
- height of unloaded spring: 2.75 mm,
- spring travel: 0.75 mm.

Figures 1a–1c illustrate the package models used in the numerical simulations.

1a)



1b)



1c)

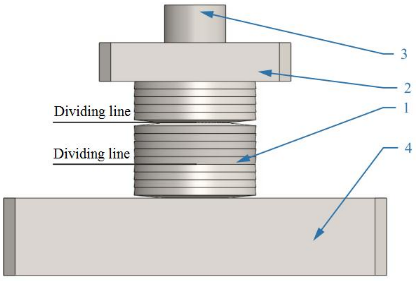


Fig. 1. Models of disk spring packages designed in Solid Works: 1 – disk spring package, 2 – pusher, 3 – guiding bolt, 4 – base, a) configuration 14V, b) configuration 7V7, c) own study

The numerical results were verified in experimental tests conducted using the testing machine HT-2402. The measurement of package deflection and load was done in two ways: with no lubricant applied (dry) and with lubrication to decrease the friction factor between individual springs in the package, following the scheme given in Table 1. The lubricating agent applied in the experiments was Megol SL-68.

The package deflection paths were obtained by averaging the results of 15 consecutive measurements. The measurements were averaged using dependence (1).

$$\bar{z} = \frac{\sum_{i=1}^{i=k} z_i}{k} \qquad (1)$$

where: z_i – the path of package deflection in the n-th measurement cycle,
k – the number of measurement cycles,
i – the number of consecutive measurement.

Fig. 2. 4V5X5 disk spring package configuration to be tested using HT-2402 machine (own study)

Fig. 2 shows one example of a disk spring package to be measured using the HT-2402 machine along with all necessary measurement instruments.

3. DISCRETE MODEL

The discrete model of a disk spring package was modeled with Abaqus. The discrete modeling was the fundamental stage of the numerical analysis. The FEM analysis illustrated operation of the lift under load applied to three disk spring packages with different configurations. The contact parameters were based on the interaction between lift components in tangential and normal directions. The load was defined for each spring package configuration separately. All packages were subjected to axial load. The aim of the simulation was to do the following: first, to generate a disk spring deflection package and, then, to determine the maximum axial load applied to the package. The spring package deflection was simulated in the range from 0% to 75% of the unloaded package height, which is the effective operating range of springs.

The material properties of the applied components are compared in Table 2. The objective of the present study is to investigate the effect of different disk.

Tab. 2. Characteristics of tested spring packages (Banaszek, 1996)

	Material	**Young's modulus E [MPa]**	**Poisson's ratio ν**	**Yield strength Re [MPa]**	**Tensile strength Rm [MPa]**
Disk springs	Steel 51CrV4	210000	0.3	1080	1280
Other components	Steel C45	210000	0.3	360	610

The numerical analysis was statics-based, therefore the lift's weight was not taken into account. The configurations contained several contact interactions between components that were active during the simulation. The assigning of boundary conditions to the lift depended on suitable fastening of the system and load determination, as shown in Fig. 3a. The component that produces spring package compression was prevented from displacement in all axes, except for the Y-axis. The bottom plane of the component with the spring package was made totally fixed in compliance with the real fastening. The load was applied as a point-concentrated force. To this end, a reference point was established in the axis of the spring package compressing component. Next, the concentrated force was assigned to the newly established point; the force was assumed to act opposite to the Y-axis (Fig. 3a). The reference point was tied by a coupling in the interaction module with the upper plane of the compression-generating component. The coupling of the point with the surface-acting load enabled us to perform further stages of the numerical analysis. The key stage of the FEM analysis included assigning the mesh to a system and dividing it into finite elements. To obtain the highest quality meshes, the elements were partitioned into smaller parts. In this way, we obtained a linear geometry mesh; the mesh was hexagonal (structured) for the springs, while for the spring fastenings it was arranged hexagonally (sweep) relative to the centre line. The size of mesh elements was set to 2, while the size of spring fastenings was set to 4. The assigned mesh element was C3D8R, i.e. a brick element with three degrees of freedom and eight nodes, with reduced integration. Reduced integration is the technique that can lessen the blockage effect, i.e. the removal of incorrect object shape deformations. As a result, the components of high-order polynomials are eliminated, which improves the numerical analysis (Zienkiewicz & Taylor, 2000). The total number of mesh elements in the entire system, in each analyzed case, is 5862. For detailed information about the mesh see Fig. 3b.

a) **b)**

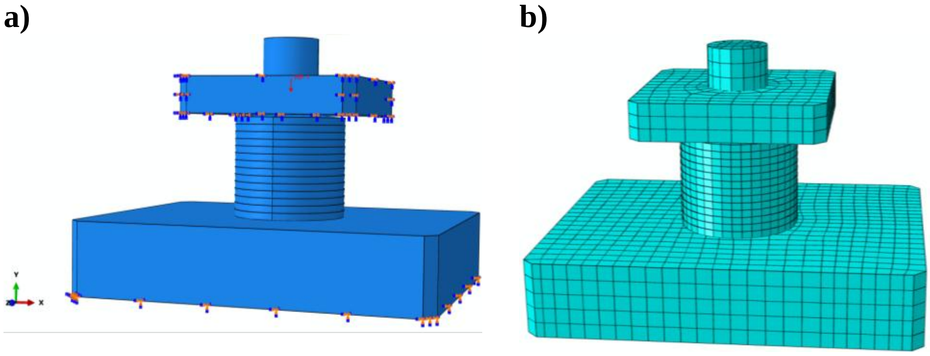


Fig. 3. a) Boundary conditions of the system , b) FEM mesh – total numbers of nodes: 10292; total numbers of elements: 5862, 5862 linear hexahedral elements of type C3D8R (own study)

The FEM analysis shows the results in integration points that were geometrically distant from the node points. The node results are the interpolated values measured in the integration points.

4. NUMERICAL AND EXPERIMENTAL RESULTS

The numerical results are illustrated as distribution patterns of stresses in crucial points. The FEM results are also compared with the experimental results of load-elongation relationships produced for three configurations. The simulation results of stresses are shown in Fig. 4.

5a)

5b)

5c)

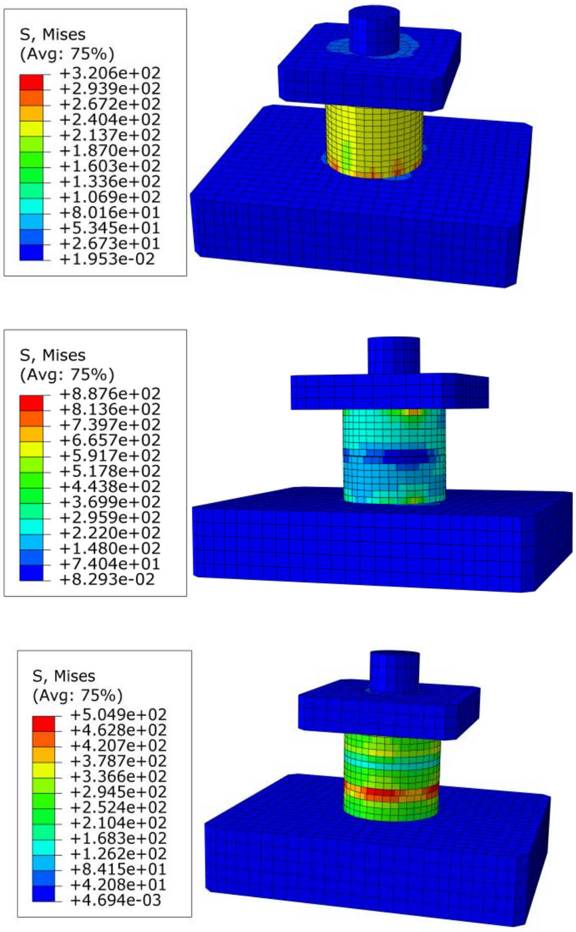
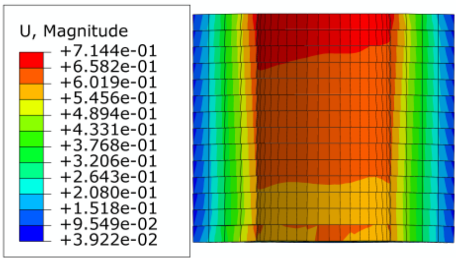


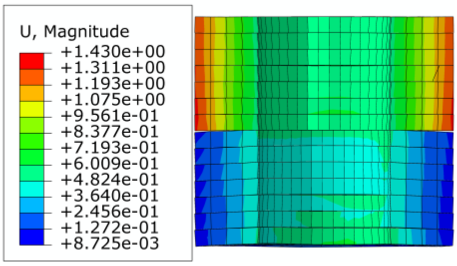
Fig. 4. Numerical results of stresses: a) package 14V under load of 21kN, b) package 7V7 under load of 38kN, c) package 4V5X5 under load of 38kN (own study)

The above results demonstrate that the package 14V exhibits the lowest stresses that are of about 321MPa. The stresses observed for the package 4V5X5 amount to about. 500MPa are considerably lower than is the case with the package 7V7, where the stresses equal 888MPa. The analysis of the three cases does not reveal that the yield strength was exceeded, therefore the system is free from plasticization and plastic strains. The numerical results of displacements are shown as axial sections of spring packages in Fig. 5.

6a)



6b)



6c)

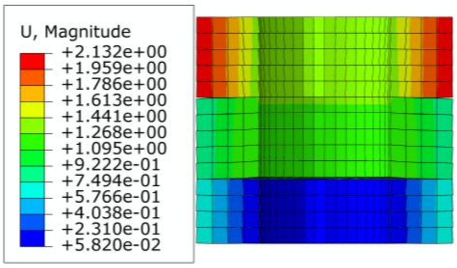


Fig. 5. Numerical results of spring displacement (deflection) [mm]: a) package 14V, b) package 7V7, c) package 4V5X5 (source: own study)

The experimental results are given in Fig. 6. At the beginning of the experiment, each disk spring configuration was pre-loaded in order to remove redundant clearance and determine the 0 measuring point. The dry-loaded packages of springs were degreased with degreasing agents.

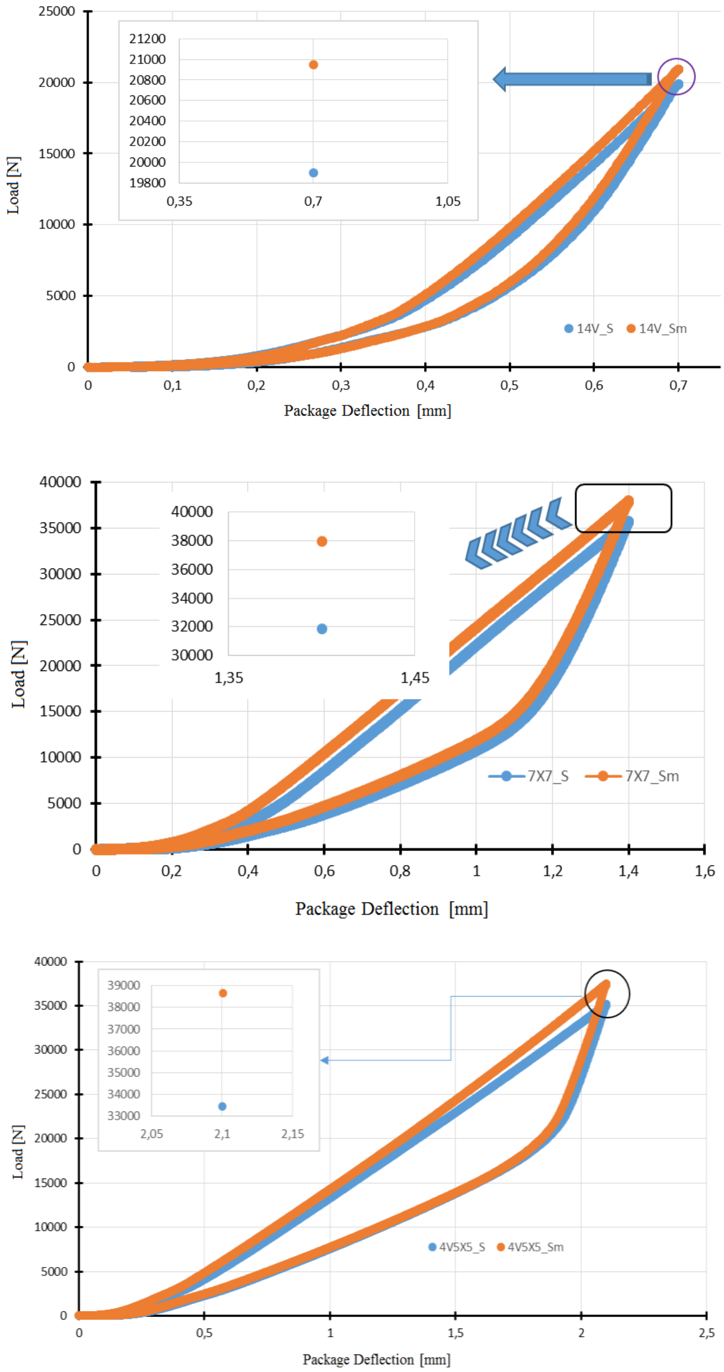


Fig. 6. Experimental results of spring package deflection (own study)

The numerical and experimental results show agreement with regard to displacements. As for the first spring package configuration, the displacement is equal to 0.7 mm, while the results measured for other configurations are a multiple of the displacement recorded for the first case. In effect, the elongation observed for the second case was approximately 1.4 mm, while for the third case it amounted to 2.1 mm. The application of different configurations of disk packages affects both stress and displacement of the system. Fig. 7 gives the comparison between the experimental and numerical results of deflection of disk spring packages.

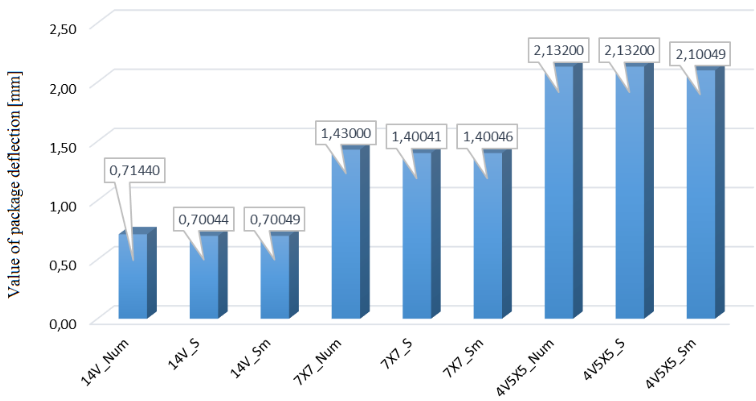


Fig. 7. Comparison of the numerical and experimental results (own study)

Analyzing the data given in Fig. 7, it can be observed that there is no significant difference between the numerical and experimental results. Despite the lack of lubrication, the generated package load is not disturbed in any way. A similar dependence can be observed for the numerical and experimental results of a dry-working (non-lubricated) spring package.

5. CONCLUSIONS

Based on the above results, the following conclusion have been drawn:

- The FEM and experimental results of the effect of load on disk spring package deflection show a good agreement. In addition, the numerical results demonstrate that stresses in crucial points of the three applied spring package configurations do not have negative effect on system operation, which means that the tested spring packages can be used in safety gears.
- The numerical and experimental results of package deflections are almost the same.

- In terms of safety gear operation, the spring package 4V5X5 seems optimum. Although the package configuration is asymmetric, the experimental results reveal that it is characterized by a high package deflection (2.1 mm) and the highest load (almost 40kN). The results demonstrate that the safety gear has the most unified structure in this particular configuration, which means that it can be used at a wide range of load.
- The symmetric package 14V has the most disadvantages out of the tested spring package configurations. Theoretically, this package should exhibit the highest load at the lowest package deflection, yet the experimental results do not confirm this relationship. This can be attributed to a high number of interacting surfaces, which had a significant impact on the experimental results.
- The numerical and experimental results confirm the suitability of using asymmetric spring packages (4V5X5) in safety gears owing to the fact that they exhibit the highest brake load and package deflection. The high package deflection in spring disks means that the energy of the lift car system will be gently reduced until the lift car's stop.
- The lubrication did not have significant effect on the experimental results. Nonetheless, lubricating agents should be applied when safety gears are used in order to prolong service life of spring packages.
- Due to lack of publications on such issues as safety gears and passenger lift brake systems in both national and international journals, it is justified that the research on this problem be continued.

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