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Investigation of Vertical Stiffness of the Front Axle Air Springs for Passenger Bus by Experimental and Finite Element Analysis

Hasan KASIM *[1], Erol ÖZKAN[2]

Abstract

Air Springs have been used for years, especially in commercial vehicles and buses, to maintain the vehicle's height regardless of the load and increase vehicle comfort. It is complex to experimentally determine the changes (reaction force, extension, strain) caused by loading alone to fully interpret the damping ability of air springs under operating conditions. The air springs are exposed to tension and force in different directions as they are made of a rubber composite structure. Therefore, discussing the damping properties of air springs with only the experimental method is difficult. The study aims to obtain information about the damping behavior of the bellows produced from composite materials, such as bellows under static loads, using both experimental and finite element analysis models. The finite element model of the air springs was obtained by modeling the three parts that provide its integrity. The material definitions required for the composite structure were determined by experimental methods and entered into the FEA program. No material is defined for rigid body members. The results of unidirectional and multidirectional tensile tests performed in a laboratory environment were used for material properties. The characteristics of the air were also entered into the analysis software with the information taken from the literature. The analyzes were carried out in three steps inflating the bellows to the specified pressure values, vertical movement, and compression to the specified displacement value. In this study, it was seen that the cord fabrics in rubber composite structures were affected more by excessive tension than rubber material, and the deviation of the static stiffness value was approximately 5% between the experimental study and the analysis studies. Thanks to FEA studies, it has been determined that more results can be obtained regarding values such as regional stress, force, and displacement in the bellows.

Keywords: Finite element analysis, cord-rubber composites, vertical stiffness, hyper-elastic materials, ride comfort

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1. INTRODUCTION

Air springs' ability to compress air in a specific volume has enabled them to be used instead of leaf springs in vehicle suspensions. Its outstanding effectiveness in vibration damping increases the use of air suspensions in cars, buses, and heavy commercial vehicles today [1, 2]. The low vibration transmission coefficient of the bellows and their ability to adapt to the load capacity has led to their use as an important vibration isolator in vehicles. It also reduces the impact of vibration on passengers and parts. An air spring's dynamic behavior depending on amplitude and frequency depends on the system's geometric structure [3, 4]. The variation of the air springs internal pressure in the suspension system is the same as the compression of a gas held in a closed container; lateral expansion occurs at the moment of compression. Air springs, which are part of air suspension systems, are the most vital element in the chassis system of operation [5]. The air spring function depends on the load it will carry, its diameter, and the supported air gap area, and the air pressure inside the bellows [6, 7]. The air spring's high flexibility due to the pressure minimizes the harmful effects of the load carried on the vehicle depending on the road conditions [8, 9]. Air suspension systems should have a high damping coefficient for more effective driving, soft and fast damping for comfortable vehicle use. Air spring can give different reactions instantly according to road and driving conditions [10]. It provides a compromise between comfort and safety in vehicles. Depending on the various internal pressure values, the spring coefficient change offers an advantage for air springs. Parts that provide structural integrity in air springs are piston, plate, and cord-rubber composite structures. The internal pressure change in the air spring first affects the rubber layer [11, 12]. Cord-rubber composite structure is a hyperelastic material consisting of two layers of rubber and two cord fabric layers [13]. Rubber material among composite layers is a more flexible and soft material than cord fabric. The part of the air spring subjected to tension is the rubber layer of the composite structure, and the mainframe that carries the load is the cord fabric layers [14]. The cord fibers in the two-layer cord fabric layer are found in the structure of rubber bellows at opposite angles. The air spring is subject to vertical displacement at different frequencies during operation. The stress values and types (compression and tension) occurring in the air spring due to displacement are different. Cord fabric layers prevent deformations caused by stress changes on the bellows. The fatigue life of air springs is affected by many interacting factors, but it is difficult to determine the relationship between these factors using analytical methods [15].

The operating performance of air springs exposed to different loads during driving depends on thermo-mechanical fatigue [16]. It is possible to observe shape change, internal pressure value, and diameter increase of air spring models with experimental studies. However, it is almost impossible to determine regional matters such as tension and reaction force occurring in the air spring in empirical investigations. Observing the regional stress and force values in air springs can be achieved with the Finite Element Analysis (FEA) study [17]. The deviation rate in the results obtained from experimental studies and FEA studies enables us to have clearer information about the working behavior of air springs. Tests determined the rubber and cord fiber's mechanical properties in prototype production for the minimum deviation value. The mechanical data obtained by experimental methods were defined as the material properties of the composite structure of the model we created in the FEA study. The air properties, which provide the change of the air bellows of internal pressure value as a compressible material, are fully defined in the FEA study [18]. Thus, the air spring's vertical reaction force values, static and dynamic stiffness values, the lateral stress, vertical stress, lateral displacement, and vertical displacement values occurring in the rubber composite structure were also obtained [19]. The effect of the piston shape on the stress values on the air spring was interpreted.

The similarity and low deviation rate between the results obtained from the finite element analysis and experimental methods add different originality to the study. The convergence in the amount of deviation between the experimental and FEA studies results will reduce the need for prototype production in the bellows designs, design changes, and product comparisons. The mechanical behavior of the air springs can be easily observed with Finite element analysis [20]. The mathematical model of the air spring created using the correct parameters in FEA will speed up the work both in the development phase and in different areas without increasing production costs.

2. MATERIALS AND METHOD

2.1. An Analytical Examination of Air springs

The prototype and FEA model of the front axle air springs of a bus produced for passenger transport are shown in Figure 1.

Figure 1 Display of prototype product (A) and FEA model (B)

The reaction force formed in the air springs depends on the compression and the shape change. The air spring's operation depends on the effective area, volume, pressure, bellows form, hardness, and rubber and cord material thickness. In vehicles with an air suspension system, the vehicle height can be kept constant by changing the air pressure in the bellows regardless of the load [21, 22].

The level control valves and electronic control unit automatically adjust the relationship between vehicle transport height and pressure. Elastic composite is exposed to compression and tensile stresses at various points due to the force that occurs due to road conditions. The volume change due to compression stresses during the damping of the bellows generally tends to decrease [23]. An air spring movement used in the suspension system changes the internal volume depending on the road conditions. When the volume decreases, the air particles in the bellows compress, and their kinetic energy increases. Accordingly, the internal pressure and temperature of the bellows also increase. Since the gas pressure inside the air spring will change according to the movement, the spring rate also varies as an isothermal, adiabatic, and polytropic process. The air spring's thermodynamic behavior is closer to the state where the temperature does not change and remains constant at low frequency operating speeds and to the position where the temperature changes due to changes in the system's internal energy at high frequency operating speeds. In other words, the minimum spring rate occurs under isothermal compression conditions, and the maximum spring rate occurs under adiabatic compression conditions. If the air spring moves slowly enough to dissipate all the heat generated during compression or expansion, this is an isothermal (constant temperature) process. If the air spring moves fast enough to maintain all the system's heat, this is an adiabatic process. Under real operating conditions, the air spring acts according to neither the isothermal nor the adiabatic process but rather the polytropic state. The polytropic process defines various expansion and compression processes, including heat transfer. The polytropic constant (n) varies between isothermal and adiabatic values 1 < n <γ. The pressure of the gas is directly proportional to the absolute temperature. As the temperature increases, the speed of the gas molecules increases, so the gases in the inner volume of the bellows contact each other more, and the internal pressure increases. This is true for air springs. If the system's compression speed is slow, there is sufficient time for the heat to propagate inside the bellows, creating conditions close to the isothermal (constant temperature) state. The new pressure generated in the air spring under isothermal conditions is calculated according to equation 1.

$$\mathrm{P_1 \,.\, V_1} = \mathrm{P_2 \,.\, V_2} \tag{1}$$

The variables P1 (bar) and P2 (bar) given in equation 1 are the initial and final absolute pressures of the air springs, V_1 (m^3) and V_2 (m^3), the initial and the final (after compression or expansion) volume. In evaluations according to equation 1, a nonlinear spring rate and an almost constant system frequency occur at system operating pressures. While the vehicle is in driving conditions, the isothermal condition is impossible as the bellows are exposed to variable stresses at high frequencies. Because there is some heat transfer from bellows to the environment due to the increase in pressure during compression, but air springs cannot recover the heat lost during volume increase. It acts according to the adiabatic process due to rapid compression and expansion process in air springs. Equation 2 is used to calculate the pressure change in air springs for the adiabatic state.

$$\mathrm{P_1 . V_1^{\gamma}} = \mathrm{P_2 . V_2^{\gamma}} \tag{2}$$

The constant γ in equation 2 varies according to the gas type and is a function of the specific temperature for gases. For air;

$$\gamma = \mathrm{C_P/C_V} = 1.4 \tag{3}$$

C_P is the specific heat value of air at constant pressure; C_V is the specific heat value of air at constant volume. In summary, the rate of compression or expansion of air has a significant effect on air properties. The high spring rate, high pressure, and fast spring movements occurring in the bellows depending on the road conditions are close to the adiabatic state. Slow and low amplitude spring movements are close to the isothermal state. Since the air suspension's operating conditions are not exactly an adiabatic process, the gamma value can be changed. Usually, the gamma values are used between 1.3 and 1.4.

Equation 4 is used to determine the bellows' internal pressure at any position during the operation of the air spring; P_a is the atmospheric pressure, and P_s gauge pressure. The force (or load) value at any point of the air spring on the working stroke is equal to the effective area multiplied by the gauge pressure. Equation 5 shows the relationship between the pressure force and the effective area.

$$\mathrm{P} = \mathrm{P_s} + \mathrm{P_a} \tag{4}$$

$$\mathrm{F_y} = \mathrm{P_s . A_e} \tag{5}$$

The relationship between equations 4 and 5 determines the force acting on the system in the vertical direction. The system's vertical spring coefficient expressed by equation 6 is derived by using equations 4 and 5 mentioned above.

$$\mathrm{K_Y} = \frac{\mathrm{dF_Y}}{\mathrm{dY}} = \mathrm{P_s}\frac{\mathrm{dA_e}}{\mathrm{dY}} + \frac{\mathrm{dP_s}}{\mathrm{dY}}\mathrm{A_e} = \mathrm{P_s}\frac{\mathrm{dA_e}}{\mathrm{dY}} + \frac{\mathrm{dP}}{\mathrm{dY}}\mathrm{A_e} \tag{6}$$

An expression giving the pressure change in the air spring due to the vertical direction displacement is obtained by deriving equation 2.

$$\frac{d}{dY}(P.V^{\gamma}) = \left(P.\gamma.V^{(\gamma-1)}\right)\frac{dV}{dY} + \frac{dP}{dY}V^{\gamma} = 0 \quad (7)$$

The effective area is shown in equation 8. The sign in front of the effective area varies according to the compression and expansion directions.

$$\frac{dV}{dY} = A_e \quad (8)$$

Equation 9, which is the displacement function of pressure, is used to find the spring rate. For this, equations 7 and 8 are used.

$$\frac{dP}{dY} = \frac{-P.\gamma.V^{(\gamma-1)}}{V^{\gamma}} = \frac{-P.\gamma.A_e}{V} \quad (9)$$

Different stiffness constants can be obtained depending on the operating frequency of the air springs. Dynamic stiffness can be expressed as shown in equation 10:

$$K_{Y,dyn} = \frac{dP}{dY}A_e = \gamma.(P_s + P_a).\frac{A_e^2}{V} + P_s\frac{dA_e}{dY} \quad (10)$$

The (quasi) static stiffness can be expressed as shown in equation 11:

$$K_{Y,stc} = \frac{dP}{dY}A_e = (P_s + P_a)\frac{A_e^2}{V} + P_s\frac{dA_e}{dY} \quad (11)$$

If the effective area change is very small, it can be assumed that the stiffness constants indicated by equations 10 and 11 are as follows:

$$K_{Y,dyn} = \frac{dP}{dY}A_e = \gamma.(P_s + P_a).\frac{A_e^2}{V} \quad (12)$$

$$K_{Y,stc} = \frac{dP}{dY}A_e = (P_s + P_a)\frac{A_e^2}{V} \quad (13)$$

The value of γ for air is equal to 1.4. Bellows' volume V (m^3). Vertical force F_y (N). $K_{Y,dyn}$ ($^N/_{mm}$) dynamic stiffness. $K_{Y,stc}$ is the static vertical stiffness ($^N/_{mm}$)), P is the absolute pressure (bar), P_s is the gauge pressure (bar), and P_a is the atmospheric pressure (bar)

2.2. Experimental Studies Applies to Air springs

Depending on the pressure change of the bellows at different heights, the reaction force, diameter change, stiffness constants, natural frequency changes can be observed by experimental studies. An air spring; It is obtained by combining basic components such as upper plate, piston, bumper (damping) , rubber-cord composite structure using special process conditions and equipment. The air spring used in this study is the front axle bellows of a bus produced for passenger transport. The aim of choosing the bellows to be used in this study as the bus air springs is to evaluate passenger comfort more critically than other parameters. The top plate of the air springs was attached to the movable plate of the testing machine, the piston base to the stationary plate and was allowed to move only in the vertical direction [24, 25]. There is no restriction on the degree of freedom of the cord-rubber composite structure, which is the most important part of air springs. The cord-rubber composite structure consists of hyper elastic material.

The height values required for the tests of air springs can be characterized by three different dimensions, including minimum, maximum and design height. The actual working height values of the selected air spring were obtained from the vehicle manufacturer and are shown in Table 1.

Table 1 Air springs working heights on the axle

Definition	*Test Height (mm)*	*Total Displacement (mm)*
Starting Height	510±1	0
Minimum Heigh	250±1	260
Design Height	295±1	215
Maximum Height	350±1	160

The air pressure inside the bellows is initially zero bar, and the test starting height is 510 mm. In experimental analysis studies, the air spring is automatically brought to the specified working heights, and tests are performed for different pressure values (1, 2, 3, 4 and 5 bar). The measurements were not started before the air pressure given into the bellows became stable. Pressure from 1 to 5 bars was sent into the air springs for three different heights, and the vertical reaction forces were measured. The spring rate in the vertical direction depends on the reaction force obtained, and the displacement applied [26, 27]. Air springs images for experimental testing are shown in Figure 2.

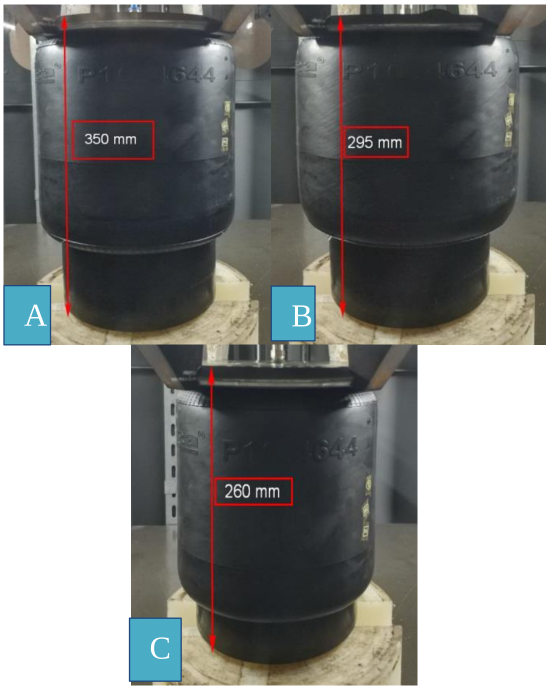

Figure 2 Air springs test heights (A) 250 mm, (B) 295 mm, (C) 350 mm, at 5 bar internal pressure

Shared images are images of different heights of air springs at 5 bar pressure.

Table 2 shows the reaction force values obtained from the experimental studies of the air spring. The gas (air) compression ratio in the air spring increases from maximum height to minimum height. Pressure and reaction forces increase as a result of the compression of the gas. Reaction forces are measured in Newton (N) units.

Table 2 Reaction force values obtained from an experimental study

Pressure (bar)	***Assembly Height (mm)***		
	250	**295**	**350**
1	3700	3800	3760
2	7980	8010	7420
3	12310	12240	10480
4	16820	16580	14030
5	20950	20670	16780

2.3. Finite element analysis model

The minimum deviation between the reaction force values obtained in the experimental study and the reaction force values obtained in the finite element analysis increases the reliability of the study. The finite element model of the air springs was achieved by modeling three parts that ensure air spring integrity. Air springs basically consist of piston, plate, and cord-rubber composite structures. Air springs components and cord-rubber composite structure are shown schematically in Figure 3. Obtaining a more reliable solution from FEA depends on the correct identification of the interactions between the components that make up the mathematical model of the bellows.

During vertical loading of the air springs, the cord-rubber composite structure between the top plate and the piston is subjected to different stresses. The rubber part of the air spring consists of a layered composite structure. The correct definition of the mechanical interactions between the plies that make up this structure directly affects the accuracy of the analysis results.

Otherwise, the obtained mathematical results may not reflect the actual situation. The up and down movements of the air bellows take place on the piston outer profile of the composite bellows. Thanks to the elastic property of the composite structure, it wraps the piston and takes its shape. For

FEA study, there is no need to model auxiliary parts on the product. The piston and top plate, one of the main parts of the air springs, have been accepted as rigid bodies in the FEA study. This means that there will be no stress and force changes in the structures chosen as rigid. The part that will be affected by the pressure change is the bellows part. The rubber layer forming the cord-rubber composite structure is a hyperelastic material that makes the analysis different. The description of a hyperelastic material's mechanical properties is quite different from metallic materials, and its mechanical properties are determined according to the Mooney Rivlin model [14, 28]. The strain energy density function (E_d) for a hyperelastic material is specified in equation 14.

$$E_d = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \frac{1}{D}(J^{el} - 1)^2 \quad (14)$$

C_{10}, C_{01}, and D values found in equation 14 are superelastic material constants obtained by testing the material. J^{el} is the elastic volume ratio, I_1 equation 15 and I_2 equation 16 are the first and second strain invariants.

$$I_1 = (\lambda_1)^2 + (\lambda_2)^2 + (\lambda_3)^2 \quad (15)$$

$$I_2 = (\lambda_1\lambda_2)^2 + (\lambda_2\lambda_3)^2 + (\lambda_1\lambda_3)^2 \quad (16)$$

In equation 16 and equation 17, λ_1, λ_2, and λ_3 are stress coefficients in three directions. In the FEA studies, the fibers in the cord fabric layer were modeled similarly to the rebar unit [29]. Cord fibers made of PA66 in the composite structure forming the air bellows model are embedded in the rubber [30]. Polyamid66 fiber cord reinforced rubber composite can be considered as an elastic, orthotropic, and homogeneous material. Cord fibers that increase the resistance against tensions in a composite structure are materials with elastic properties. Elastic modulus, poison rate, and cord fibers' density values were entered into the software as data. The advantage of the cord fabric's elastic structure allows the bellows to return to their original state when the bellows' load and pressure are removed. Thanks to this situation, the bellows structure is not damaged, and the bellows gain strength.

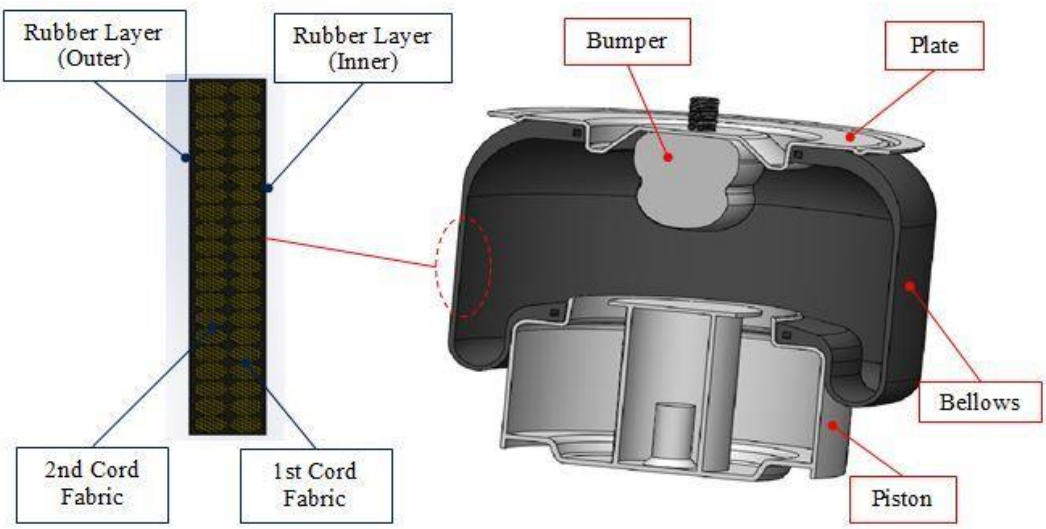

Figure 3 Schematic represantation of the air springs structure

All technical dimensions of the air spring prepared for FEA study are the same as the prototype. The material definitions required for the composite structure were determined by experimental methods and entered into the FEA program. No material is defined for rigid body members. Results data of one-way and multi-directional tensile tests performed in the laboratory environment are placed in the analysis software. The degrees of freedom of the air springs components are the same as to FEA and experimental work. The most critical point of analysis is that the air properties inside the bellows are correctly defined in the FEA program. Air is the primary material that will allow the reaction force to vary due to the bellows' pressure. It is essential to determine the properties of the air correctly. The air in the air springs can be compressed at different rates. For this reason, the air weight and atmospheric pressure values were entered as data after selecting the reference point in the middle of the bellows and the inner surface where the air contacts in the analysis program. Other parameters required for air are absolute temperature and gas constant value [31, 32].

Table 3 Material properties required for air spring FEA study

Material Properties	***Unit***	***Value***
Cord Fiber		
Elasticity Module	MPa	4640
Poisson Ratio	-	0.3
Density	T/mm^3	$1.16x10^{-9}$
Rubber		
C_{10}	-	0.382
C_{01}	-	0.096
D	-	0
Air		
Gas Constant (R)	Kj/kgK	$8.317x10^3$
Temperature	K	-273.15+25
Molecular Weight	Kg/mol	0.02897

The material properties of the bellows components are also entered into the analysis program as data. The properties of the materials used in the analysis are obtained as a result of the experimental studies and shown in detail in Table 3.

The production parameters of the cord fabric forming the layers of the bellows determine the spring stiffness during the air spring operation, the operating frequency, the friction coefficient between the piston and the rubber surface, the spring rate, and the reaction forces formed in the system [33, 34]. Correct association of the composite structure layers prevents structural deformations from occurring in the air spring and extends the product life. The air spring used in the study is a product that has received design validity as a result of field and laboratory tests. The production parameters of the layers of bellows are also approved data. The composite part of the air spring parameters used in the experimental studies is available in Table 4. These data were entered as dimensional properties during the composite design in the FEA study [35].

Table 4 Structural features of the cord-rubber composite bellows part

Parameters	***Unit***	***Value***
Cord Fabric Layer Count	piece	2
Composite Total Thickness	mm	5
1st Cord Angle	°	55
2nd Cord Angle	°	-55
Distance Between Cords	mm	0.3968
Area per Pressure	mm^2	0.049

2.4. Air springs finite element analysis study

The definition of the FEA model boundary conditions is fixed to the press floor from the lower base of the metal piston of the air spring, and the degree of freedom is set to zero. The upper connection plate of the air spring was defined to move only in the vertical direction, and the degree of freedom was set as one. FE analysis was defined as three steps respectively: inflating the air spring to the specified pressure values, defining motion in the vertical direction, and compressing it to the specified displacement value. Depending on the top cover's vertical movement, the load of the air spring can be determined. In this study, thanks to the FE analysis study, the air spring's vertical stiffness performances are determined by analyzing the load fluctuations caused by the stress values caused by the different internal pressure and displacement of the air spring. Table 5 shows the reaction force values of the air spring obtained from FE analysis studies. As the air spring moves from the maximum height to the minimum height, the reaction forces increase due to the pressure of the gas trapped inside. However, some reaction force values are lower while the air spring is compressing towards the minimum height. The reason for this is that the frictional force due to the if movement on the outer diameter of the piston limits the diameter of the bellows. Reaction forces are measured in units of Newton (N).

Table 5 Reaction force values obtained as a result of FE analysis

Pressure (bar)	*Assembly Height (mm)*		
	250	**295**	**350**
1	3886	3970	3880
2	8020	8320	7460
3	12610	12360	10750
4	17000	17200	14220
5	21280	20800	16380

According to the assembly heights, the changes of reaction force values obtained from FE analysis and experimental studies are shown in Figure 4 comparatively. A deviation value below 5% between the two studies is significant for the study's reliability.The comparative graphs shown in Figure 4 show the relationship between the pressure increase in the air spring and the reaction force change. The reaction force formed in the air spring depends on the air pressure and effective area in the bellows. The deviation values between the reaction forces obtained in FEA study and experimental studies become more in the free position and with increasing pressure.

The lower reaction force values obtained at 350 mm mounting height are due to the less interaction of the cord-rubber composite structure with the piston.

In other words, the composite structure has the freedom to extend laterally and upwards. As the air spring starts to compress from the design height, the interaction between the bellows and the piston increases. The resulting friction force prevents the composite bellows structure from expanding sideways. Thus, the reaction force decreases a little. However, when the compression is maximum, the deviation value between the FEA study and experimental studies decreases to approximately 1.5%. Tests were performed at vertical compression values of 160 mm, 215 mm, and 260 mm respectively, starting from a height of 510 mm.

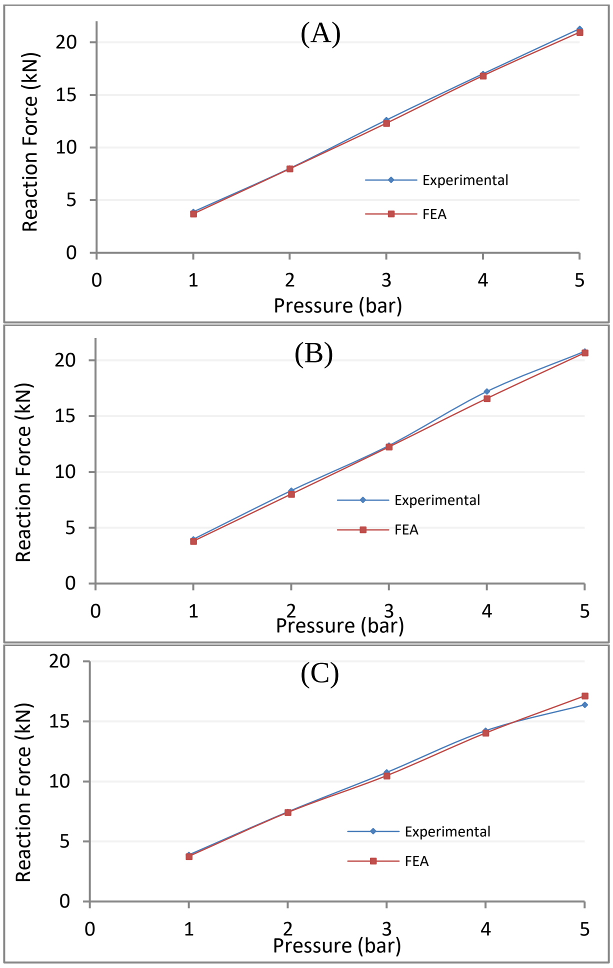

Figure 4 Reaction force comparison graphs depending on assembly heights, (A) 250 mm, (B) 295 mm, (C) 350 mm

Figure 5 shows the displacement values of the air spring in the hyperelastic material structure at different amounts. Since the rubber composite structure movement does not occur linearly, the displacement values at the nodes are different. The maximum displacement value in the rubber composite structure occurs in areas close to the upper plate. The part where the nodes are less displaced is at the base of the rubber composite structure. As the compression amount in the air spring increases, the rubber composite structure moves depending on the shape of the piston. The rubber composite structure takes the piston's shape, while the rubber composite structure folds from the bottom base. The folding movement that occurs at the bottom of the bellows causes the knots to rotate. For this reason, the vertical displacement value is higher in the upper plate part and less in the base part.

Figure 6 shows the bellow's lateral displacement values in the air spring depending on vertical movement and internal pressure. Bellows are composite structures consisting of inner rubber, two layers of cord fabric, and an outer rubber. The system that limits the amount of lateral expansion in the bellows is the cord fabrics, which are opposite to each other. Cord fabrics restrict the growth of bellow's diameter at internal pressure increase. The higher lateral displacement in the middle part is due to the more remarkable angle change between the cord fibers in this region. Excessive angle variation between cord fabrics increases lateral displacement. The lateral displacement values of the bellows are high in the middle section.

Figure 7 shows the stress values in the vertical direction of rubber bellows due to the displacement of the air spring. The pressure increase in the bellows also increases the stress values in the air spring.

Since the rubber composite structure is hyperelastic, it resists changes in stress values. The main structure affected by the tension changes in the bellows is the cord fabrics. Cord ropes are affected more by high-stress values than rubber material.

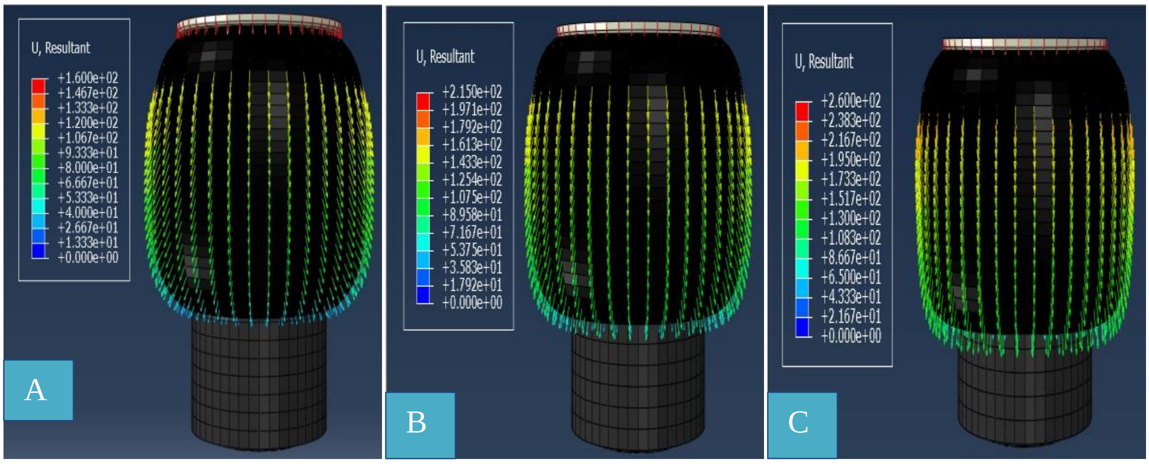

Figure 5 The movement of the nodes on the vertical displacements, (A) 160 mm, (B) 215 mm, (C) 260mm

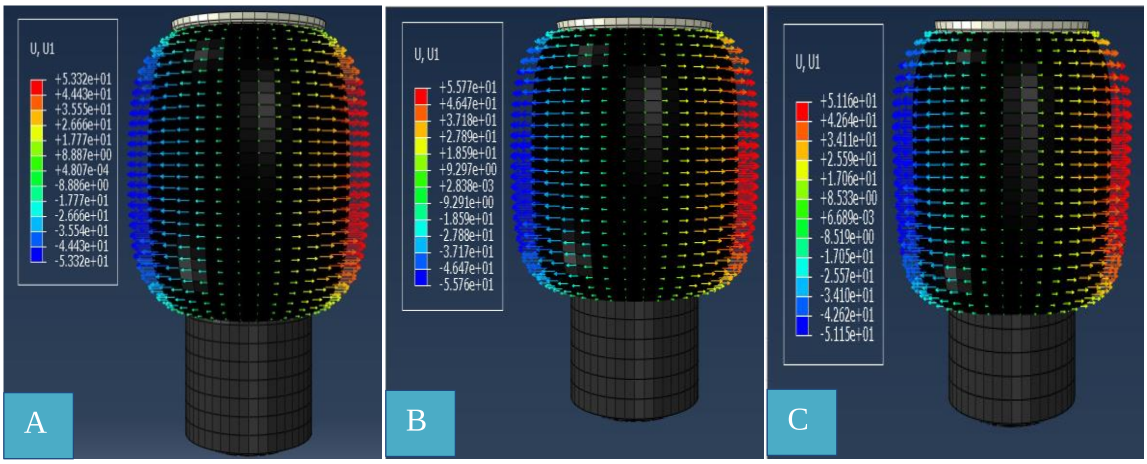

Figure 6 The movement of the nodes undergoing lateral expansion, (A) 160 mm, (B) 215 mm, (C) 260mm

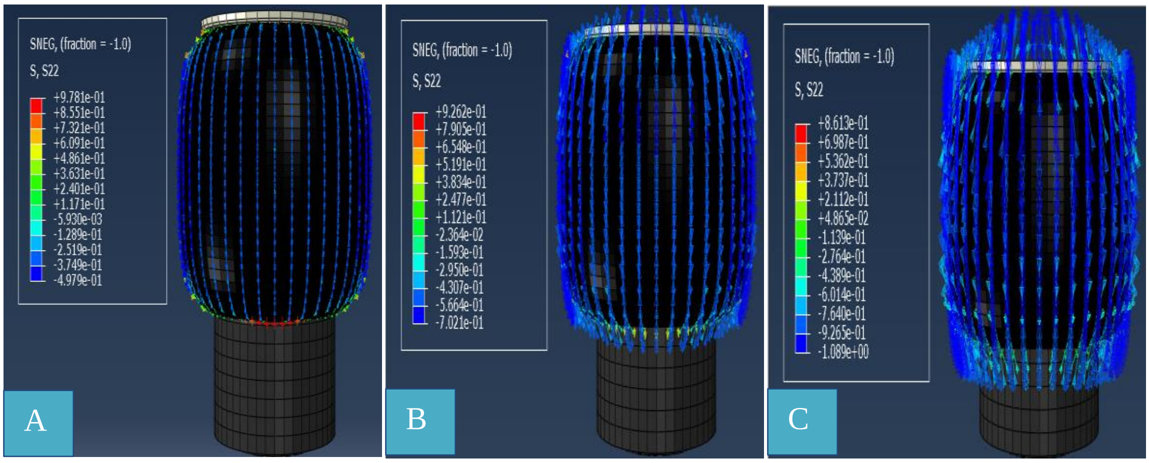

Figure 7 Vector representation of vertical stresses, (A) 160 mm, (B) 215 mm, (C) 260mm

Figure 8 shows the lateral stress values of the air spring due to different displacements. The changes in the lateral stress values change in proportion to the lateral displacement values. Since the lateral displacement values in the middle part of the bellows are high, the stress values are also high. Stress values were observed depending on three different displacements in the study. The increase in the vertical displacement causes the lateral stress values in the bellows to decrease. Because with vertical displacement, bellows contact and curl more on the outer diameter of the piston. When the bellows take the piston's shape, some of the stresses that occur in the bellows are met by the piston. In this case, high displacement reduces the lateral stresses that occur in the bellows.

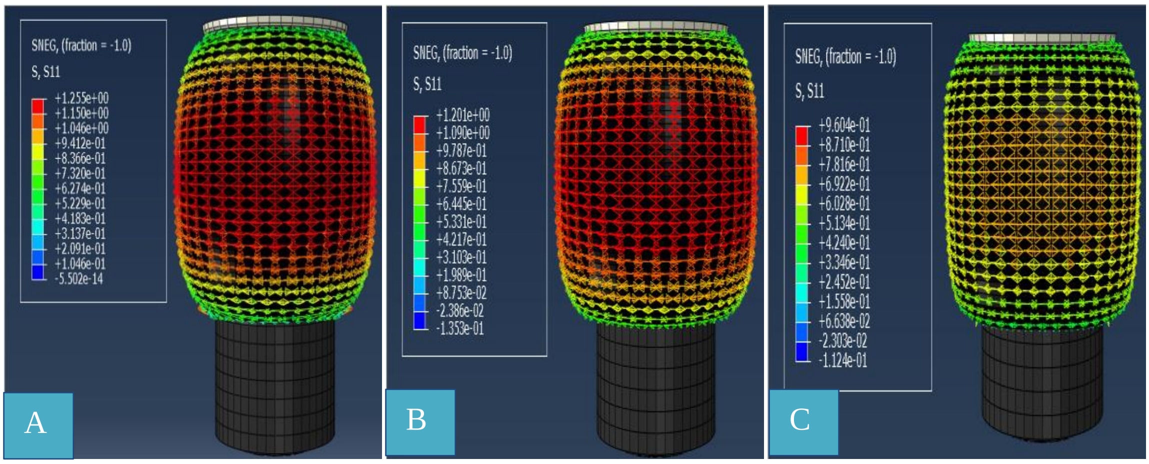

Figure 8 Vector representation of lateral stresses, (A) 160 mm, (B) 215 mm, (C) 260mm

Figure 9 shows the reaction force values caused by the change in the internal pressure of air spring moving in the vertical direction. The bellows vertical stiffness has been analyzed to determine the reaction force we have obtained by finite element analysis. With the finite element study, the air spring differences due to internal pressure variation and displacement are clearly observed. The development of the air spring is possible by knowing more about the changes in the air spring. According to the experimental method, more information about the stress, displacement, and reaction force values in the air spring can be obtained by finite element analysis. Different data can be provided with finite element analysis designed correctly for the air spring, which is difficult to work on due to its material structure. The shared visuals show that values in different situations can be easily obtained through finite element analysis.

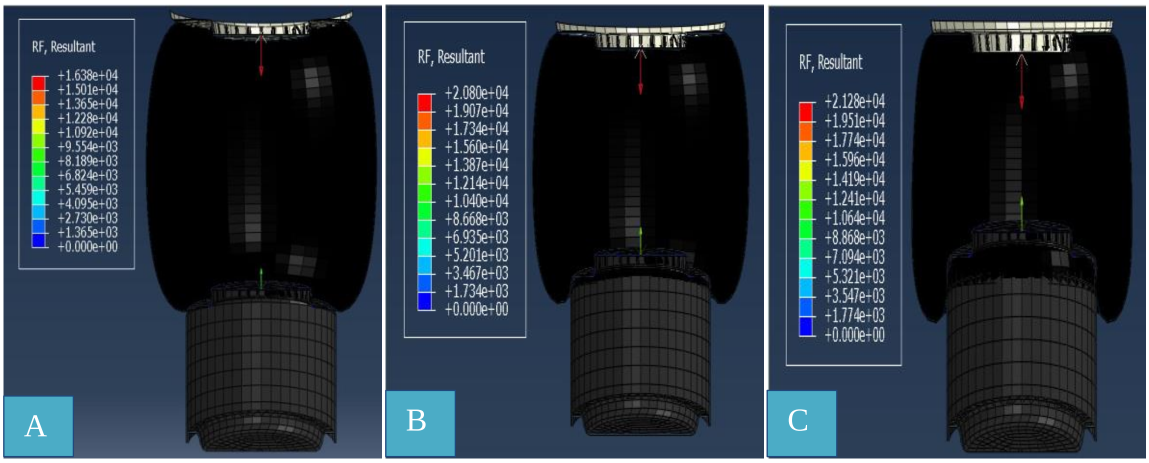

Figure 9 Display of the vertical reaction forces on the air spring, (A) 160 mm, (B) 215 mm, (C) 260mm

3. RESULT AND DISCUSSION

The design features (stiffness, reaction forces, displacements, etc.) of the air springs used in the passenger bus suspension system were determined by FE analysis. FE analysis results with experimental field tests were verified by capturing deviation values below 5%. Air springs are subjected to loads while the vehicle is in motion, but a certain amount of compression occurs in the air springs when the vehicle is not moving and is loaded. Air springs work by mounting on the axle under the chassis and vehicle. Internal pressure and compression ratios vary according to the load and road conditions during operation. The damping properties, stiffness, and frequency of bellows depend on internal pressure and displacement [36]. In the study carried out, considering the vehicle's condition loaded and not being in motion, stiffness properties were obtained depending on the tests performed at different heights and internal pressures. Determining the damping properties of air springs with analytical solutions contributes greatly to the design process. Air springs create a reaction force to the forces coming to the air suspension systems depending on the road conditions. Depending on the vehicle's loading and road conditions, there are constant changes in the internal pressure of the air springs, and these changes form the reaction forces. By using the reaction force values obtained in experimental and numerical studies, it is possible to calculate the stiffness of the air spring and interpret the damping properties. The spring coefficients calculated with the reaction force values obtained in experimental and analytical studies are given in Table 6. The values obtained are N/mm.

The values in Table 6 were established using the data obtained from the experimental studies in Table 2 and the reaction force values obtained as a result of the FEA studies in Table 5. The results enable interpretation by looking at the deviations between the finite element analysis and experimental study values. The deviation between the stiffness values of experimental and analytical studies varied between 0.5% and 6%. The fact that the percentage deviation values obtained are very close to the experimental data is promising in terms of verifying the design inputs of the bellows with analysis. The closeness between the results obtained depends on the fact that many tests have been carried out between the minimum and maximum working height of the air spring, and the material properties are defined very well. Static stiffness curves obtained as a result of experimental and FEA simulation are compared as shown in Figure 10. It is seen from the studies that FEA studies can be used effectively in air spring analysis.

Table 6 Damping coefficient values calculated at different pressure and displacement values with experimental and FEA studies

	Experimental Results			FEA Results		
Pressure (bar)	***Displacement (mm)***			***Displacement (mm)***		
	260 mm	**215 mm**	**160 mm**	**260 mm**	**215 mm**	**160 mm**
1	14 230	17 674	23 500	14 920	18 465	25 031
2	30 692	37 255	46 375	31 000	38 697	46 375
3	47 346	56 930	65 500	48 500	57 488	67 187
4	64 682	77 116	87 687	65 384	80 000	88 875
5	80 576	96 139	108 875	81 846	96 744	102 375

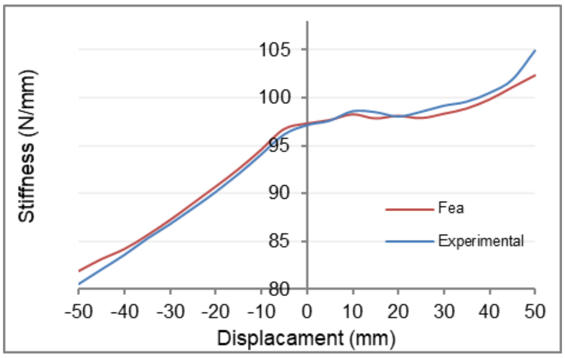

Figure 10 Comparision of static stiffness curves of the air spring

4. CONCLUSION

This study obtained information about the damping behavior of the bellows produced from composite materials such as air bellows under static loads, thanks to both the experimental and finite element analysis models. As a result of the studies, the following information was obtained;

1. The approximate deviation between the static stiffness value obtained from the experimental study and the mathematical study of the bellows was determined as 5%. Values close together indicate that the two study results can be reconciled.

2. Thanks to the FEA study, more results can be obtained regarding values such as regional stress, force, and displacement in the air spring.

3. Analysis studies have shown that the increase in the vertical displacement value of the bellows decreases the lateral stress values. Some of the stresses in the bellows, which take the shape of the piston, are covered by the piston. However, the vertical stress values occurring in the bellows increase proportionally as the displacement value increases.
4. In our study, it has been seen that the cord fabrics in the rubber composite structure are affected by excessive stress more than the rubber material. Cord fibers limit the excessive expansion of the bellows in the event of a sudden pressure increase. It is the main element that carries the loads that occur in instant pressure increases.

5. The effect of air is important in both our work. For analysis studies, it is important to correctly define the characteristics of the air that creates the internal pressure of

the bellows, such as pressure, absolute temperature, weight, and effective area.

6. The 5% deviation between the stiffness values obtained by the experimental results of the prototype and the results obtained from FEA studies can be caused by ambient temperature, prototype internal pressure, and errors that can occur in the prototype production process.

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Authors' Contribution
The authors contributed equally to the study.

The Declaration of Conflict of Interest/ Common Interest
No conflict of interest or common interest has been declared by the authors.

The Declaration of Ethics Committee Approval
This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics
The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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