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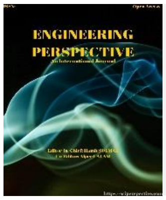

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Stress-Strain Deformation Analysis of Conventional Vehicle Shock Absorber Materials Under In-Service Multi-Translated Non-Proportional Loading Conditions

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ABSTRACT

The in-service condition of a vehicle eventually subject the shock absorber to unforeseen deformations due to external forces such as damping, friction, resistance forces and other factors such as poor road condition characterized by potholes and speed bumps. In this study, a vehicle shock absorber was analysed, considering the in-service condition. Using SOLIDWORKS software, 2020 version the shock absorber component was modelled with three different materials which were simulated with ANSYS software. From the simulated results, maximum total deformations of 54.286, 49.26 and 47.603 mm as well as maximum directional deformations of 53.303, 48.762 and 47.569 mm were obtained for hard drawn spring wire (A227), alloy steel (A213) and stainless steel (A313) selected as the shock absorber materials. On the other hand, maximum equivalent von-mises stresses of 1205.8, 1204.7 and 1084.6 MPa as well as maximum equivalent strain values of 0.0065269, 0.0061912, 0.0060882. From the simulated results obtained, stainless steel (A313) out of the three shock absorber material exhibited the least deformations, von-mises stress and equivalent strain. However, the three materials had satisfy the failure distortion-energy theory, and may be feasible for shock absorber application in actual scenario because the Von-mises stress obtained had not exceeded any of the material's yield strength. This was evidence in the low equivalent strain values and the colour distribution across the shock absorber models which was dominated by royal blue colour, indicating that the shock absorber models can still accommodate multiple translated non-proportional loading or still had significant load bearing capacity. The stress-strain deformation analysis in this study can help predict and prevent premature failure, ensuring the longevity of vehicle shock absorbers.

Keywords: Deformations, External forces, Loading conditions, Materials, Shock absorber

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1. Introduction

The automotive industry is constantly evolving, with manufacturers striving to enhance vehicle performance, safety, and comfort. One critical component that plays a significant role in achieving these objectives is the shock absorber. The shock absorber is responsible for dampening the vibrations and impacts experienced by a vehicle, ensuring a smooth and controlled ride [1, 2]. Their primary function is to dampen the oscillations and vibrations caused by uneven road surfaces, bumps, and other disturbances. By absorbing and dissipating the kinetic energy generated during these movements, shock absorbers help maintain tire contact with the road, ensuring better traction and handling [3, 4]. These components are subjected to various loads and forces including compression, extension, and torsion during operation, which can significantly result in deformation failure, thereby, affecting their performance and longevity [5, 6]. In other words, these forces can cause significant stress and strain on the shock absorber components, leading to potential failure. Analysing the stress-strain deformation helps in understanding the behaviour of these components under different operating conditions. Over the years, failure deformations, stress-strain deformation characteristics, continuous improvement and optimization of shock absorbers have evolved through various academic research cited in this study.

The dynamic behaviour of a vehicle shock absorber system was investigated by Sani et al. [7]. An interchangeable shock absorber test rig integrated with computer systems was designed and fabricated to record the signals. An experiment was conducted to identify the stiffness and damping parameter for 850 cc and 1600 cc shock absorber. The stiffness and damping conditions were simulated using COSMOS Motion software. Findings obtained indicated discrepancy of 10%. Optimum range of stiffness for the shock absorber was between 20 N/mm and 60 N/mm while optimum damping range was between 1 Ns/mm and 6 Ns/mm.

Zhang [8] studied a vehicle regenerative shock absorber by developing a 2 degrees of freedom oscillating system resembling the quarter vehicle suspension system with electromagnetic harvester and validated the model using ANSYS Maxwell software simulation. The peak power output was observed to occur at a natural frequency. A novel indirect drive regenerative shock absorber with the arm-teeth system was also modelled and fabricated. Findings obtained revealed that power output can be increased compared to the traditional direct drive regenerative shock absorber. A full vehicle suspension system model was also modelled as an extension of the half vehicle suspension system. It was observed that at high frequency range, the peak power output ratio of full vehicle suspension system was the same with the half and quarter vehicle suspension system.

Natural frequencies of the shock absorber in a 2 degree-of-freedom system were investigated by Tan et al. [9] using Wolfram Mathematica 11, CATIA, and ANSYS. Both theoretical and simulation were employed in the study to determine the resonance effects on the vehicle shock absorber. Failure was found to occur on coil spring of the shock absorber earlier before proceeding to the body of the shock absorber. Two natural frequencies had been obtained as 1.0 Hz and 9.1 Hz for sprung mass and un-sprung mass which where the frequencies that acceleration was recorded as maximum.

SelvaKumar et al. [10] modelled a vehicle shock absorber system with CATIA software and analysed the same model using ANSYS software. The analysis was to determine the equivalent stresses and principal elastic strains on the shock absorber system using two engineering materials including carbon fibre and beryllium copper. Using different diameters of 10.9, 11.2, 11.4, 11.6, 11.8, maximum equivalent stress and principal elastic strain of 3.2768e5, 5.2883e5, 4.7892e5, 4.5751e5 and 4.328e5 as well as 6.9334e-5, 0.00010763, 9.794e-5, 9.4869e-5 and 8.7578e-5 were obtained for carbon fibre. However, using the same diameter for beryllium copper, maximum stress and strain of 3.2709e5, 5.3297e5, 4.8135e5, 4.584e5 and 4.3532e5 as well as 2.7096e-6, 4.2369e-6, 3.8459e-6, 3.7097e-6 and 3.4421e-6 were obtained.

A 3D model of a vehicle suspension system was developed by Bhasha et al. [11] using CATIA V5 R21. Structural analysis and modal analysis was carried out on the shock absorber system using different materials. The materials were titanium alloy, phosphor bronze, beryllium copper, and spring steel, and maximum stress intensity of 36.102, 36.5865, 36.4637 and 36.4265 N/mm^2 were obtained while maximum displacements vectors of 2.6326, 4.9247, 4.8582 and 3.0123 mm were obtained. It was observed that the stress intensity and displacement vectors were less for titanium alloy than other materials.

The stress-strain deformation analysis of vehicle shock absorber models is essential for several reasons. Firstly, it allows engineers and researchers to evaluate the structural integrity and durability of shock absorbers under various loading conditions [12, 13]. By subjecting shock absorber models to different stress levels, it becomes possible to identify potential failure points and design flaws, thereby improving their overall performance and reliability. Secondly, understanding the stress-strain deformation behaviour of shock absorber models aids in optimizing their design and material selection [14]. By analysing the stress distribution and strain patterns, engineers can identify areas of high stress concentration and modify the design accordingly. This optimization process ensures that shock absorbers can withstand the forces they encounter during vehicle operation, leading to improved safety and longevity.

Furthermore, stress-strain deformation analysis provides valuable insights into the performance characteristics of shock absorbers. By simulating real-world conditions, researchers can evaluate the damping capabilities of different shock absorber models. This information is crucial for selecting the most suitable shock absorber for specific vehicle applications, ensuring optimal ride comfort and stability [15]. Moreover, stress-strain deformation analysis can aid in the development of advanced shock absorber technologies. By studying the behaviour of shock absorber models under extreme conditions, such as high-speed impacts or off-road terrain, engineers can identify opportunities for innovation. This study can lead to the development of shock absorbers with enhanced performance, such as adjustable damping systems or adaptive control mechanisms.

Stress-strain deformation analysis on vehicle shock absorber models is a critical aspect of understanding their behaviour and performance. By evaluating the structural integrity, optimizing the design, and assessing the damping capabilities, the safety, comfort, and durability of shock absorbers can be enhanced. The evaluation was adopted in this study for stress-strain deformation analysis of conventional vehicle shock absorber materials under in-service multi-translated non-proportional loading conditions. This can provide a foundation for the development of advanced shock absorber technologies, contributing to the continuous improvement of vehicle suspension systems. Therefore, stress-strain deformation analysis carried out in this study is crucial for understanding the behaviour of vehicle shock absorbers under different operating conditions. By identifying potential problems, material limitations, and areas of high stress concentration, engineers can optimize the design, enhance performance, and ensure the reliability and longevity of shock absorbers. This analysis also aids in validating the design and manufacturing processes, leading to improved overall vehicle dynamics and customer satisfaction.

2. Research Methodology

2.1 Theoretical Background

In static structural deformation analysis, mathematical equations are used to calculate total and directional deformations, as well as equivalent Von-Mises and elastic strain. These equations are derived based on principles of mechanics and material behaviour, and are essential for understanding the behaviour of shock absorbers under applied loads. To calculate directional deformations, the material's properties and the direction of the applied load were considered. To obtain mathematical equations for total and directional deformations on vehicle shock absorber system, the basic principles of elasticity was considered. In addition to deformations, it is also important to calculate the equivalent Von-Mises stress and elastic strain. These calculations are essential for predicting the performance and failure of structures and components. These equations form the underlying principles behind the operation of vehicle shock absorbers, and are essential for analysing their behaviour under applied loads and ensuring their safety and reliability. Shock absorbers operate based on the principle of converting kinetic energy into heat energy. They consist of a piston, cylinder, and hydraulic fluid. When a vehicle encounters a bump or uneven surface, the suspension system compresses the shock absorber [16]. This compression forces the piston to move inside the cylinder, displacing the hydraulic fluid. The hydraulic fluid, usually oil, flows through small orifices or valves within the shock absorber, creating resistance against the piston's movement. This resistance slows down the compression and extension of the suspension system, controlling the rate at which the vehicle's weight shifts during these movements. The damping force generated by the shock absorber is determined by various factors, including the design, size, and viscosity of the hydraulic fluid, as well as the orifice size and valve characteristics. If these components are not carefully engineer, it becomes difficult to achieve the desired damping characteristics for different vehicle types and driving conditions. Performance efficiency of the shock in the vehicle's suspension must be evaluated by taking into account the vibrating system being a linear single-mass single-support mechanism with fixed elastic and damping characteristics at a harmonic frequency as seen on Figure 1.

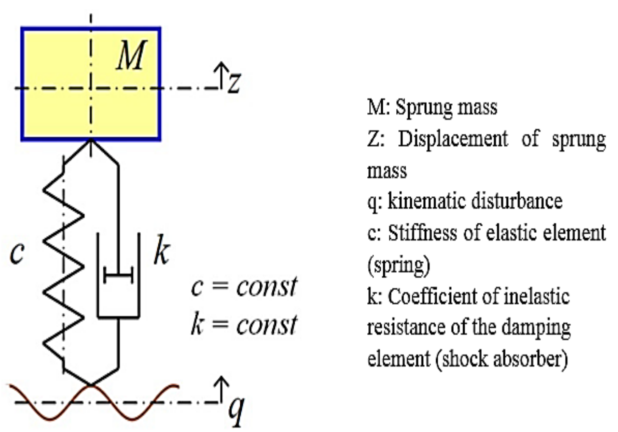


Figure 1. Linear vibrating system with damping characteristics

The linear vibrating system is based on the following differential equation presented in Eq.(1) and Eq. (2):

$$M\dot{z} + k\ (\dot{z} - \dot{q}) + c(z - q) = 0 \tag{1}$$

or

$$\dot{z} + 2h\ (\dot{z} - \dot{q}) + \omega_0^2\ (z - q) = 0 \tag{2}$$

To compute the absolute and relative oscillations, it is important to rewrite Eq. (2) in the following forms:

$$\dot{z} + 2h\dot{z} + \omega_0^2\ z = 2h\dot{q} + \omega_0^2\ q = Q_Z \tag{3}$$

$$\dot{x} + 2h\dot{x} + \omega_0^2\ x = \dot{q} = Q_x \tag{4}$$

prepared Where $x = q - z$ is the suspension deformation, $\dot{x} = \dot{q} - \dot{z}$ represents velocity of suspension deformation, $\ddot{x} = \dot{q} - \dot{z}$ is the suspension deformation due to acceleration, $\dot{q}$ denotes disturbing kinematic effect, Q_x and Q_Z denotes disturbing functions for steady state forced oscillations on *x* and *z* coordinates. Eqs.(5-9) was obtained based on the principles of linear vibrating system, in which the damping effect of the suspension system induces stress-strain deformations on the shock absorber. In this case, the amplitude of perturbing function causing forced absolute oscillations of the sprung mass is given by Eq. (5).

$$Q_{Z0} = q_0\sqrt{\omega_0^4 + 4h^2\omega_0^2} \tag{5}$$

The amplitude of perturbing function causing forced relative oscillations of the sprung mass is given by Eq. (6).

$$Q_{X0} = \ \ q_0\omega^2 \tag{6}$$

In cases where resistance force versus deformation velocity is linear, the total work on the shock absorber over oscillation cycle is given by Eq. (7):

$$A = \frac{2\pi}{\int_0^w k\dot{x}\dot{x}dt} = kx_0^2\omega\pi \tag{7}$$

Where $\dot{x} = x_0\ \ \omega\cos(\omega t + \beta_x)$ represents deformation velocity of vehicle suspension. Suspension force acting partially on the linear shock absorber over oscillation cycle is expressed in Eq. (8).

$$P_\mathrm{f} = \frac{\frac{\left(\frac{\pi}{2}\beta_x\right)}{\omega}}{2\int k\dot{x}\dot{x}dt = kx_0^2\omega(sin\beta * cos\beta - \beta),\quad \frac{\left(\frac{\pi}{2}\beta_Z\right)}{\omega}} \tag{8}$$

Suspension force acting fully on the linear shock absorber system over oscillation cycle is expressed in Eq. (9).

$$F_\mathrm{f} = f - P_\mathrm{f} = kx_0^2\omega\pi - kx_0^2\omega\ \ (sin\beta * cos\beta - \beta) = kx_0^2\omega\ \ (\pi + \beta - sin\beta * cos\beta) \tag{9}$$

Thus, Effective Work Ratio (EWR) of the shock absorber with linear characteristic can be determined using Eq. (10).

$$\eta = \frac{P_\mathrm{f}}{f} = \frac{kx_0^2\omega\ \ (\pi + \beta - sin\beta * cos\beta)}{kx_0^2\omega\pi} = \frac{\pi + \beta - sin\beta * cos\beta}{\pi} \tag{10}$$

Under isothermal conditions, the pressure variations in the rebound chamber and the compression chamber are expressed in Eq. (11) and Eq. (12).

$$\frac{dp_1}{dt} = \frac{E}{V_{10} + S_1x_1}\left((Q_1 + Q_2 + Q_3 + Q_4) - (S_1\dot{x}_1)\right) \tag{11}$$

$$\frac{dp_2}{dt} = \frac{E}{V_{20}+S_3x_2-S_2x_1}\begin{pmatrix}(Q_1 - Q_2 - Q_3 - Q_4)\\ -(S_3\dot{x}_2 - S_2\dot{x}_1)\end{pmatrix} \tag{12}$$

where E is Oil Bulk modulus, V_{10} and V_{20} are the initial volumes of the rebound and compression chambers, Q is the oil flow rate of corresponding orifices, S_i is the cross-section area of the relevant chamber, $\dot{x}_1$ is the velocity of the main piston, $\dot{x}_2$ is the velocity of floating piston, x_1 is the displacement of the main piston, x_2 is the displacement of the floating piston. The opened area for variable orifice with a blunt needle for oil flow during compression and rebound strokes is given by Eq. (11).

$$A_3 = \frac{\pi}{4}d_b^2\left(1-\left(1-\frac{\eta_c}{2M_c}\right)^2\right) \tag{13}$$

where d_b is the diameter of the additional orifice, n_c is the click number of the variable diameter needle, M_c is the maximum possible number of the needle clicks. For total forces on the floating piston, the equation of motion for the floating piston is given by Eq. (14). In addition, equation of motion for the main piston is given by Eq. (13).

$$m_2\ddot{x}_2 = S_3P_2 - S_3P_3 - F_f2\ sign(\dot{x}_2 - \dot{x}_1) - m_2g \tag{14}$$

$$m_1\ddot{x}_1 = S_1P_1 - S_2P_2 - F_f1\ sign(\dot{x}_1) - m_1g + F \tag{15}$$

where m_1 is the mass of the main piston, x_1 is the acceleration of the piston motion, S_1 is the area of the rebound chamber cross section, S_2 is the area of the compression chamber cross-section, F_f1 is the friction force appearing between the piston and the body of the shock absorber, and F is the damping force caused by the shock absorber. The damping force caused by the shock absorber due to its motion is expressed in Eq. (16).

$$F = m_1\ddot{x}_1 - S_1P_1 + S_2P_2 + F_f1\ sign(\ddot{x}_1) + m_1g \tag{16}$$

2.2 Analytical Background

The shock absorber assembly is presented in Figure 2. The CAD model was done on SolidWorks 2018 while all analysis was done on ANSYS 2023 R1. The CAD model was imported to ANSYS workbench for Finite Element Analysis (FEA). The Finite Element method was used to study the maximum shear stress, the Von-mises stress and the displacement due to the force. The model was simplified for to enable us obtain quality meshing and reduce the analysis time and computational resources required. It can be observed that the spring base support was rid of any complex curves. Furthermore, the contact between the rod and the cylinder was ignored and the model was adjusted to ignore such contact. This is because we are only interested in the spring's behaviour under load and not the entire strut assembly. The other parts were assigned the default structural steel material found in the applications database.

The procedure for geometry and mesh generation in FEA plays a critical role in obtaining accurate and reliable analysis results. It involved creating an accurate geometric model, simplifying the geometry, generating a suitable mesh, selecting appropriate element types and sizes, defining boundary conditions, and performing a quality check. Following this procedure ensures that the FEA analysis is based on a sound foundation, leading to more accurate predictions and better engineering decisions. Step-by-step procedure for conducting FE simulation of shock absorber model in this study are enumerated as follows:

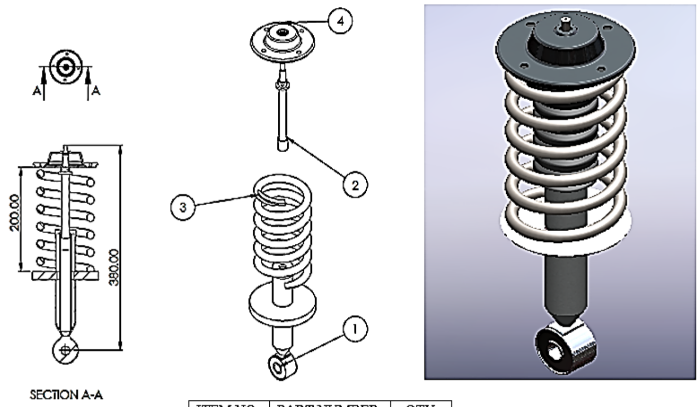
i. Geometry Generation: The first step in Finite Element (FE) modelling process was to create a geometric CAD model of the shock absorbing structure or component being analysed. This was done using computer-aided design (CAD) software known as SOLIDWORKS. The geometry included all relevant components, such as the piston, cylinder, coil spring and strut mount.
ii. Clean-up and Simplification: Once the CAD geometry was created, it was important to clean-up and simplify the model. Some unnecessary details, such as small fillets or chamfers were removed, and the geometry was simplified to reduce the computational effort required for mesh generation and analysis.
iii. Mesh Generation: Once the geometry was created, clean-up and simplification done, a mesh was generated to discretize the model into smaller elements. The mesh generation process involved division of the geometry into a finite number of smaller, interconnection of 8 nodded tetrahedral brick element. The mesh was fine enough to capture the important features of the shock absorber geometry and ensure accurate results with less computational time. The selection of element size depends on the complexity of the geometry and the desired level of accuracy. Smaller elements provide more accurate results but require more computational resources.
iv. Material Properties: Accurate material properties are essential for realistic simulations. The material properties of the shock absorber components, such as the piston, cylinder, coil spring and strut mount, needed to be determined. In the outline window on the ANSYS material library, the Geometry tab was expanded while the Solid Body 1 was highlighted. The shock absorber model was then highlighted in green, indicating it is selected. Right below the outline window was "Details of Solid Body 1". The material was expanded, the material properties desired or defined for the model was then assigned to the shock absorber model.
v. Boundary Conditions and Constraints: Boundary conditions and constraints which defined constraints and loading conditions applied to the shock absorber model were specified. These included fixed supports, applied loads, damping and stiffness coefficients and constraints on displacements or rotations. Boundary condition represented the physical connection between the shock absorber and the structure it is mounted on. The fixed constraints were applied to simulate the mounting points of shock absorbers. These constraints restricted the translational and rotational degrees of freedom, ensuring that the shock absorber remained fixed at its mounting locations. Shock absorbers are subjected to various loads during their operation, such as compression, extension, and torsion. For example, a compressive load can be applied to simulate the impact of

a vehicle hitting a bump. In this case, a load of 4300N representing the cars sprung weight and luggage loads was applied in the positive y direction. This force was constrained to simulate the forces on an actual shock absorber. A fixed support was placed on a strut mount. The magnitude, direction, and distribution of these loads were properly represented in order to obtain reliable results. Shock absorbers are designed to provide damping and stiffness to control the motion of a system. These characteristics were incorporated into the FE model by defining appropriate damping and stiffness coefficients.

vi. Quality Check: After generating the mesh, it was important to perform a quality check to ensure the mesh is suitable for analysis, as mesh quality directly affects the accuracy of the analysis results. This involved checking for element distortion, aspect ratio, and element size variation. Mesh quality directly affects the accuracy of the analysis results. Errors found were adequately addressed before proceeding with the FEA analysis.

vii. Finite Element Analysis: Once the geometry, mesh, material properties, and boundary conditions were defined, a finite element analysis (FEA) was performed using the ANSYS software. This involved solving the governing equations of motion using numerical methods. The ANSYS software calculated the total deformation, directional deformation, equivalent Von-mises stresses and equivalent strain, of the shock absorber model. The accuracy of the results depended on the quality of the mesh, material properties, and boundary conditions.

Internal damping and viscous parameters were not considered because the study was static structural deformation analysis. Static structural deformation analysis focuses on the equilibrium state of a structure under applied loads, where the structure is assumed to be in a state of rest. In this scenario, the effects of internal damping and viscous parameters, which are related to dynamic behaviour and energy dissipation of the shock absorber, are not relevant. Internal damping and viscous parameters are typically considered in dynamic structural analysis, where the response of a structure to time-varying loads is of interest. In dynamic analysis, the damping characteristics of a structure play a crucial role in determining its response to dynamic loads, such as vibrations or seismic forces. However, in static analysis, where the focus is on determining the static deformation and stresses on the sock absorber, the consideration of internal damping and viscous parameters is unnecessary. Furthermore, the inclusion of internal damping and viscous parameters in static structural deformation analysis can complicate the analysis and introduce additional uncertainties. These parameters are often difficult to quantify accurately and can vary significantly depending on the material properties, geometry, and boundary conditions of the structure. By neglecting these parameters in static analysis, the analysis becomes more straightforward and the results are more reliable.



ITEM NO.	PART NUMBER	QTY.
1.	Cylinder	1
2.	Piston Rod	1
3.	Coil Spring	1
4.	Strut Mount	1

Figure 2. Shock absorber assembly

The shock absorber was modelled in SolidWorks 2020. The material properties were selected from conventional spring materials, with design parameters adequately considered. The wire diameter (d), spring diameter and spring height were 15.5 mm, 155.57 mm and 200 mm. The computational analysis was carried in ANSYS 2023 R1. Mesh visualization of the shock absorber model is shown in Figure 3 while the properties of shock absorber materials are presented in Table 1. Modelling details of the shock absorber components are presented in Table 2 while mesh details of the shock absorber model are presented in Table 3.

Table 1. Properties of shock absorber materials

Material Properties	Hard Drawn Spring Wire (A227)	Stainless Steel (A313)	Alloy Steel (A213)
Young's Modulus (MPa)	2.07e+05	1.9305e+05	2.0684e+05
Poisson's Ratio	0.3	0.4	0.30435
Bulk Modulus (MPa)	1.725e+05	3.2176e+05	1.762e+05
Shear Modulus (MPa)	79615	68948	79290
Tensile Yield Strength (MPa)	1591	2240.8	2068.4

In finite element simulations, contact conditions are typically defined using contact algorithms that determine how two surfaces interact when in contact with each other. These algorithms consider factors such as friction, penetration, and separation between the surfaces to accurately model the contact behaviour. For shock absorbers, contact conditions are particularly important as they directly affect the static behaviour and overall performance of the system.

Table 2. Modelling details of the shock absorber components

Shock Absorber Components	Strut Mount	Coil Spring	Piston Rod	Cylinder
Material				
Assignment	Structural Steel	Stainless Steel		Structural Steel
Nonlinear Effects	Yes			
Thermal Strain Effects	Yes			
Bounding Box				
Length X	176.69 mm	122.7 mm	33.803 mm	120. mm
Length Y	29. mm	175.54 mm	200. mm	255. mm
Length Z	176.69 mm	122.7 mm	33.803 mm	120. mm
Properties				
Volume	68533 mm³	2.4589e+005 mm³	27752 mm³	1.5043e+005 mm³
Mass	0.53798 kg	1.9057 kg	0.21507 kg	1.1809 kg
Centroid X	8.8548e-005 mm	6.2259e-002 mm	-4.495e-009 mm	-1.7033e-005 mm
Centroid Y	412.53 mm	319.08 mm	335.22 mm	176.13 mm
Centroid Z	5.6181e-005 mm	0.62281 mm	2.2488e-009 mm	7.2457e-003 mm
Moment of Inertia Ip1	610.93 kg·mm²	7025.3 kg·mm²	6.4163 kg·mm²	7790.7 kg·mm²
Moment of Inertia Ip2	1174.2 kg·mm²	4647.7 kg·mm²	763.84 kg·mm²	554.03 kg·mm²
Moment of Inertia Ip3	610.94 kg·mm²	7016. kg·mm²	763.86 kg·mm²	7830.8 kg·mm²
Statistics				
Nodes	21091	13616	18958	43137
Elements	11115	6549	12322	23032

Table 3. Mesh details of the shock absorber model

Object Name	Mesh	Object Name	Mesh
State	Solved	Quality	
Display		Check Mesh Quality	Mesh Quality Worksheet
Display Style	Use Geometry Setting	Error Limits	Aggressive Mechanical
Defaults		Target Element Quality	5.e-002
Physics Preference	Mechanical	Smoothing	Medium
Element Order	Program Controlled	Mesh Metric	None
Element Size	8.0 mm	Inflation	
Sizing		Use Automatic Inflation	None
Use Adaptive Sizing	Yes	Inflation Option	Smooth Transition
Resolution	Default (2)	Transition Ratio	0.272
Mesh Defeaturing	Yes	Maximum Layers	5
Defeature Size	Default	Growth Rate	1.2
Transition	Slow	Inflation Algorithm	Pre
Span Angle Center	Coarse	View Advanced Options	No
Initial Size Seed	Assembly	Advanced	
Bounding Box Diagonal	462.39 mm	Number of CPUs for Parallel Part Meshing	Program Controlled
Average Surface Area	1799.4 mm²	Straight Sided Elements	No
Minimum Edge Length	1.0472 mm	Rigid Body Behavior	Dimensionally Reduced
Statistics		Triangle Surface Mesher	Program Controlled
Nodes	96802	Topology Checking	Yes
Elements	53018	Pinch Tolerance	Please Define
Show Detailed Statistics	No	Generate Pinch on Refresh	No

In the context of SOLIDWORKS Simulation, defining contact conditions involves specifying how different components interact with each other under loading conditions. This is essential for predicting the performance and durability of the shock absorber assembly. One of the key challenges in defining contact conditions is determining the type of contact between components. There are various types of contact conditions that can be defined in SOLIDWORKS Simulation, including bonded, no penetration, and frictional contact. Each type of contact condition has its own set of parameters that need to be carefully defined to accurately represent the physical behaviour of the components. Defining contact conditions for shock absorbers in SOLIDWORKS Simulation, factors such as material properties, surface roughness, and loading conditions were considered. For example, the coefficient of friction between the piston and cylinder surfaces can have a significant impact on the damping characteristics of the shock absorber.

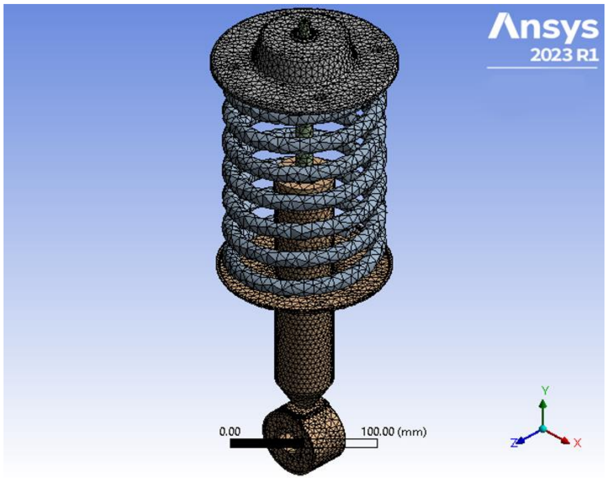


Figure 3. Mesh visualization of the shock absorber model

While analysing the shock absorber system in this study, the following contact conditions were defined:

i. Bonded contact assumed that the two components are perfectly joined together and do not move relative to each other. This was considered suitable for components that are rigidly connected, such as the spring and its seat or piston and cylinder of the shock absorber.
ii. No penetration contact allowed components to move relative to each other, but prevents them from interpenetrating. This was considered useful for simulating the movement of components within a shock absorber, such as the piston sliding within the cylinder.
iii. Frictional contact introduced a frictional force between components, which can be useful for simulating the damping effect of the shock absorber. By adjusting the friction coefficient, the behaviour of the shock absorber under different conditions can be modelled accurately.

One common approach that was used in defining contact conditions in shock absorber simulations in this study was the use of contact elements. These elements are inserted at the interface between the contacting surfaces and allow for more accurate modelling of the contact behaviour. Contact elements can account for factors such as friction, separation, and sliding between the surfaces, providing a more realistic representation of the contact conditions. Boundary conditions (connections and contacts as well as coordinate systems) for the shock absorber stress-strain deformation analysis are presented in Table 4.

Table 4. Boundary conditions for the shock absorber stress-strain deformation analysis

CONNECTIONS AND CONTACTS		COORDINATE SYSTEM	
Object Name	Contacts	Object Name	Global Coordinate System
State	Fully Defined	State	Fully Defined
Definition		Definition	
Connection Type	Contact	Type	Cartesian
Scope		Coordinate System ID	0
Scoping Method	Geometry Selection	Origin	
Geometry	All Bodies	Origin X	0. mm
Auto Detection		Origin Y	0. mm
Tolerance Type	Slider	Origin Z	0. mm
Tolerance Slider	0.	Directional Vectors	
Tolerance Value	1.156 mm	X Axis Data	[1. 0. 0.]
Use Range	No	Y Axis Data	[0. 1. 0.]
Face/Face	Yes	Z Axis Data	[0. 0. 1.]
Face-Face Angle Tolerance	75°	Analysis	
Statistics		Physics Type	Structural
Connections	4	Analysis Type	Static Structural
Active Connections	4	Solver Target	Mechanical APDL

2.3 Background Details on SOLIDWORKS and ANSYS Simulation Software

In the field of engineering, simulation software plays a crucial role in the design and analysis of various products and systems. Two widely used simulation software programs are SOLIDWORKS and ANSYS. Both programs offer powerful tools for engineers to simulate and analyse the behaviour of their designs before they are physically built. The background details of SOLIDWORKS and ANSYS simulation software, and their key features and capabilities are provided as follows:

i. SOLIDWORKS: SOLIDWORKS is a 3D CAD and modelling tool developed by Dassault Systèmes to run on Microsoft Windows. It is widely used in the engineering industry for designing and modelling mechanical components and assemblies [17]. SOLIDWORKS offers a user-friendly interface that allows engineers to create complex 3D models with ease. The software also provides a wide range of tools for simulation and analysis, including finite element analysis (FEA) and computational fluid dynamics (CFD). One of the key features of SOLIDWORKS is its integration with other software programs, such as ANSYS, for more advanced simulation capabilities. This allows engineers to transfer their designs seamlessly between the two programs, enabling them to perform detailed analysis and optimization of their models.
ii. ANSYS: ANSYS is a simulation software developed by

ANSYS Inc. It is known for its advanced capabilities in structural analysis, fluid dynamics, and electromagnetics. ANSYS offers a wide range of tools for engineers to simulate and analyse the behaviour of their designs under various conditions. One of the key features of ANSYS is its ability to perform Multiphysics simulations, where multiple physical phenomena are simulated simultaneously. This allows engineers to study the interactions between different aspects of their designs, leading to more accurate and realistic results.

Both SOLIDWORKS and ANSYS simulation software programs offer unique features and capabilities for engineers to design and analyse their products. While SOLIDWORKS is more focused on 3D modelling and design, ANSYS is known for its advanced simulation capabilities. By integrating these two programs, engineers can take advantage of the strengths of each software to create more efficient and optimized designs. Also, being adequately versed on the background details of these software programs, can enable engineers make informed decisions on which program to use for their specific needs.

3. Results and Discussions

Total deformation refers to the overall change in shape or dimensions of the shock absorber due to external forces such as damping, friction, resistance forces etc. A number of deformations (bending, twisting, compression, and elongation) due to these operating forces acting on the shock absorber results in total deformation of the system. Deformation can occur in various components of the shock absorber, such as the piston rod, cylinder, and mounting brackets. Various factors contribute to the total deformation experienced by shock absorbers, including vehicle weight, road conditions, and driving style. Poor road conditions, such as potholes and speed bumps, can subject shock absorbers to higher levels of deformation. Aggressive driving, such as hard braking and cornering, can increase the forces acting on the shock absorbers, leading to greater deformation.

Figures 4-6 illustrates total deformation profiles for three (3) conventional shock absorber materials including Hard Drawn Spring Wire (A227), Stainless Steel (A313) and Alloy Steel (A213). The total deformation profile in Figures 4-6 are characterised by several colours such as royal blue, sky blue, lemon, yellow and red colours, each representing minimum and maximum total deformation safe values or critical values. These values indicate that the shock absorber material may fail depending on the severity of deformations involved. Therefore, royal blue colour represents the minimum total deformation values, red colour represents maximum total deformation values. However, the colours in between royal blue and red represents the operating range of values that can either be considered high or low depending on their proximity to the said red and royal blue colours. From Figures 4-6, total deformations of 47.603, 54.286 and 49.216 mm were exhibited by hard drawn spring wire (A227), stainless steel (A313) and alloy steel (A213) shock absorber materials. The ability of these shock absorber materials to resist and withstand the loads and forces acting on them during service condition is a function of their tensile yield strength. In this case, hard drawn spring wire (A227) possessed the lowest tensile yield strength of 1591 MPa followed by tensile yield strength of 2068.8 MPa for alloy steel (A213) while stainless steel (A313) had tensile yield strength of 2240.8 MPa. This clearly indicate that shock absorber material with the highest yield tensile strength exhibited the least maximum total deformation among the three materials. This findings are graphically represented in Figure 7, which shows maximum total deformations for the for the three shock absorber materials. Careful observation of the shock absorber total deformation simulated profiles indicate that maximum deformation occurred around the area with concentrated by red colour which is the cylinder. In this case, the design can be altered to distribute the load more evenly, reducing stress concentrations and improving overall performance around this areas.

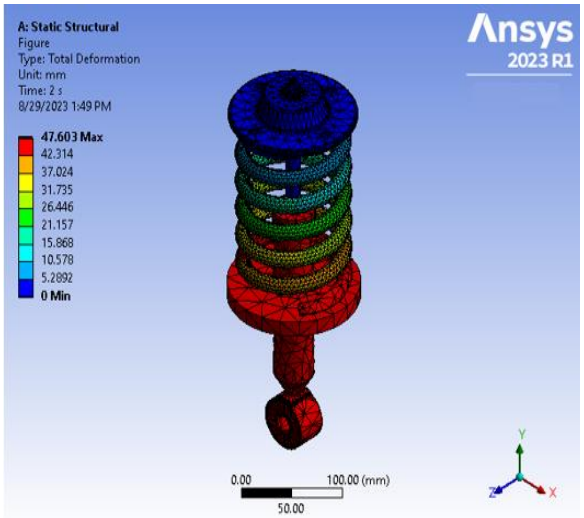


Figure 4. Shock absorber total deformation profile for stainless steel wire (A313)

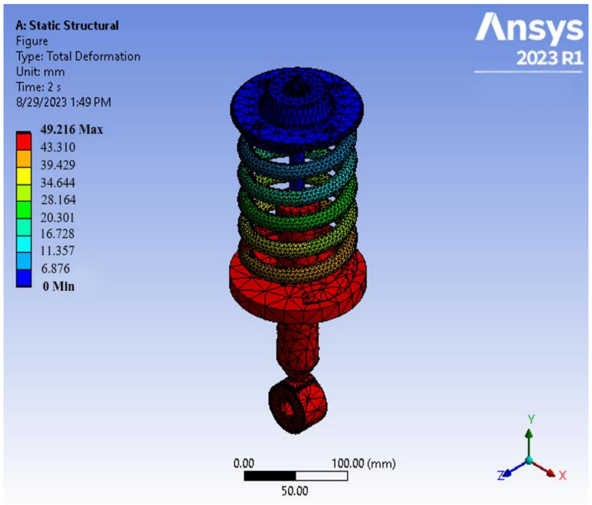


Figure 5. Shock absorber total deformation profile for alloy steel wire (A231)

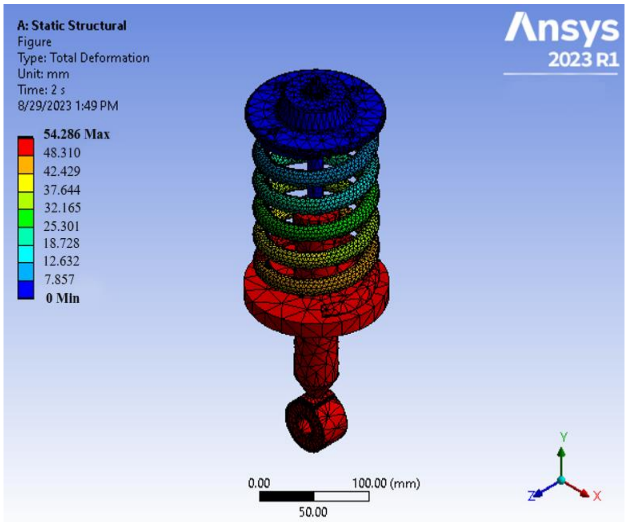


Figure 6. Shock absorber total deformation profile for hard drawn spring wire (A227)

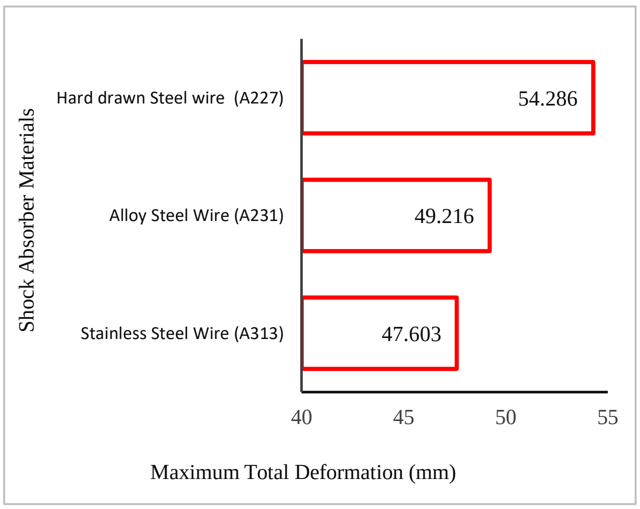


Figure 7. Plot of maximum total deformations for the three shock absorber materials

Similar to the case of total deformation, directional deformation was also analysed statically in this study. The FEA results which illustrates directional deformation profiles for three (3) conventional shock absorber materials including Hard Drawn Spring Wire (A227), Stainless Steel (A313) and Alloy Steel (A213) are presented in Figures 8-10. The same description provided for the significance and characteristics of colour profiles in the case of total deformation also apply to directional deformations.

From Figures 8-10, total deformations of 47.569, 48.762 and 53.303 mm were exhibited by stainless steel (A313), alloy steel (A213) and hard drawn spring wire (A227) shock absorber materials. As mentioned earlier, these shock absorber materials resist and withstand the loads and forces acting on them during service condition due to their tensile yield strength. This is evidence in the yield tensile properties of the materials presented in Table 1. Relationship between the material yield tensile strength property and directional deformation indicates that higher tensile yield strength property is responsible for lower directional strength and vice versa. In this case, it is observed that Hard Drawn Spring Wire (A227) which has the lowest tensile yield strength value of 1591 MPa yielded the highest directional deformation of 53.303 mm. The same findings are applicable to Stainless Steel (A313) and Alloy Steel (A213) shock absorber materials which has tensile yield strength value of 2240.8 as well as 2068.4 MPa, yielded directional deformations of 47.569 and 48.762 mm. Maximum directional deformations for the three shock absorber materials are graphically represented in Figure 11. Like the case of total deformations, the shock absorber directional deformation simulated profiles indicate that maximum directional deformation occurred around the area concentrated by red colour which is the cylinder.

Deformation can lead to changes in the internal hydraulic or mechanical mechanisms of the shock absorber. Increased deformation may result in reduced damping capabilities, leading to a harsher and less controlled ride. Excessive deformation can cause the shock absorber to lose its ability to absorb and dissipate energy effectively. Deformation can also lead to misalignment or binding of components, further compromising performance. Inadequate shock absorber performance due to deformation can negatively impact vehicle stability and handling. Reduced damping capabilities may result in increased braking distances and compromised tire grip on the road. Excessive deformation can lead to premature wear of other suspension components, such as springs and bushings. The overall safety of the vehicle and its occupants can be compromised if shock absorbers are not functioning optimally. Aggressive driving, such as hard braking and cornering, can increase the forces acting on the shock absorbers, leading to greater deformation. In FEA, maximum deformation refers to the highest displacement experienced by a shock absorber model under a given load condition. This parameter provides valuable insights into the structural integrity and potential failure points of the shock absorber. By identifying areas of excessive deformation, engineers can modify the design to ensure that the shock absorber can withstand the expected loads without compromising its performance or safety.

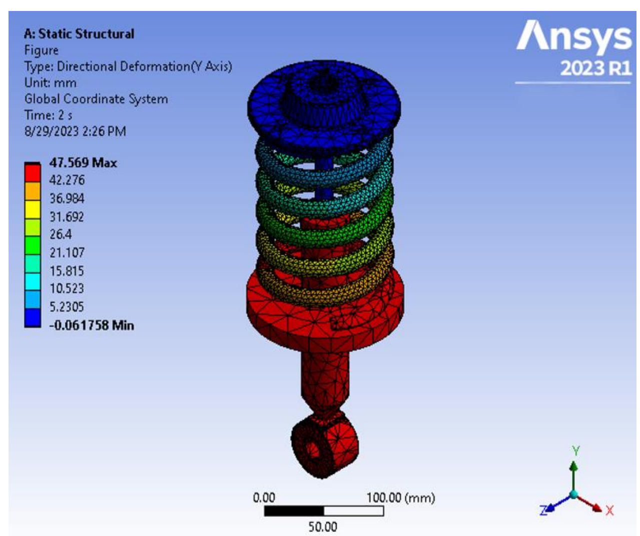


Figure 8. Shock absorber directional deformation profile for stainless steel wire (A313)

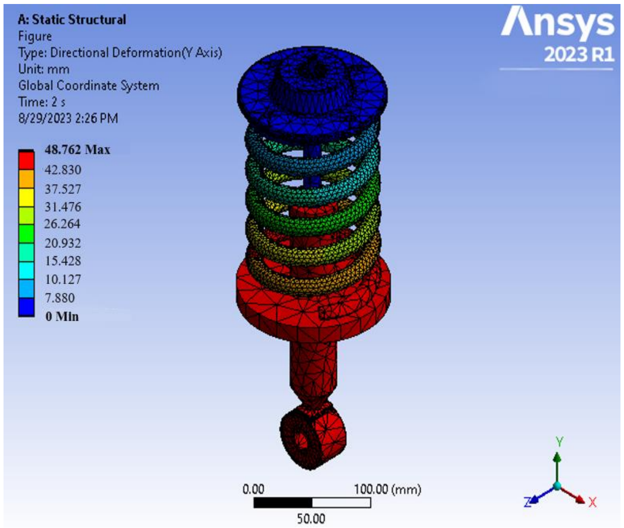


Figure 9. Shock absorber directional deformation profile for alloy steel wire (A231)

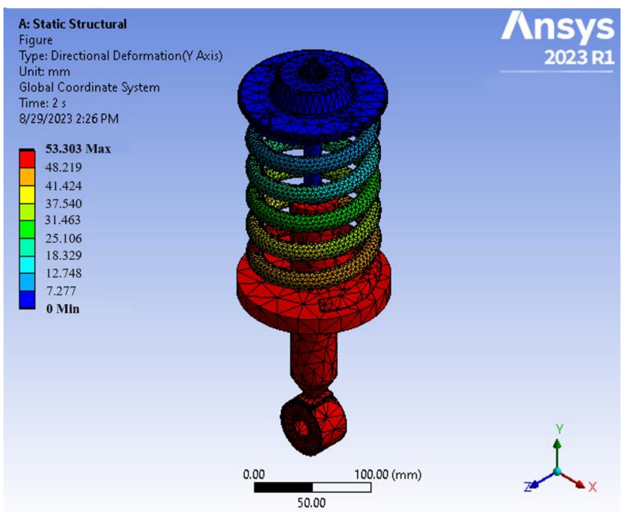


Figure 10. Shock absorber directional deformation profile for hard drawn spring wire (A227)

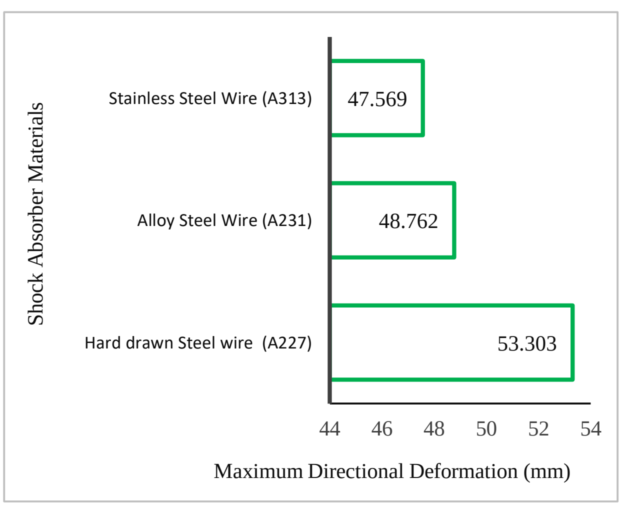


Figure 11. Maximum directional deformations for the three shock absorber materials

The maximum distortion criterion, also known as the von Mises failure criterion, implies that the failure of an elastic material under a constant load commences when the second variable of the deviatoric stress attains a critical stress value. This is governed by plasticity theory which applies primarily to elastic materials such as metals. In this study, the ability of the material to respond to external load conditions prior to deformation is considered visco-elastic, linear elastic, or nonlinear elastic [18, 19]. In this case, von Mises failure was modelled based on von Mises stress theory or equivalent tensile stress after observing that the shock absorber material under intense loading condition began to yield when the von Mises stress of the material attained the yield stress value [20]. In other words, the shock absorber materials are considered to fail if the von mises exceeds the yield strength of the material and vice versa.

The Von-Mises stress failure criterion satisfies the condition where two stress properties with the same distortion energy have the same Von-Mises stress. Von-mises stress profiles were obtained from the shock absorber models which were statically analysed with three different materials namely: Hard Drawn Spring Wire (A227), Stainless Steel (A313) and Alloy Steel (A213). The Von-mises stress profiles consisted of colour bands of royal blue, sky blue, lemon, yellow and red colors, each representing minimum and maximum values. Von-mises stress safe values or critical values at which shock absorber materials can fail depend on whether these Von-mises stress values in question have exceeded the shock absorber material tensile yield strength or not.

From the static analysis shown on the Von-mises stress profile in Figure 12-14, hard drawn spring wire (A227) had maximum equivalent Von-mises stress of 1205.8 MPa with tensile yield strength of 1591 MPa, alloy steel wire (A231) had maximum equivalent Von-mises stress of 1204.7 MPa with yield strength of 2068.4 MPa while stainless steel wire (A313) had maximum equivalent Von-mises stress of 1084.6 MPa with yield strength of 2240.8 MPa. Equivalent Von-mises stress results, seen on Figure 15, obtained from each of the three shock absorber materials indicated that shock absorber material with the highest tensile yield strength value exhibited the lowest equivalent Von-mises stress value under loading condition and vice versa. In this case, stainless steel wire (A313) exhibited the lowest equivalent stress value due to its tensile yield strength which is higher than that of the other two materials.

This findings also applies to the other two materials (hard drawn spring wire (A227) and alloy steel wire (A231)) that were employed in the analysis of this study. Considering the colour distribution across each of the shock absorber, blue and lemon colour dominated the entire profile, indicating that the shock absorbers still had the capacity to accommodate more load, and as well perform optimally under the statically loading conditions. The difference between the tensile yield strength values and maximum equivalent Von-mises stress obtained from each shock absorber material further buttressed that the shock absorber materials can still accommodate more load.

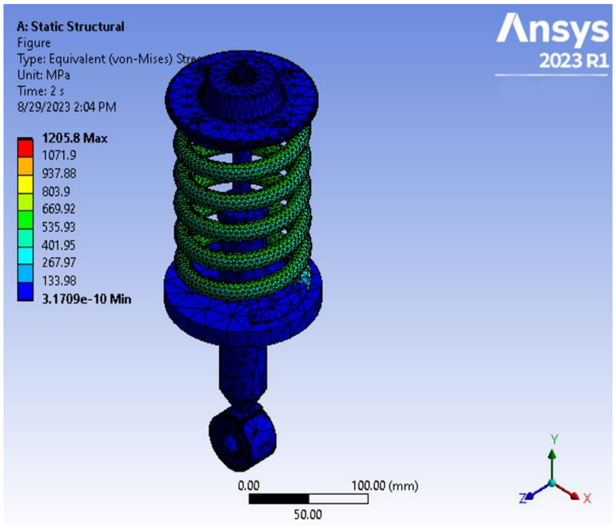


Figure 12. Shock absorber equivalent von-mises stress profile for hard drawn spring wire (A227)

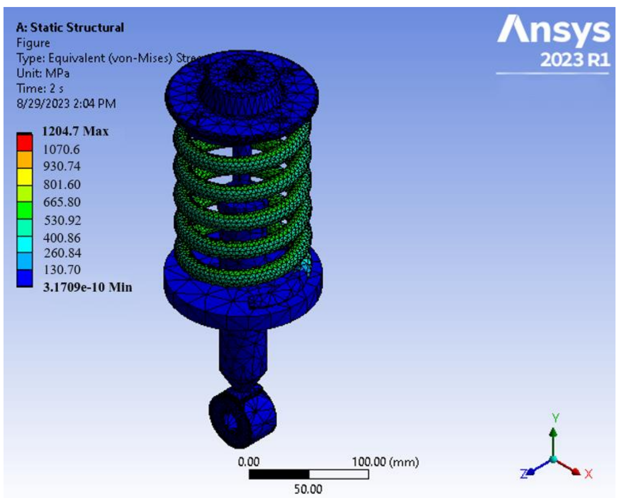


Figure 13. Shock absorber equivalent von-mises stress profile for alloy steel wire (A231)

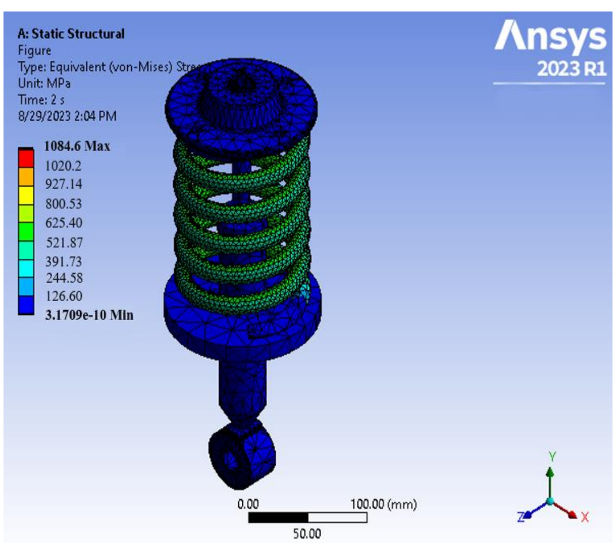


Figure 14. Shock absorber equivalent von-mises stress profile for stainless steel wire (A313)

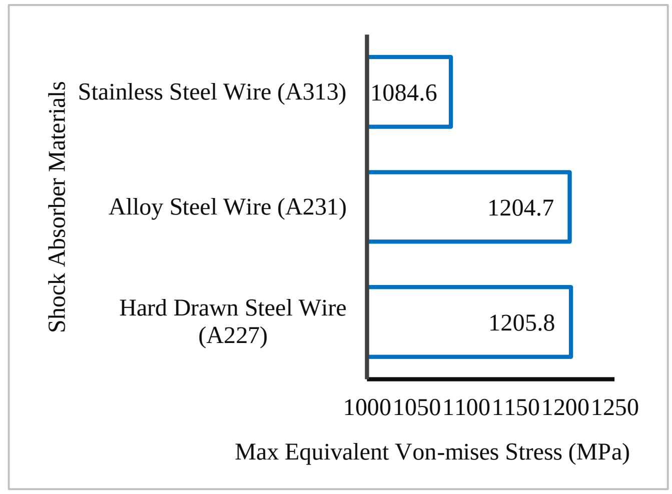


Figure 15. Plot of maximum equivalent von-mises stress for the three shock absorber materials

Static strain deformation is a property that relates to the rate at which a solid body changes or deforms in response to a load or force relative to its length, shape, or geometry. Therefore, if a random deformation mode is used when the normal stress value reaches a critical point, the structure may be exposed to failure, or when the total energy per unit volume exceeds the magnitude of the deformation, the structural unit is vulnerable to failure. From the concept of maximum strain energy, also referred to as octahedral shear stress theory, the absolute strain energy is broken down into static and geometric strain energy. The Static loading can take the form of compression or stretching, which can result in tension of the material, weakening and detaching the atomic bonds in the material's atomic structure and pulling them apart. This phenomenon is called strain elongation [21, 22]. If the loading effect is very intense, atoms in the metallic lattice will slide from their original deformed positions to new equivalent positions in the crystalline structure of the metal, causing permanent plastic deformation. The main reason why atoms slide over each other is related to the theory of dislocations, or defects in the metal crystalline arrangement of atoms [23]. In structural parts such as shock absorber as load-bearing parts, the shock absorber material is also subjected to compression strain elongation under long-term operating conditions, upward as well as the downward motion of the vehicle becomes alternating motion. This can also be caused by thermal expansion when the vehicle is in operating condition, which can be thought of as the equivalent load divided by the temperature change in the shock absorber material. Therefore, as the shock absorber temperatures increase during vehicle operation, this causes increased strain along the bonded areas within the atoms in the metal lattice of the shock absorber material.

Static equivalent strain analysis was carried out on three different materials namely: Hard Drawn Spring Wire (A227), Stainless Steel (A313) and Alloy Steel (A213). Figure 16-18 shows the maximum equivalent elastic strain derived from three shock absorber materials employed in this study, while maximum equivalent elastic strain for the three shock absorber materials are graphically represented in Figure 19. From the static strain profile, Hard Drawn Spring Wire (A227) had maximum equivalent strain of

0.0065269, Stainless Steel (A313) had maximum equivalent strain of 0.0060882 while Alloy Steel (A213) had maximum equivalent strain of 0.0061912. Like the case of Von-mises stress, equivalent strain results obtained from each of the three shock absorber materials showed that shock absorber material with the highest tensile yield strength value produced the lowest equivalent strain value under loading condition and vice versa. None of the three shock absorber materials indicated signs of failure under static loading condition analyzed in this study. This is evidence on the colour profiles (see Figure 16-18) which is predominantly constituted by lemon colour on the coil spring and blue colour on the cylinder, piston rod and strut mount. It should be noted that the blue colour represents minimum equivalent elastic strain value while lemon colour represents values in between minimum and maximum equivalent elastic strain.

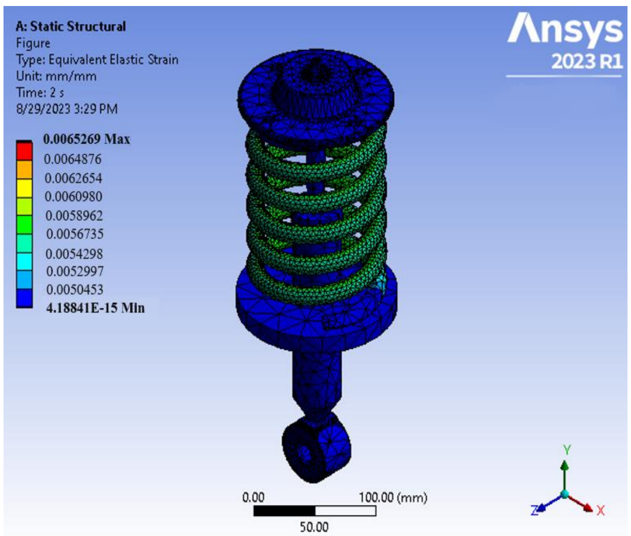


Figure 16. Shock absorber equivalent elastic strain profile for hard drawn spring wire (A227)

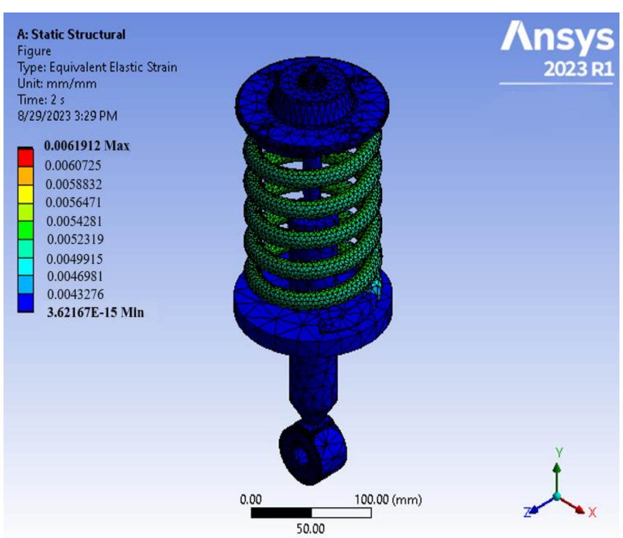


Figure 17. Shock absorber equivalent elastic strain profile for alloy steel wire (A231)

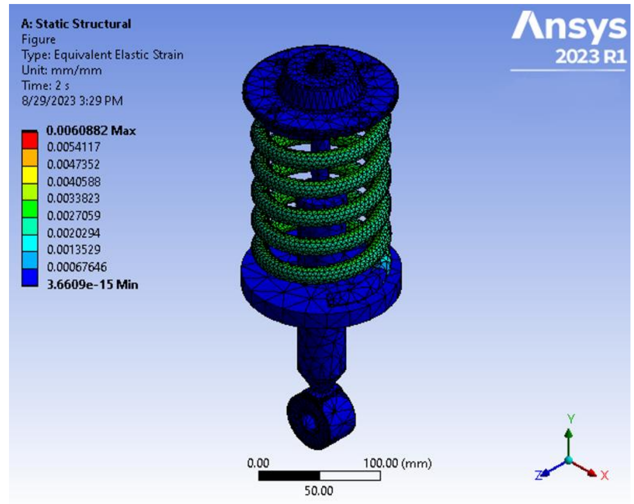


Figure 18. Shock absorber equivalent elastic strain profile for stainless steel wire (A313)

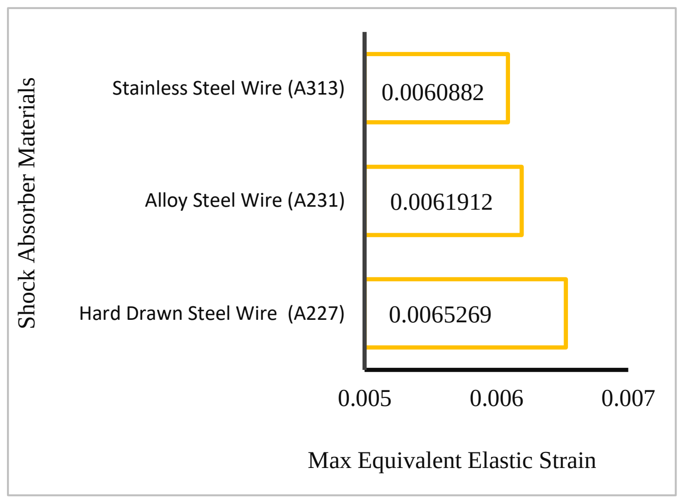


Figure 19. Plot of maximum equivalent strain for the three shock absorber materials

3.1. Preventive Measures for Total and Directional Deformations as well as Equivalent Von-mises stress and Equivalent Elastic Strain on Vehicle Shock Absorbers

Preventive measures for total deformation and directional deformation on vehicle shock absorber are crucial in ensuring the safety and performance of vehicles. Both types of deformation can lead to reduced effectiveness of the shock absorber, resulting in compromised vehicle handling and safety. They can be prevented in the following ways:

i. One preventive measure for total deformation is to regularly inspect the shock absorber for signs of wear and tear. This can include checking for cracks, dents, or other forms of damage that may indicate potential deformation. By identifying and addressing these issues early on, the risk of total deformation can be minimized.

ii. In terms of preventing directional deformation, proper installation and maintenance of the shock absorber and its connecting components is essential. Ensuring that the components are securely fastened and aligned correctly with one another can help prevent excessive stress and strain that may lead to directional deformation. This includes following manufacturer guidelines for installation and regularly checking and replacing worn-out components. Proper maintenance can help prevent premature wear and deformation of the shock absorbers. Additionally, using high-quality materials and components that are designed to withstand the forces and pressures experienced during vehicle operation can also help prevent deformation.

iii. In addition to preventing directional deformation, it is important to drive carefully and avoid rough terrain or aggressive driving maneuvers that can put excessive stress on the shock absorbers. Additionally, using high-quality shock absorbers that are designed to withstand directional forces and pressures experienced during vehicle operation can also help prevent deformation.

iv. Another preventive measure for both total and directional deformation is to avoid overloading the vehicle beyond its recommended capacity. Excessive weight can put undue stress on the shock absorber components, increasing the likelihood of deformation. By adhering to the manufacturer's guidelines for vehicle weight limits, the risk of deformation can be significantly reduced.

Preventive measures for total deformation and directional deformation on vehicle shock absorber are essential for maintaining the safety and performance of vehicles. By regularly inspecting the components, ensuring proper installation and alignment, and avoiding overloading the vehicle, the risk of deformation can be minimized. Implementing these measures can help prolong the lifespan of the shock absorber components and ensure optimal vehicle performance.

On the other hand, preventive measures for equivalent Von-Mises stress and equivalent elastic strains on vehicle shock absorber components are crucial in ensuring the safety and longevity of these critical. The Von-Mises stress and elastic strains are key indicators of the structural integrity and performance of shock absorbers, and excessive levels of these parameters can lead to premature failure and potential safety hazards. They can be prevented in the following ways:

i. One of the primary preventive measures for managing Von-Mises stress and elastic strains on shock absorbers is proper material selection. The choice of materials with high strength, stiffness, and fatigue resistance properties can help reduce stress concentrations and minimize the risk of failure under dynamic loading conditions. Additionally, the use of advanced manufacturing techniques, such as precision machining and heat treatment processes, can further enhance the structural integrity and durability of shock absorbers.

ii. Another preventive measure for controlling Von-Mises stress and elastic strains on vehicle shock absorbers is proper design. The shock absorber should be designed to withstand the expected loads and operating conditions. Additionally, the design should incorporate features such as reinforcements, fillets, and stress-relieving features to distribute the stress and strains more evenly and reduce the likelihood of failure.

iii. Another important preventive measure is regular inspection and maintenance of shock absorbers. Periodic visual inspections and performance testing of the shock absorber can help identify potential issues, such as corrosion, fatigue cracks, wear, or damage before they escalate into more serious problems. Timely replacement of worn or damaged components can help prevent excessive stress and strain levels from compromising the overall performance and safety of the shock absorber system. Proper maintenance, such as lubrication and adjustment, can also help prolong the life of the shock absorber and prevent excessive stress and strains from developing.

iv. Furthermore, proper design and engineering practices play a critical role in preventing excessive Von-Mises stress and elastic strains on shock absorbers. The use of finite element analysis (FEA) and computer-aided design (CAD) tools can help optimize the design and geometry of shock absorbers to minimize stress concentrations and improve load distribution. Additionally, incorporating safety factors and design margins can help ensure that shock absorbers can withstand the expected operating conditions and potential variations in loading.

Preventive measures for managing equivalent Von-Mises stress and elastic strains on vehicle shock absorbers are essential for ensuring the reliability and safety of the suspension system. By implementing proper material selection, regular inspection and maintenance, and sound design practices, manufacturers and engineers can mitigate the risk of premature failure and enhance the performance and longevity of shock absorber systems. Ultimately, prioritizing preventive measures can help optimize the overall performance and safety of vehicle suspension systems, contributing to a smoother and more comfortable driving experience.

3.2. Augmentation of Vehicle Shock Absorbers

Shock absorbers are an essential component of a vehicle's suspension system, responsible for dampening the impact of bumps and vibrations on the road. The performance of shock absorbers directly affects the comfort, stability, and safety of the vehicle. In recent years, there has been a growing interest in augmenting vehicle shock absorbers to improve their performance and efficiency. The augmentation of vehicle shock absorbers can lead to significant benefits in terms of ride comfort, handling, and overall vehicle performance. These are discussed in the following highlights:

i. Improved Ride Comfort: One of the primary reasons for augmenting vehicle shock absorbers is to improve ride comfort. Traditional shock absorbers are designed to absorb and dissipate energy from bumps and vibrations, but they may not always provide a smooth and comfortable ride. By augmenting shock absorbers with advanced technologies such as adaptive damping systems or electronic control units, vehicle manufacturers can tailor the damping characteristics to suit different driving conditions and road surfaces. This can result in a more comfortable and refined ride for passengers, especially over rough or uneven terrain.

ii. Enhanced Handling and Stability: In addition to improving ride comfort, augmented shock absorbers can also enhance vehicle handling and stability. By adjusting the damping force in real-time based on factors such as vehicle speed, steering input, and road conditions, augmented shock absorbers can help improve cornering performance, reduce body roll, and enhance overall stability. This can lead to a more engaging and dynamic driving experience, as well as improved safety and control in emergency situations.

iii. Increased Performance and Efficiency: Another benefit of augmenting vehicle shock absorbers is the potential for increased performance and efficiency. By optimizing the damping characteristics of the shock absorbers, vehicle manufacturers can improve the overall performance of the suspension system, resulting in better traction, reduced tire wear, and improved fuel efficiency. Additionally, augmented shock absorbers can help reduce the impact of road noise and vibrations on the vehicle, leading to a quieter and more comfortable driving experience.

The augmentation of vehicle shock absorbers can lead to significant benefits in terms of ride comfort, handling, and overall vehicle performance. By incorporating advanced technologies and control systems into shock absorbers, vehicle manufacturers can tailor the damping characteristics to suit different driving conditions and improve the overall driving experience for passengers. As the automotive industry continues to evolve, the augmentation of vehicle shock absorbers will play an increasingly important role in enhancing the comfort, stability, and efficiency of vehicles on the road.

4 Conclusions

The stress-strain deformation of vehicle shock absorbers plays a crucial role in ensuring the safety and performance of vehicles. This study explored the various factors that contribute to stress and strain in shock absorbers, including the material properties, design considerations, and operating conditions. By understanding these factors, manufacturers and engineers can make informed decisions to optimize the performance and durability of shock absorbers. One key finding is that the material properties of shock absorbers significantly influence their stress-strain deformation. The choice of materials, such as steel or alloys, can impact the overall strength and stiffness of the shock absorber. Additionally, the manufacturing process and heat treatment techniques can further enhance the material properties, reducing the risk of failure under extreme conditions. Furthermore, the design considerations of shock absorbers also play a vital role in managing stress and strain. Factors such as the size, shape, and geometry of the shock absorber can affect its ability to withstand external forces and absorb energy. Additionally, the presence of features like grooves, ribs, or reinforcements can enhance the structural integrity and reduce stress concentrations. Operating conditions, including the vehicle's weight, speed, and road conditions, also contribute to stress and strain in shock absorbers. Heavy loads and rough terrains can subject the shock absorbers to higher stress levels, potentially leading to premature failure. Therefore, it is crucial to consider these factors during the design and selection of shock absorbers to ensure their optimal performance and longevity. Based on the findings discussed above, several recommendations can be made to improve the stress-strain deformation of vehicle shock absorbers:

i. Material Selection: Manufacturers should carefully select materials with appropriate strength and stiffness properties for shock absorbers. Conducting thorough material testing and analysis can help identify the most suitable materials for specific applications.

ii. Manufacturing Process: Employing advanced manufacturing techniques, such as precision machining and heat treatment, can enhance the material properties and reduce the risk of stress and strain deformation. Strict quality control measures should be implemented to ensure consistent production.

iii. Design Optimization: Engineers should focus on optimizing the design of shock absorbers to minimize stress concentrations and improve overall structural integrity. Utilizing computer-aided design (CAD) software and conducting finite element analysis (FEA) can aid in identifying potential weak points and optimizing the design accordingly.

iv. Regular Maintenance: Vehicle owners should adhere to regular maintenance schedules, including inspecting and replacing worn-out shock absorbers. This will help prevent excessive stress and strain on the components, ensuring their optimal performance and longevity.

v. Road Infrastructure: Governments and road authorities should invest in improving road infrastructure to minimize the impact of rough terrains and potholes on shock absorbers. Well-maintained roads can significantly reduce stress and strain on vehicles, enhancing their overall safety and performance.

vi. Other failure mechanisms such as fatigue, bending, buckling, corrosion, etc. should also be investigated. This can form a broad body of knowledge on shock absorber failures and prolongment of its duty cycle.

In conclusion, stress-strain deformation in vehicle shock absorbers is a critical aspect that requires careful consideration. By implementing the recommendations mentioned above, manufacturers, engineers, vehicle owners, and road authorities can collectively contribute to the improved performance, durability, and safety of shock absorbers in vehicles.

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