Shock Absorber Made of Natural Rubber for Motorcycle

Veasna Mann

A Thesis Submitted in Fulfillment of the Requirements for the Degree of Master of Engineering in Mechanical Engineering

Prince of Songkla University

2019

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Author Mr. Veasna Mann
Major Program Mechanical Engineering

Major Advisor	**Examining Committee:**
………………………………..................	……..……………………. Chairperson
(Assoc.Prof.Dr.Charoenyut Dechwayukul)	(Asst.Prof.Dr.Watthanaphon Cheewawuttipong)
	……..……………….…….. Committee
Co-advisor	(Assoc.Prof.Dr. Charoenyut Dechwayukul)
………………………………..................	………….………………...Committee
(Assoc.Prof.Dr. Wiriya Thongruang)	(Assoc.Prof.Dr.Wiriya Thongruang)
………………………………..................	…..……………………...Committee
(Asst.Prof.Dr. Pornsiri Kaewpradit)	(Asst.Prof.Dr. Passakorn Vessakosol)

The Graduate School, Prince of Songkla University, has approved this thesis as fulfillment of the requirements for the Master of Engineering Degree in Mechanical Engineering.

…………………………………………
(Prof. Dr. Damrongsak Faroongsarng)
Dean of Graduate School

This is to certify that the work here submitted is the result of the candidate’s own investigations. Due acknowledgement has been made of any assistance received.

……………………………….……… Signature
(Assoc.Prof.Dr. Charoenyut Dechwayukul)
Major Advisor

….……………………………………. Signature
(Mr. Veasna Mann)
Candidate

I hereby certify that this work has not been accepted in substance for any degree, and is not being currently submitted in candidature for any degree.

…...…………………………………. Signature

(Mr. Veasna Mann)

Candidate

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ABSTRACT

The objective of this research is to design and fabricate the lightweight shock absorber made of natural rubber for motorcycle which has the stiffness and damping property like the commercial shock absorber. The study was carried out in four main steps. Firstly, the commercial shock absorber was tested for its damping and spring stiffness property. Secondly, the rubber material was formulated and tested to obtain the desired mechanical properties. Thirdly, the shock absorber made of natural rubber was designed and analyzed using the finite element method to investigate the corresponding to commercial shock absorber model. Finally, the prototype of the shock absorber made of natural rubber was fabricated and tested. The results of the prototype testing showed that the weight of the shock absorber made of natural rubber was lower than the commercial shock absorber about 25%. The damping and stiffness property of the shock absorber made of natural rubber was different from the commercial shock absorber around 11% and 9%, respectively. The implementation of the shock absorber made of natural rubber in the real motorcycle and its further fatigue life tested with different frequencies should be studied in the future.

Keywords: Shock absorber, Natural rubber, Stiffness property, Damping property

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Veasna Mann

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CHAPTER 1
INTRODUCTION

Millions shock absorbers are produced every year to supply the market demand of automotive industry. Right now, there are many well-known brands of shock absorber are using for motorcycle, car, and truck such as Ohlins, KYB, Manitou, KONI, Fox Racing, Skyjacker, etc. Those commercial shock absorbers are designed for a specific requirement of automobile and their price are generally high depend on each brand. The light-weight shock absorber would still be required to reduce body loading of automotive.

The shock absorber made of natural rubber are designed to be lighter in weight and more flexible in use. The rubber shock absorber is mainly composed of rubber pads and aluminium plates. Each rubber pad and aluminium plate are assembled independently. This concept provide the ease of maintenance and it can be used with many different brands of motorcycle.

1.1 Introduction to Background of Study

1.1.1 Vibration Theory

A vibration is a repeated motion of a system around its equilibrium point over a period of time. Based on the source of vibration, it is categorized into two types such as free vibration and forced vibration. Both free and forced vibration can be divided into two groups like damped vibration and undamped vibration.

Free vibration when a system oscillates itself without external force after its initial disturbance, for example, a pendulum system.

Forced vibration when a system is kept oscillated by subjected to an external force.

Damped vibration when there is an energy lost during oscillation by a friction or a resistance. A damper is usually added into a system. An oscillation amplitude of a system is gradually degreased by the time until a system become stable, for example, a shock absorber.

Undamped vibration when there is no energy lost during the oscillation. A system is continuously oscillated overtime with the same amplitude. It is hard to find an undamped vibration system in a real life except some frictions like air are ignored [John, C.D., 2007, & Singiresu, S.R, 2011].

There is only forced vibration damped recalled here. Figure 1 represents a model of damped (1-dof) vibration system subjected to an external harmonic force.

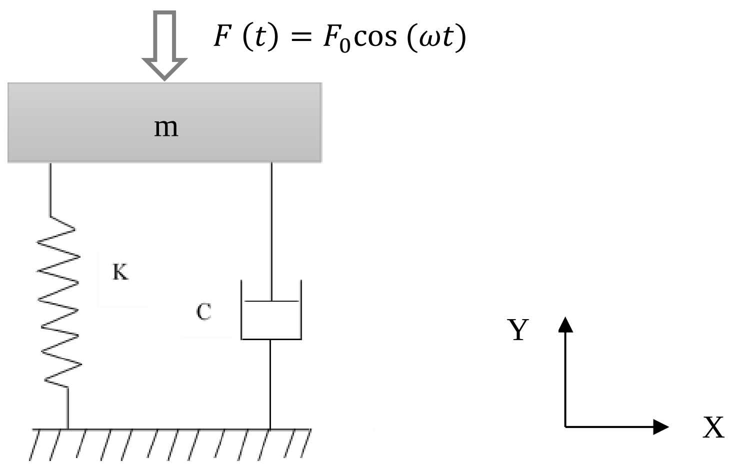


Figure 1 Damped 1-dof system under harmonic force

The system consists of an object with mass of m, a spring element with constant K and a damper with damping coefficient C. When a system is subjected to an external harmonic force $F\ (t) = F_0\cos\ (\omega t)$ in y direction, the equation of the motion becomes [Singiresu, S.R, 2011]

$$m\ddot{y} + c\dot{y} + ky = F_0 cos(\omega t) \tag{1}$$

The particular solution of the equation (1) will be the form of,

$$y_p(t) = Y sin(\omega t - \varphi) \tag{2}$$

Y and φ refers to the amplitude and phase angle of the response, respectively. The amplitude Y will be the form of

$$Y = \frac{F_0}{\sqrt{(k - m\omega^2)^2 + (c\omega)^2}}$$

$\varphi = tan^{-1}\left(\frac{c\omega}{k-m\omega^2}\right) = tan^{-1}(\frac{2\xi r}{1-r^2})$, ($r = \frac{\omega}{\omega_n}$ denotes a frequency ratio)

With $\omega_n = \sqrt{\frac{k}{m}}$ is undamped natural frequency,

$\xi = \frac{C}{C_c} = \frac{C}{2m\omega_n} = \frac{c}{2\sqrt{mk}}$ is a damping ratio, (c denotes a damping coefficient)

If $\xi = 0$ the system is undamped.

$0 < \xi < 1$ the system is underdamped.

$\xi = 1$ the is system is critical damped.

$\xi > 1$ the system is overdamped.

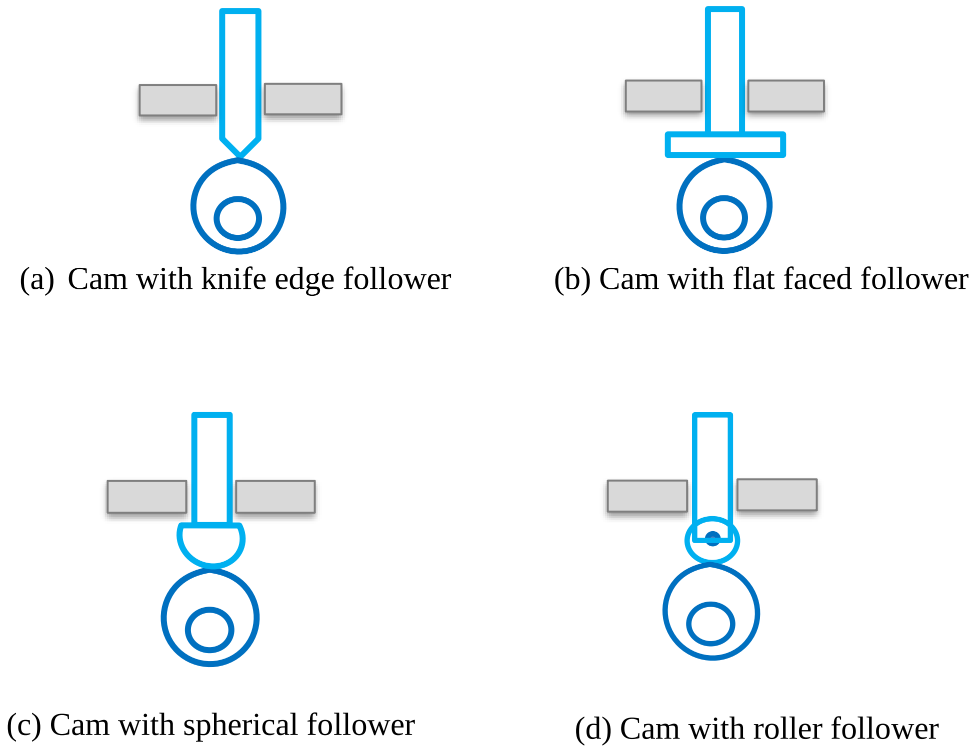
1.1.2 Cam Analysis Theory

A cam is a mechanical machine used in converting a rotary motion to a linear motion. It specially transmits an oscillation motion rotated by a shaft directly to a follower. The application of cam can be found in intake and exhaust valve of internal combustion engines, paper cutting machine, feed mechanism of automatic lathes, so on. There are two important types of cam such as a disc or radial cam and a cylindrical cam [Khurmi, R.S., 2015].

- Disc cam: a follower oscillates perpendicular to the cam axis.
- Cylindrical cam: a follower oscillates parallel to the cam axis.

Based on the surface contact, a follower is divided into four types like knife edge follower, roller follower, flat faced follower, and spherical follower.

- Knife edge follower in figure 2(a): a follower has a sharp knife edge. Due to its small contacting surface, it is rarely used in practice.
- Flat faced follower in figure 2(b): follower has a completely flat contact surface. Sometime is called a mushroom follower. This kind of follower is used where a space is limited like a valve of automotive engine.
- Spherical faced follower in figure 2(c): a follower has a spherical shape. It is used when the high surface stress is needed to be minimized.
- Roller follower in figure 2(d): a follower has a contacting end in roller shape. The roller follower is used in stationary gas, oil engine, aircraft engine, etc.



(a) Cam with knife edge follower (b) Cam with flat faced follower

(c) Cam with spherical follower (d) Cam with roller follower

Figure 2 Type of cam follower

For the simple harmonic motion, the rise and return function of the cam will be the form of [Michael, M.J., 2009],

- Rise: $\theta_0 \leq \theta \leq \theta_1$

$$s = b + \frac{h}{2}\left(1 - cos\frac{\pi}{\beta}(\theta - \theta_0)\right), \tag{3}$$

$$s' = \frac{h}{2}\frac{\pi}{\beta}sin\frac{\pi}{\beta}(\theta - \theta_0), \tag{4}$$

$$s'' = \frac{h}{2}\left(\frac{\pi}{\beta}\right)^2 cos\frac{\pi}{\beta}(\theta - \theta_0) \tag{5}$$

- Return: $\theta_1 \leq \theta \leq \theta_2$

$$s = h_0 - \frac{h}{2}\left(1 - cos\frac{\pi}{\beta}(\theta - \theta_1)\right), \theta_1 \leq \theta \leq \theta_2 \tag{6}$$

$$s' = \frac{h}{2}\frac{\pi}{\beta}sin\frac{\pi}{\beta}(\theta - \theta_0), \tag{7}$$

$$s'' = -\frac{h}{2}\left(\frac{\pi}{\beta}\right)^2 cos\frac{\pi}{\beta}(\theta - \theta_1) \tag{8}$$

With s = displacement of the cam,

b = radius of the base circle,

h_0 = radius at the start of the return,

h = stroke of follower at the rise or the return,

θ_0 = starting angle of the rise,

θ_1 = starting angle of the return,

$\beta = \theta_1 - \theta_0$ = angular range of the rise,

$\beta = \theta_2 - \theta_1$ = angular range of the return

1.1.3 Finite Element Analysis Theory

Any engineering problems can be solved by three ways such as by using analytical method, numerical method, and experimental method [Nitin, S. G., et al., 2008]. An analytical method is a classical approach which the problem is solved by a specific mathematic formula. This method gives 100% of accuracy but it can be applied to a simple problem only. A numerical method is a mathematical method which a solution of the problem is approximated. This method is used in complex problem that it cannot be solved by an analytical method. The result from numerical method is not 100% accurate. It needs to be verified with experimental method hand calculation to know the percentage of its error. On the other hand, experimental method is an actual experiment. The result needs to be verified with at least 3 prototypes of testing. This method is time consuming and it needs many experimental equipment to capture the data from testing.

There are several approaches of numerical method like finite element method, finite volume method, finite different method, boundary element method. Finite element method deals with buckling, fatigue, dynamic, thermal, linear, and nonlinear analysis, etc. On the other hand, finite volume method is applied in CFD and computational electromagnetic. For finite different method is used to analyse a problem of thermal & fluid flow. Yet, boundary element method usually solves an NVH and acoustic analysis.

A finite element analysis is a numerical method for solving the engineering problem by discretize a whole body of object to smaller units called finite element and the solution will be carried out at its interconnected point called node [Daryl, L.L., 2007; Liu, G. R., & Quek, S.S., 2013]. The advantages of the finite element method includes: easily solve a complex shape bodies, be able to deal with many load and boundary conditions, possible to model in different materials, time and cost cutting, etc.

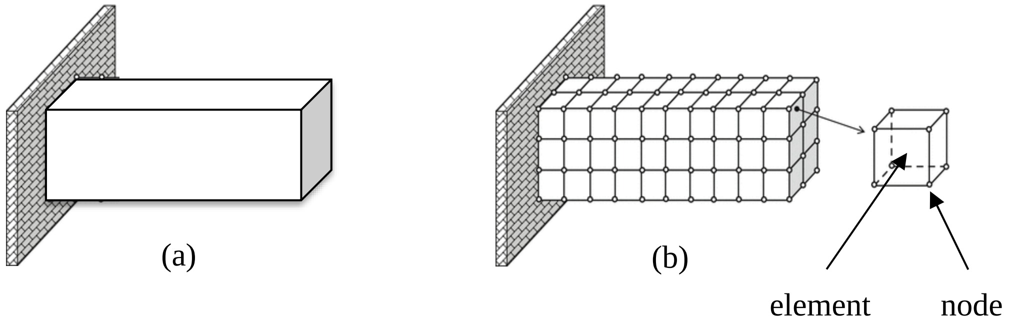


Figure 3 (a) Beam in 3D solid; (b) Beam element in hexahedron mesh

There are 8 steps to solve a finite element analysis.

1. Discretization and element type selection

   Body is divided into small units and element type is needed to be selected. Choosing an appropriate element is very important to the result accuracy. Element need to be small enough to give an acceptable result but large enough to reduce the computer performance effort. Element is categorized into three types:

   a). 1-D or line element

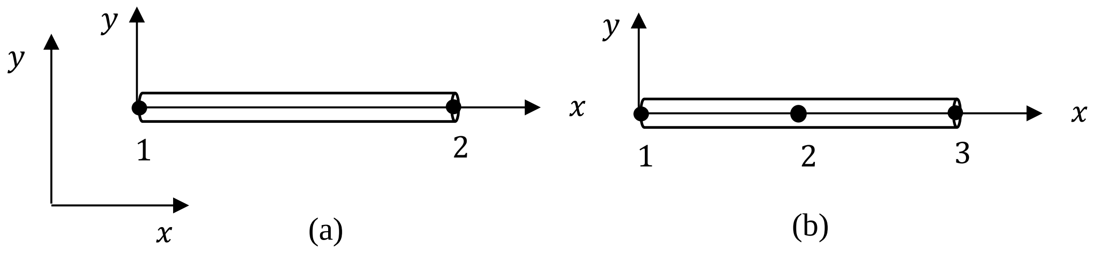


Figure 4 (a) 1D element with 2 nodes; (b) 1D element with 3 nodes b). 2-D element

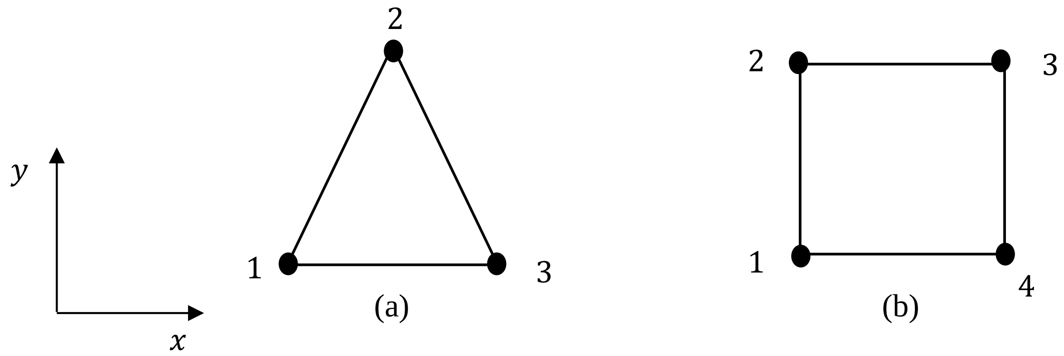


Figure 5 (a) 2D triangular element with 3 nodes; (b) 2D quadrilateral element with 4 nodes

c). 3-D element

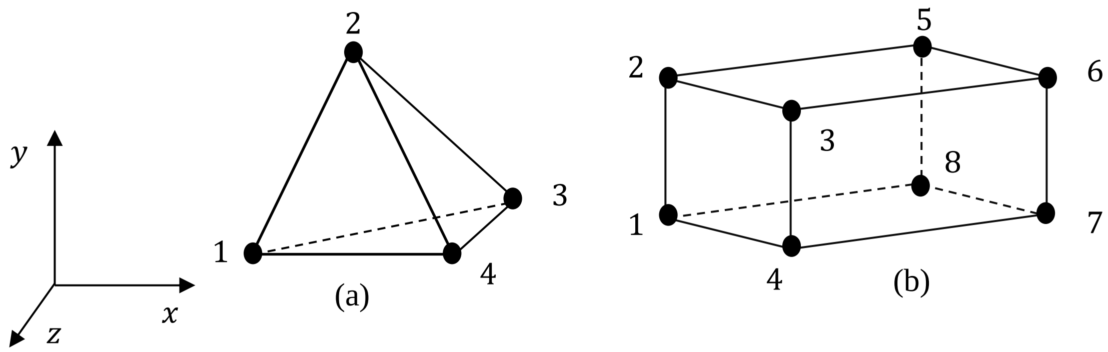


Figure 6 (a) 3D tetrahedral element with 4 nodes;

2. Displacement function selection

A function is chosen at the nodal point of element. Simple function like linear, quadratic, cubic polynomials, and trigonometric function are usually used. It is expressed in the function of an x and y for 2D model, and x, y, z for 3D model in term of nodal unknown.

3. Strain/Displacement and Stress/Strain Relationship

Equation of element is expressed in strain and displacement relationship or stress and strain relationship. For one direction (x) deformation, the strain-displacement and stress-strain relationship is expressed in form of,

$$\varepsilon_x = \frac{du}{dx} \tag{9}$$

Where ε_x denotes a strain in x direction.

$$\sigma_x = E\varepsilon_x \tag{10}$$

Where σ_x is a stress in x direction of deformation and E is an elastic modulus.

4. Derive the Element Stiffness Matrix and Equations

The relationship of strain and displacement with stiffness at each node of element is expressed in term of matrix form. Figure 7 represents a spring element with two nodes and local stiffness k along a $\hat{x}$ axis. the local force and local displacement are denoted by $\hat{f}_{1x}$ and $\hat{d}_{1x}$ for node 1 and $\hat{f}_{2x}$ and $\hat{d}_{2x}$ for node 2.

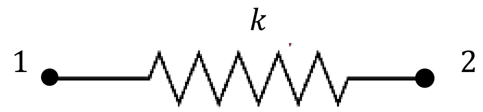


Figure 7 Spring element with 2 nodes and stiffness k

$$\begin{Bmatrix} \hat{f}_{1x} \\ \hat{f}_{2x} \end{Bmatrix} = \begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \begin{Bmatrix} \hat{d}_{1x} \\ \hat{d}_{2x} \end{Bmatrix} \tag{11}$$

5. Assemble the Element Equation to Obtain the Global Equation

Every single equation at each node is assembled into global equation. $\{F\}$ denotes a total force matrix, $[k]$ is for global stiffness matrix, and $\{d\}$ is an unknow or known generalized displacement.

$$\{F\} = [k]\{d\} \tag{12}$$

6. Solve for the Unknown Generalized Displacements

The global equation of boundary condition can be expanded in matrix form as

$$\begin{Bmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{Bmatrix} = \begin{bmatrix} K_{11} & K_{12} & \dots & K_{1n} \\ K_{21} & K_{22} & \dots & K_{2n} \\ \vdots & & & \vdots \\ K_{n1} & K_{n2} & \dots & K_{nn} \end{bmatrix} \begin{Bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{Bmatrix} \tag{13}$$

The equation can be solved by using Gaussian elimination method or Gauss-Seidel Iteration method.

7. Solve for the Unknown Generalized Displacements

   Some engineering problems like structure analysis it is necessary to find stress and strain. Stress can be a principle stress, a von mises stress or a shear stress.

8. Interpret the Result

   Finally, the result needed to be interpreted for using in analysis or design decision. It is necessary to show the location of maximum stress and displacement of structure
subjected to a loading condition.

Using computer software, finite element analysis is usually processed into three steps:

a) Pre-processing: all tasks like CAD, material assigning, boundary condition, load, type of analysis, meshing, etc. are carried out in this step.
b) Processing: computer will be responsible for this stage. Using small mesh might make much computational effort.
c) Post-processing: the result is visualized in this step. The user can modify their analysis based on the result given. Some necessary works are done in this step including checking displacement or stress amplitude, factor of safety, strain energy, animate behaviour of dynamic model, so on.

1.1.4 Introduction to Shock Absorber

A shock absorber, commonly known as a hydraulic pump used to control overshoot vibration force affected to the springs or suspension system in a vehicle for keeping the driving condition more stable and comfortable. The shock absorber works by converting a kinetic energy from shock effect when the car meet a bump on a road to a thermal energy and then dissipating those energies into the atmosphere through a heat exchanger mechanism. There are several types of shock absorber are invented and used in the automotive industry like scissor shock absorber, snubber shock absorber, lever-arm shock absorber and telescopic shock absorber. Now a day, only hydraulic telescopic shock absorber remains popular in the automotive industry because of its better life on wearing road surface, consistency of performance, cost effective, so on.

Shock absorber generally consists of two main parts are spring and dashpot. Spring has a function to absorber a force or energy applied from the external impact and a dashpot contained fluid it plays a main role to reduce an oscillation amplitude of the motion of a suspension system or an automotive body. The most important parameters of shock absorber for mechanical engineering design are stiffness of spring (K) and damping constant of the dashpot (C). Stiffness is a resistance of the spring responded to the deformation and damping (viscous damping) is an internal friction of fluid element of the dashpot to resist the motion of a system. There are two types of hydraulic shock absorber including mono-tube shock absorber and twin-tube shock absorber. Mono-tube shock absorber consists of single shell case working as a tube that contains oil, gas, piston valve, etc. A free piston in mono-tube shock absorber separates cylinder into two parts are one for oil chamber and other part for gas chamber. When an external force is compressed, the free piston moves down and create high pressure in the gas chamber and it will be gradually rebounded back when the external force is removed. On the other hand, a twin-tube shock absorber has two sperate tubes are cylinder inside and shell case outside. There is no free piston in twin-tube shock absorber. A piston valve and other parts are inside inner cylinder. When it is compressed, oil in inner cylinder moves to the outer shell where the pressure is rise.

1.1.5 Introduction to Natural Rubber

A natural rubber, generally from a Hevea brasiliensis tree, is an elastomer from isoprene polymers (poly-cis-1.4-isoprene) whose chemical structure contains longs and regular molecule chains. Their segment can move along each other and freely rotate around simple chemical bonds at the low temperature. The number of cis-1, 4-polyisoprene, figure 8, consists of from 10,000 to 10,000,000 units [Rubber Chemistry, 2007].

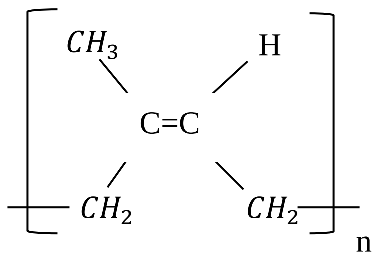


Figure 8 Chemical view of poly-cis-1.4-isoprene

- Mechanical Property of Natural Rubber

The natural rubber has two outstanding properties are hyperelasticity and viscoelasticity. A hyper-elastic property is an ability to undergo a large deformation under tensile load while a viscoelasticity is an ability to absorb energy form an external shock. Natural rubber has a large deformation. It can be elongated until 500% under tensile load. When a natural rubber is stretched, its molecule chains are straightened and aligned. When the stress is released, the chains returns to the original state [Callister, W. D., 2010].

When the rubber is subjected to the loading condition, it stores energy (W1) and it returns some part of energy when it is unstressed (W2). The energy lost (W3) is dissipated into the atmosphere in form of heat [Chai, A., Shamsul, K., et al., 2016]. The area of energy lost is called hysteresis loop. This phenomenon is a result of viscoelastic behaviour of the natural rubber. The energy absorption capacity of rubber-like material can be expressed in term of hysteresis lost ratio, γ = W3/W1, in figure 9.

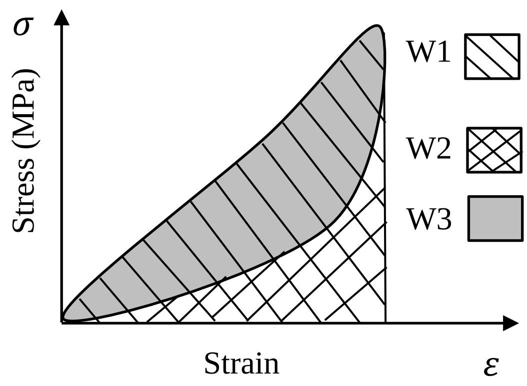


Figure 9 Definition of energy absorption of natural rubber

Another special viscoelastic behaviour of natural rubber is a stress softening or Mullins effect. When rubber-like material is subjected to repeated load, the force required to extend the material at the same strain for the next cycle of deformation is required lower. Mullins effect is usually happened at the first deformation after that the hysteresis loop remains stable [Rebouah, M. & Chagnon, G., 2013].

- Rubber Formulation

Rubber formulation is a process of adding chemical substances to a raw material to get a desired property of rubber. There are seven important substances always use in rubber formulation process including raw rubber material [Limper, A., 2012].

- Raw material (natural rubber): natural rubber commonly used are STR20 or SMR20, RSS1, RSS3. Every type of natural rubber is different on its percentage of dirty, amount of chemical composition, property, etc.
- Activator: an additive chemical used to increase effectiveness of accelerator, state of cure, filler dispersion, and enhance cross-link density of rubber vulcanization. The common activators used in rubber industries are zinc oxide and stearic acid.
- Accelerator: a substance used to speed up the vulcanization or curing process of rubber compound. It can also improve aging properties of

rubber and some accelerators have function the same as a sulfur. Accelerator is classified into two types are primary accelerator and secondary accelerator. Most popular accelerators used in industry are MBT or MBTS.

- Anti-degradant: a chemical ingredient used to increase aging of rubber. It protects rubber product from environment effect. Anti-degradant includes antioxidant and antiozonants. Some important anti-degradants are 6PPD, MTQ, and Winstay L.
- Plasticizer: an additional ingredient used to improve elastic property, flexibility of rubber, and dispersion of filler. The plasticizer can be oil, fatty acid, polyester, etc.
- Filler: a reinforcement ingredient used to improve mechanical properties of rubber like strength, hardness, and energy dissipation, etc. Some commonly fillers include carbon black, silica, clay, calcium carbonate, so on.
- Curing agent (sulfur): one of the most important ingredients in rubber compound used to bond a crosslink between rubber molecules.

Rubber compounding can be processed in both internal mixer and open roll mill.

- Rubber Vulcanizing

Rubber curing or vulcanizing is a chemical process to form a cross-link between each molecule chain of rubber. The most practical curing agent of rubber vulcanization is sulfur. The Sulfur is added into a rubber compound with other chemical additions and it is heated under a specific temperature and time depending on thickness and chemical composition of the rubber compound. MDR testing can be used to determine the curing time and temperature for rubber compound. The process is commonly carried out inside the mould in a hot press machine [Vergnaud, J.M., & Rosca., L.D., 2008].

- Mechanical Properties Testing of Rubber Material

Mechanical properties like tensile strength, hardness, compression set, ozone test, etc. of rubber material are determined by testing. Polymer or rubber is tested for some reasons like for quality control, prediction product performance, providing product design data, and investigating failure, so on [Brown, R., 2002]. The standard of testing can be followed international organization, national organization, or individual company. Most of mechanical testing of polymer or rubber is available in ASTM standard. In real world application, rubber products are subjected to compression, shear, and tension loading.

- Tensile Test

  A tensile test is frequently used in rubber testing. The tensile test allows engineer or scientist to measure tensile stress or strain, tensile yield stress, elongation at rupture, etc. Tensile test of rubber is followed the standard of ASTM D412 [ASTM D412, 2016]. ASTM D412 has two methods, method A and method B. Method A uses a dog bone or dumbbell specimen with 25 mm in width, 115 mm in length, and around 2mm in thickness. The speed of testing is 500mm/min while method B used a rubber ring specimen. Method B is not commonly used in a real practice.

- Compression Test

  Compression test in rubber is used to determine the compressive deflection or stiffness of rubber. The testing is followed the standard of ASTM D575. The testing has two methods. Method A is a testing for specific deflection. The desired deflection is set, and the force is applied to reach that deflection. On the other hand, method B is the test at specific force and the deflection is measured. The test specimen has a diameter of 28.60±0.1mm, and a thickness of 12.5±0.5 mm as shown in figure 10. The testing speed required is 12±3 mm/min.

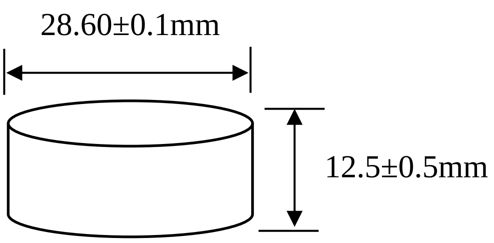


Figure 10 Cylindrical specimen for ASTM 575

- Fatigue Test

  Under repeated deformation, rubber product loss in stiffness and mechanical strength and it could result in cracking or rupture of the rubber product. [Brown, R., 2006]. So, it is important to carry out a fatigue test to prevent the safety of product performance. Some recommended method for the fatigue test including flexing method and cyclic tension test. Flexing test of rubber is covered in ASTM D1052 [ASTM D1052, 1999]. The flexing test is used to estimate the crack growth resistance of vulcanized rubber under bending flexing. Ross flexing machine is always used for the flexing test. The rubber specimen with 25±1 mm in width, 152 mm in length, and 6.35±0.03mm in thickness is bent 90^{o} freely over a rod with 10mm in diameter under a frequency around 1Hz. Furthermore, tension fatigue test is available in ISO 6943 [ISO 6943, 2011]. This test method used to determine the number of cycles required to break the specimen. The specimen needed to be formed as dumbbell shape by one of three types of cutting die. The test is performed at the frequency of 1-5 Hz.

1.2 Literature Review

1.2.1 Effect of Automotive Weight on Fuel Consumption

The weight of a vehicle provided great effect on fuel consumption. When the weight was increased, the fuel required for the vehicle performance was also increased. The fuel consumption was decreased 8% when the weight of the Heavy-Duty Diesel Truck (HHDDT) was reduced 20%. The fuel was saved 20% when the WVU vehicle weight was decreased from 36,000 lbs. to 28,800 lbs [Wang, L., et al., 2015]. Reducing the vehicle weight 10% could decrease fuel consumption 6% for car and 7% for light truck [Cheah, L., et al., 2007].

Recently, some researchers and automotive industries have been studied on weight reduction to cut down fuel consumption by trying to use a light-weight material for each automotive component especially for steel coil spring of shock absorber. Alternative material like carbon fiber and Kevlar fiber were used to replace the steel coil spring. The weight of the coil spring was reduced 80% by using carbon fiber and 83% by using Kevlar fiber [Sequeira, A.A., et al., 2016].

The polymeric glass fiber-reinforcement was also used as a coil spring. It was lighter than steel coil spring 40% [Pawsey, C., 2019]. Composite material was also addressed to use for the weight reduction. The carbon composite compression spring was invented to replace the steel coil spring. Using carbon composite could reduce weight 60% and it helped to avoid side loading during operation [MW industries inc.,2019].

Using composite material was good for weight reduction; however, it was expensive due to its complicated manufacturing process.

1.2.2 Natural Rubber Price Crisis

Thailand has been known as a world leader in natural rubber production. It exported around 4.56 million tons or 36% of the global production in 2017. The capacity of production was followed by Indonesia (26.00%), Vietnam (8.60%), China (8.00%), Malaysia (5.50%), and India (5.00%) [International Trade Centre, 2017]

Due to the weak global economic and oversupply, Thai natural rubber price has been dropping down and this caused many farmers into trouble. The rubber price has been plummeted from the highest rate 179.25 bath per kg in 2011 to 47.75 per kg in 2017 [Thakral, S., 2017]. As a solution, Thai government has been helped farmer to pay for cutting their rubber tree and grow other crops instead [Theparat, C., 2018]. Another solution, both public and private sectors have been working too hard to transfer rubber raw material into finished products. Some local products can be found like rubber pillow, protective boot, footwear, etc. that could earn three times more than selling natural rubber as the raw material [Sitthitool, R., n.d., Parato4u, n.d., OKI, n.d., & PY, n.d.].

1.2.3 Design of Shock Absorber Made of Rubber-like Material

Rubber is used in many applications. Recently, it was used as an elastomeric draft gear for the railway vehicle. In this model, the compressible elastomeric pad was enclosed by the metal plate on its both sides. The elastomeric-metal pads were formed together with an axial projection. The application had a capacity to absorb energy from the impact force during the driving performance [Ronald J. S., et al., 2013].

Another invention on material-like rubber was a rubber-metal spring. The rubber pads were connected separately with metal plates and a screw was placed in the central. The rubber and metal plate worked together to provide the high displacement and reduce the impact load. In the relaxation state, the energy was dissipated in form of heat through the metal to the atmosphere [Banic, M., et al., 2013].

The further application of rubber was the spring buffer. It was made of thermoplastic rubber inserted in the automotive coil spring to improve the stiffness and damping property of the shock absorber. It helped the driving more stable and extending the lifetime of steel coil spring [Elitebuffer Advansprings, n.d.].

Rubber material used in automotive application has been addressed. However, it still had a limitation in shock absorber. There was no automotive shock absorber made of natural rubber has been developed or invented.

1.2.4 Rubber Formulation

Property of rubber was changed with chemical compositions used in the compound. Filler made a great influence on mechanical property of rubber. Carbon black provided the great effect to the tan delta than other fillers like silica, starch, and calcium carbonate [Kamal, M.M, et al., 2009].

The type of filler and its amount of use also effected on the elastic modulus property of natural rubber. At 300% elongation, the rubber compound with carbon black N550 had a higher modulus of elasticity than carbon black N330, N660, $CaCO_3$. The modulus was increased when the amount of filler was added [Chuayjuljit, S., et al., 2002].

Rubber ingredient was developed for shock absorber component with different hardness. The rubber compound ingredient of hardness 55^oA had the highest tensile strength than the other compounds. However, the rubber compound of hardness 65^oA provided the lowest rebound resilience or highest dissipated energy while the rubber compound of 60^oA hardness showed in moderated properties [Chandrasekaran, V.C., 2007].

1.2.5 Finite Element Method

Since rubber-like material had a hyperelastic property, it needs to use the strain energy function to model a finite element analysis. The strain energy was defined as an energy stored per unit of reference volume when a material subjected to an external load. There were many strain energy functions developed for the hyperelastic material.

Some useful hyperelastic models were [ABAQUS V6.13, 2013]:

- *Neo-Hookean model*

$$U = C_{10}(\bar{I}_1 - 3) + \frac{1}{D_1}(J^{el} - 1)^2 \quad (14)$$

Where U is a strain energy per unit of reference volume (MPa),

C_{10} and D_1 are temperature-dependent material parameters,

$\bar{I}_1 = \bar{\lambda}_1{}^2 + \bar{\lambda}_2{}^2 + \bar{\lambda}_3{}^2$ is the first deviatoric strain invariant,

λ_i is a principle stretch,

J^{el} is the elastic volume ratio.

- *Mooney-Rivlin model*

$$U = C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) + \frac{1}{D_1}(J^{el} - 1)^2 \quad (15)$$

Where U is a strain energy per unit of reference volume (MPa),

C_{10}, C_{01} and D_1 are temperature-dependent material parameters,

$\bar{I}_1 = \bar{\lambda}_1{}^2 + \bar{\lambda}_2{}^2 + \bar{\lambda}_3{}^2$ and

$\bar{I}_2 = \bar{\lambda}_1{}^{(-2)} + \bar{\lambda}_2{}^{(-2)} + \bar{\lambda}_3{}^{(-2)}$ are the first deviatoric strain invariant,

λ_i is a principle stretch,

J^{el} is the elastic volume ratio.

- *Yeoh model*

$$U = C_{10}(\bar{I}_1 - 3) + C_{20}(\bar{I}_1 - 3)^2 + C_{30}(\bar{I}_1 - 3)^3$$
$$+ \frac{1}{D_1}(J^{el} - 1)^2 + \frac{1}{D_2}(J^{el} - 1)^4 + \frac{1}{D_3}(J^{el} - 1)^6 \quad (16)$$

Where U is a strain energy per unit of reference volume (MPa),

C_{10} , C_{20}, $C_{30}, D_1, D_2,$ and D_3 are temperature-dependent material parameters,

$\bar{I}_1 = \bar{\lambda}_1{}^2 + \bar{\lambda}_2{}^2 + \bar{\lambda}_3{}^2$ is the first deviatoric strain invariant,

λ_i is a principle stretch,

J^{el} is the elastic volume ratio.

- *Ogden model*

$$U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}(\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3) + \sum_{i=1}^{N} \frac{1}{D_i}(J^{el} - 1)^{2i} \quad (17)$$

Where U is a strain energy per unit of reference volume (MPa),

μ_i, α_i , D_i are temperature-dependent material parameters,
λ_i is a principle stretch,
J^{el} is the elastic volume ratio.

Material model coefficients were defined by using curve fitting technique from experiment test data. The essential experimental tests for hyperelastic material model include:

- Uniaxial testing

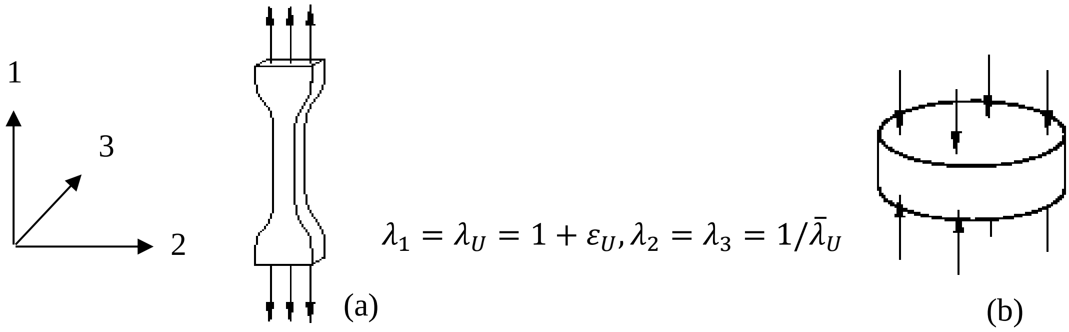


Figure 11 (a) Uniaxial tensile test; (b) Uniaxial compression test

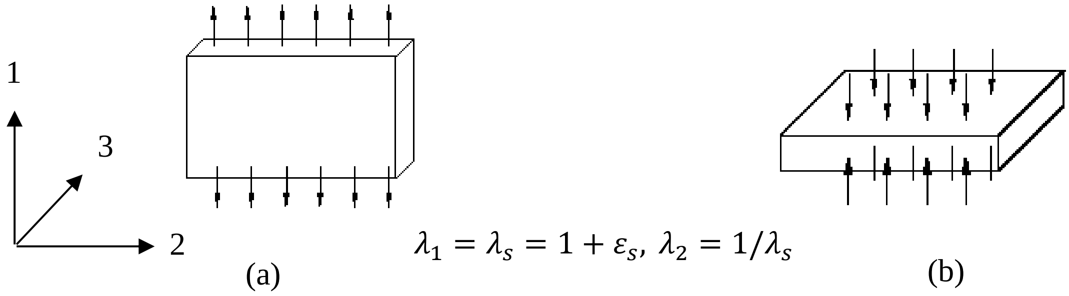


Figure 12 (a) Planar tensile test; (b) Planar compression test

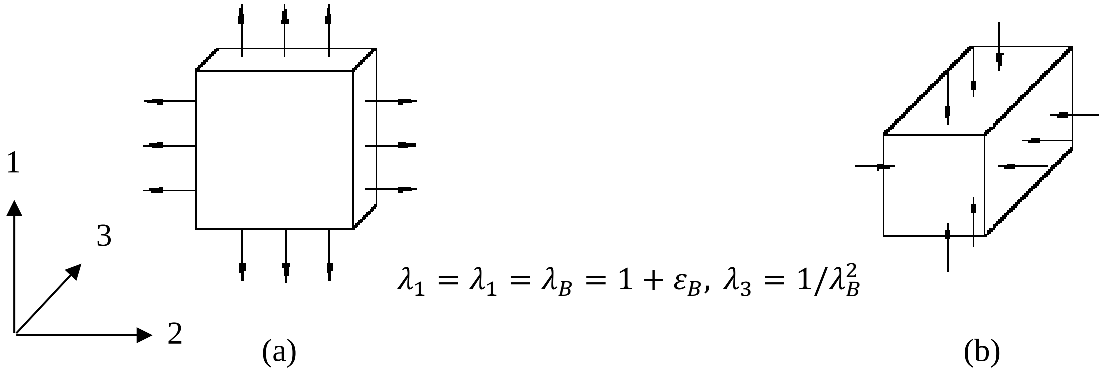


Figure 13 (a) Biaxial tensile test; (b) Biaxial compression test

The most practical model for non-linear viscoelastic property of rubber material was Bergstrom Boyce model in figure 14. The model consists of two networks. Network A corresponded to the state of long-time stress relaxation tests of the material (elasticity) and network B represented the time-dependent deviation from the equilibrium state (viscoelasticity) [ABAQUS V6.13, 2013].

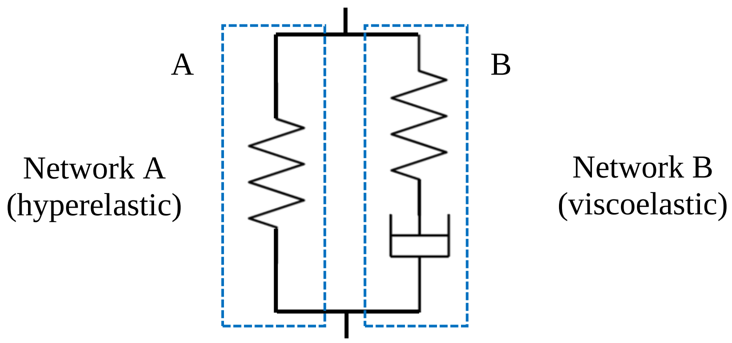


Figure 14 Symbolic representation of the BB model

In network (A), the model was expressed in term of hyperelastic property and in network (B), the model was represented in term of power creep law as a following expression.

$$\dot{\epsilon}_B = A[\lambda_B - 1]^{\,C}(\sigma_B)^m \qquad (18)$$

Where $\dot{\epsilon}_B$ is an effective creep strain rate,

A is a dimensional consistency,

$\lambda_B - 1$ is a normal creep stain,

C is a creep strain dependence (C = [-1,0]),

σ_B is an effective stress (MPa),

m is an effective stress dependence (m > 1),

S is ratio of the stress in network B to the stress in network A under instantaneous loading.

Curve fitting for Bergstrom Boyce model could be carried out through the finite element software. The experimental testing data was required depend on each software. Relaxation and creep test were usually performed to determine the material constants. However, some powerful finite element software like Abaqus, the material parameters of BB model could be derived from the load and unload test at different strain rate.

1.2.5.1 Hyperelastic Simulation

There were many strain energy function models were developed and used to study the hyperelastic property of rubber-like material such as Neo-Hookean model, Yeoh model, Ogden model, Mooney-Rivlin model, etc. The accurate strain energy function model needs to be selected based the application.

In comparison of different strain energy function for flexible join application Yeoh model showed a good agreement between simulation and experiment than Mooney Rivlin, Neo-Hookean, Arruda-Boyce, and Ogden for all three testing like the uniaxial test, biaxial test, and planar test [Shahzad, M., et al., 2015]. Using only one testing data like uniaxial tension test in hyperelastic simulation was still be able to predict the behaviour of rubber-like material. Yeoh, Ogden, and Mooney-Rivlin provided a good fit between simulation and experiment [Carlescu, V., et al., 2014].

1.2.5.2 Non-linear Viscoelastic Simulation

To simulate viscoelastic property of elastomer, Bergstrom Boyce and Prony Series were widely used. Yeoh-Bergstrom Boyce showed a good agreement than Yeoh-Prony series especially at the medium [Ghoreishy, M.H.R., 2012].

Material parameters of Bergstrom Boyce model were calibrated with uniaxial data like tension test at different strain rates using Matlab code or a commercial software like Mcalibration [Bergström, J.S., n.d., Veryst Engineering, n.d.].

Yeoh model were widely used in both hyperplastic and viscoelastic simulation with the high rate of accuracy with the less experiment data. Moreover, the commercial material calibration software like Mcalibration was used to ease the curve fitting process.

In conclusion, some lightweight materials have been used in automotive applications like carbon fibber, carbon composite, and Kevlar fibber. There were many natural rubber products invented for automotive applications; however, there was no natural rubber used for the shock absorber or the coil spring. Due to those limitation and the price of natural rubber has been going down, this would give us a motivation to develop a shock absorber made of natural rubber in order to add value for natural rubber and promote the idea of local product development.

1.3 Objectives

Aims of this research are:

1. To invent a shock absorber made of natural rubber for a motorcycle.
2. To model and analyse shock absorber made of natural rubber with finite element analysis software.
3. To design rubber compound for shock absorber made of natural rubber.

1.4 Scopes of Study

The scopes of the study are:

1. Natural Rubber used in this study is assumed to be isotropic and compressible.
2. Only uniaxial compression test is carried for natural rubber material due to the lack of equipment.
3. The prototype of shock absorber is not yet applied in the real motorcycle due to the time limitation and shortage of testing equipment.

CHAPTER 2
RESEARCH METHODOLOGY

2.1 Work Procedure

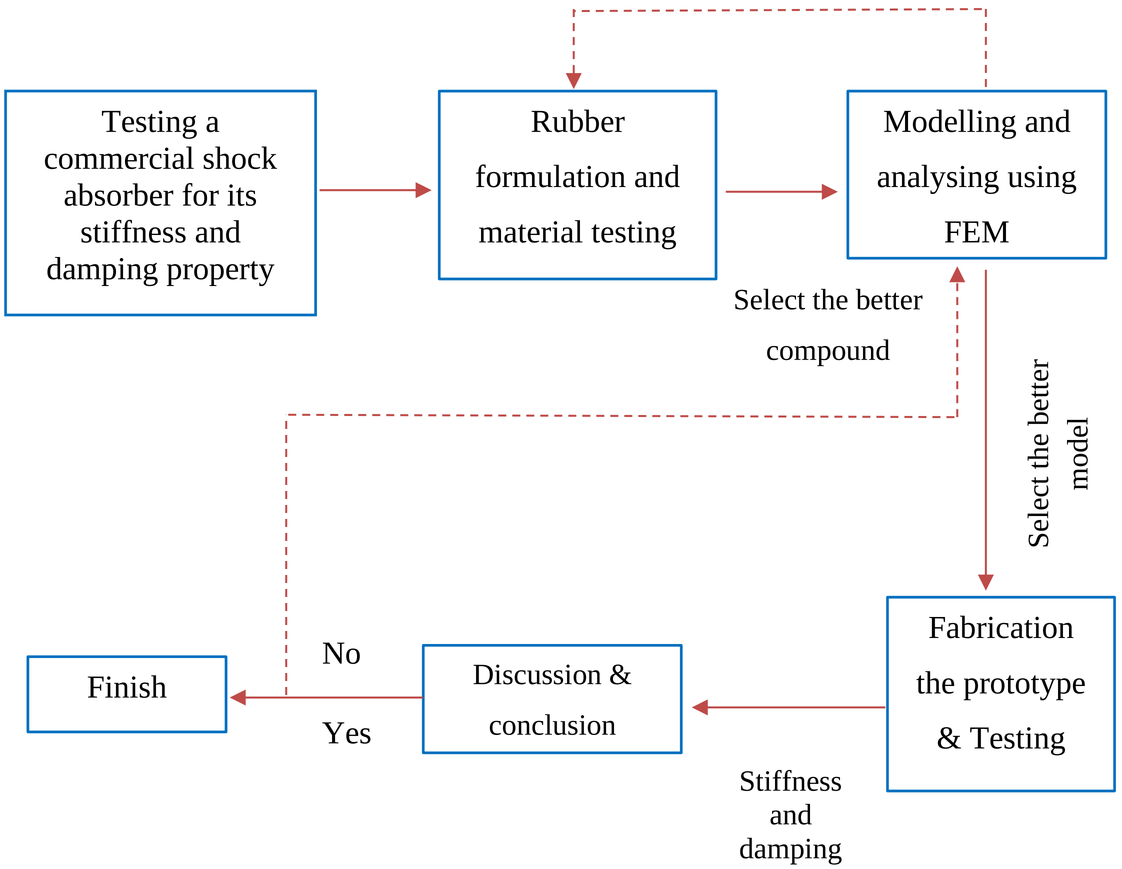


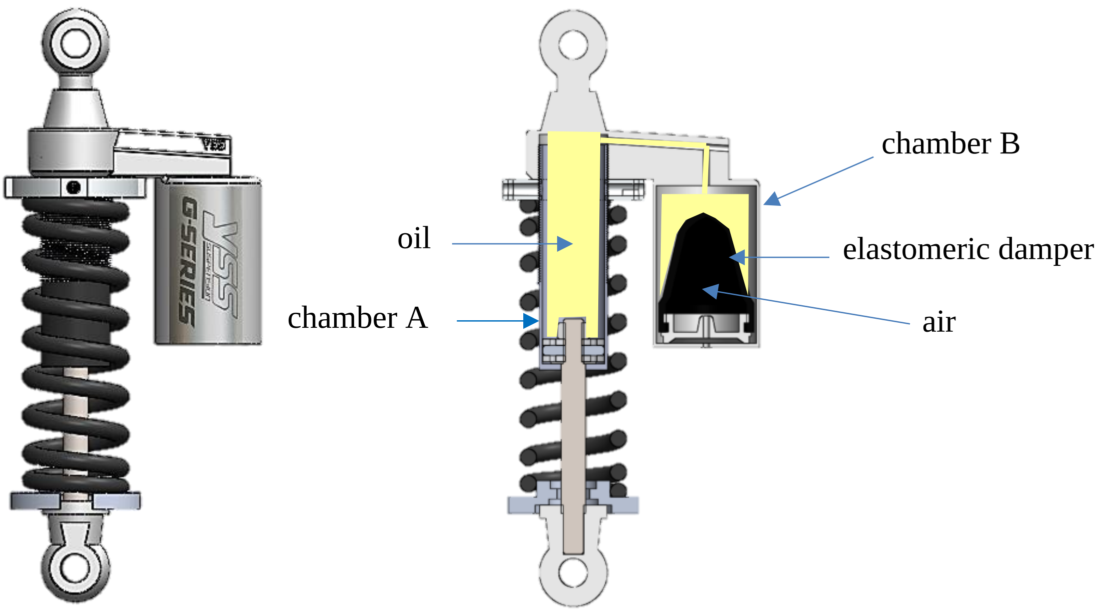
Figure 15 Flow chart of work procedure

This research is divided into four steps as shown in figure 15. Firstly, the commercial shock absorber is tested for its spring stiffness and damping property using an Instron® material testing machine and a test rig. Secondly, the rubber compounds are formulated and tested to get the material properties like elastic modulus and energy dissipation capacity (hysteresis lost ratio). The compound with the desired material properties is selected to be used in the next design. Thirdly, the finite element method is used to model and analyse the shock absorber made of natural rubber. The better model is chosen to be fabricated. Finally, the selected prototype is fabricated and tested to get its stiffness and damping property. The results from testing of the shock absorber made of natural rubber are compared with the commercial shock absorber. The final discussion and conclusion are carried out.

2.2 Testing Damping and Stiffness Properties of the Commercial Shock Absorber

2.2.1 Damping Property Test

The commercial shock absorber in figure 16 consists of two elements including spring and dashpot. A steel coil spring has a height of 145 mm, an outside diameter of 52mm and an inside diameter of 32mm. A YSS G-series dashpot has two parts, chamber A and chamber B where are filled by hydraulic element(oil). Inside the chamber B, there is an elastomeric damper. When it is compressed, the piston moves along inside the chamber A pushing oil to chamber B. When a pressure inside elastomeric damper is increased, it makes piston return to the origin position.



(a) (b)

Figure 16 (a) Shock absorber with full view; (b) Shock absorber in section view

The damping property of shock absorber and spring stiffness are defined by testing in figure 17. The damping property test is carried out by using a test rig. The test rig consists of a 3hp electric motor single phase and it is linked to a cam through its shaft. The cam is indirectly connected to a shock absorber by a follower. The shock absorber is compressed under a harmonic force with frequency of 1Hz for one minute. The force and time are recorded by a force sensor which is attached at the top of the shock absorber.

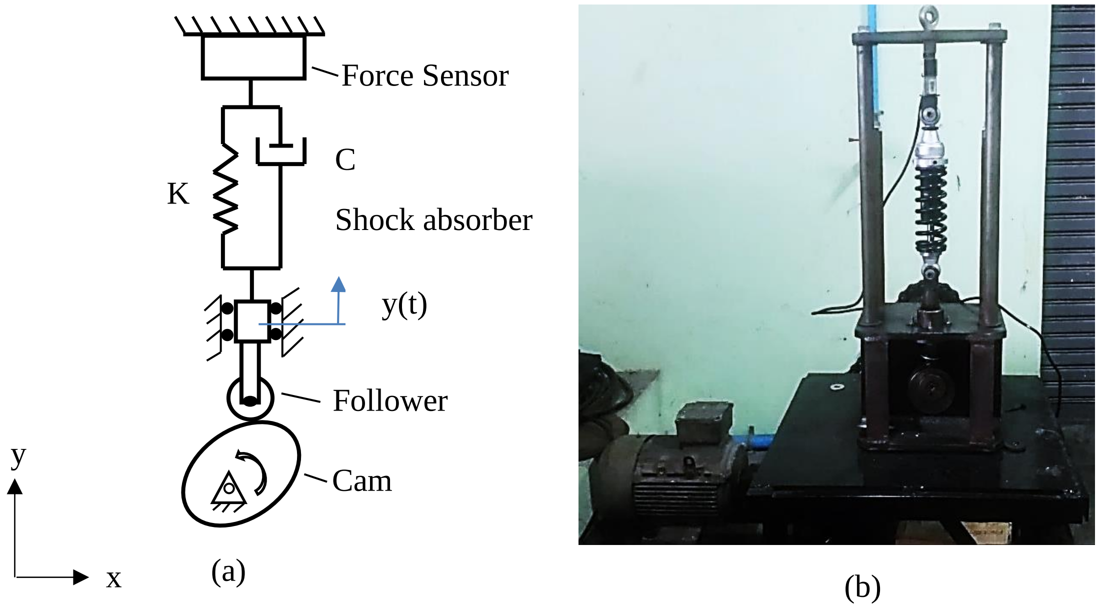


Figure 17 (a) Free body diagram of the test rig; (b) A commercial shock absorber with a test rig

The displacement and velocity function of the cam is determined from the cam profile. The eccentric cam has a 10 mm of offset (e) from its center (M) moved around the origin (O) in anti-clockwise direction at the starting angle of -90^{o} to create a liner motion for follower (N).

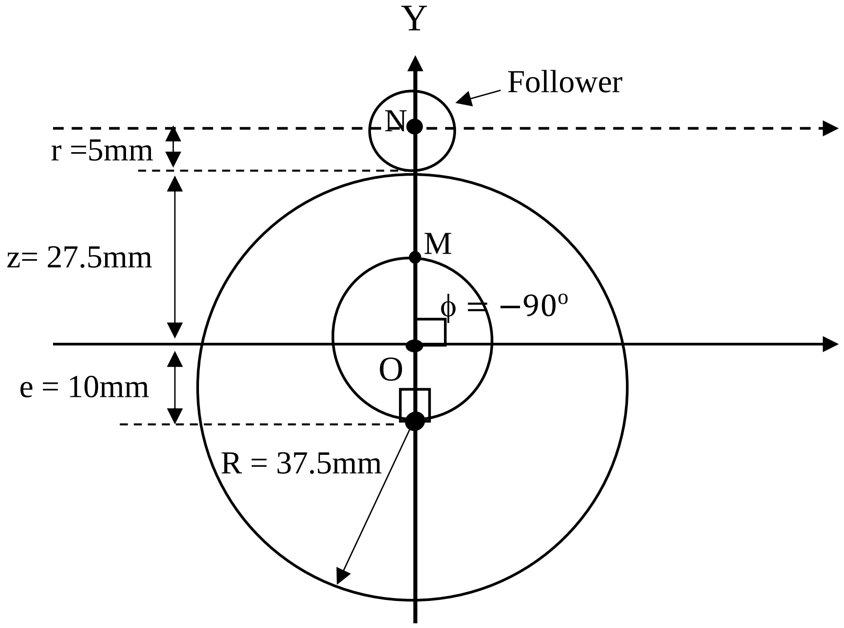


Figure 18 Nomenclature of eccentric cam at ϕ= -90o and t = 0s

At $\text{time(t)} = 0s$, the cam is at the position of angle $\phi = -90^{o}$ and the position of the follower is $y = 0$ mm. Therefore, the displacement and velocity function of the cam will be the form of,

$$y(t) = 10\sin\left(\omega t - \frac{\pi}{2}\right) + \sqrt{42.5^2 - 100\left[1 - sin^2\left(\omega t - \frac{\pi}{2}\right)\right]} - 32.5 \text{ (mm)} \quad (19)$$

$$y'(t) = \frac{20\pi .\cos\left(2\pi t - \frac{\pi}{2}\right) + \frac{1}{2}(400\pi .\cos\left(2\pi t - \frac{\pi}{2}\right).\sin\left(2\pi t - \frac{\pi}{2}\right))}{\sqrt{42.5^2 - 100(1 - sin^2\left(2\pi t - \frac{\pi}{2}\right))}} \quad (20)$$

In both hyerpelastic and non-linear viscoelastic simulation, the analysis procedure is followed by the displacement control which the known amplitude is required. The value of amplitude used in the simulation is defined from the equation (19). The damping of the shock absorber is calculated from a force and velocity function. The force is obtained from the load cell while the velocity is obtained from the equation (20).

2.2.2 Spring Stiffness Test

A spring stiffness testing is performed using an Instron® material testing machine model 8872(25kN). The Instron® 8872 is a servohydraulic testing system designed for static and fatigue test of advance material, mechanical, biomedical, automotive components, etc. with the force capacity up to ±25kN and stroke 100mm [Instron®8872, n.d.]. The steel coil spring is placed in the machine between two sample grips where it is fixed at the bottom side. The steel coil spring is compressed 20mm at the top side under a static load for three times and the load is recorded until it is reached the desired deformation as in figure 19.

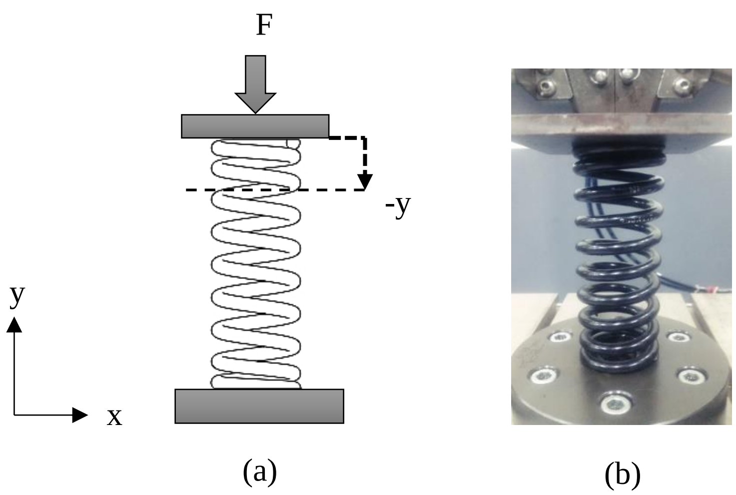


Figure 19 (a) Free body diagram of the steel coil spring under compression; (b) Steel coil spring under compression test

2.3 Material Formulation

Six rubber compounds with different fillers like carbon black N330, calcium carbonate, ($CaCO_3$), and Silica (SiO_2) are formulated as listed in table 1. The compound which provide the best mechanical properties will be selected. Two important mechanical properties are hysteresis lost ratio and modulus of elasticity of the material are determined.

The natural rubber (STR5L) is used in this study. Steric acid and zinc oxide are activator while MTB is an accelerator of the compound. Wingstay L is an anti-degradant and paraffinic oil is a plasticizer. Carbon black N330, $CaCO_3$, and SiO_2 are the fillers used to improve mechanical properties of the rubber material. Sulfur is a curing agent and it is one of the most important ingredients in the rubber vulcanization. It helps to create cross-links between molecular chains of the rubber. Six rubber compounds are created by changing the amount of filler since it affects on the mechanical property of rubber.

Table 1 Ingredients for six different rubber compounds

No.	Chemical Compositions (Phr.)	A-1	A-2	A-3	B-1	B-2	B-3
1	NR (STR5L)	100	100	100	100	100	100
2	ZnO	5	5	5	5	5	5
3	Wingstay L	1	1	1	1	1	1
4	Steric acid	1.5	1.5	1.5	1.5	1.5	1.5
5	Carbon black (CBN330)	60	-	-	30	30	-
6	Silica	-	60	-	30	-	30
7	$CaCO_3$	-	-	60	-	30	30
8	Paraffinic Oil	2	2	2	2	2	2
9	MBT	1	1	1	1	1	1
10	Sulfur	2	2	2	2	2	2

Rubber and chemical addiction are mixed using a two-roll mill machine, figure 20(a), about 30 minutes and cured by the hydraulic hot press machine, figure 20(b), under a temperature of 140°C for 20 minutes.

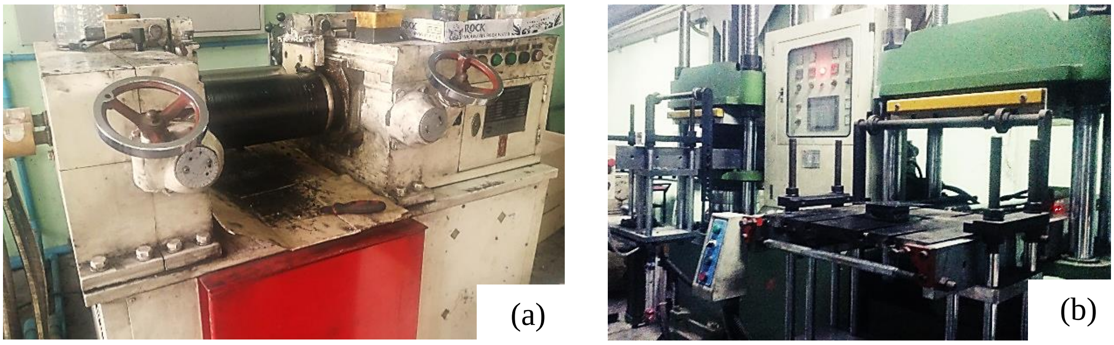

(a) (b)

Figure 20 (a) Two-roll mill machine; (b) Hydraulic hot press machine

Two mechanical material testing like cyclic loading and uniaxial compression test are carried out to get the hysteresis lost ratio and elastic modulus of rubber material. For the cyclic loading test, vulcanized filled rubber specimens with diameter of 28 mm and thickness of 12mm are compressed 25% strain under the load-unload condition for five times with the crosshead speed of 12mm/min. On the other hand, the uniaxial compression test is followed the standard of ASTM D575 using the material testing machine Zwick Roell, Germany (Z010). Three rubber specimens, figure 21, are used in each testing.

Figure 21 Vulcanized filled rubber specimens

2.4 Finite Element Analysis

2.4.1 Design for Shock Absorber Made of Natural Rubber

Finite element method is used to design and analyse the stiffness and damping property of shock absorber made of natural rubber using ABAQUS® CAE since it is capable of Bergstrom Boyce model with the ease of use.

The design concept of rubber shock absorber is needed to be machinable and fabricable by rubber moulding. Its structure needs to be very simple and easy to install in the different kinds of motorcycle. The natural rubber shock absorber is consisted of two main components such as a rubber part and an aluminium plate. Each type of rubber shock absorber is composed of six aluminium plates and five rubber pads. The aluminium is used in this design for three reasons including light weight, good in thermal conductivity, and low cost. The function of using aluminium with rubber pad is to enhance the stiffness of the structure. Figure 38 illustrates three models of shock absorber made of natural rubber. The rubber shock absorber has five rubber pads which are inserted by six aluminium plates. Different models have the different shapes. The shock absorber made of natural rubber model-1 has a cylindrical shape, figure 22(a), model-2 has a biconcave shape, figure 22(b), and model-3 has a biconvex shape, figure 22(c). Each type of rubber pad has the same thickness of 24mm, inside diameter of 40mm, and maximum outside diameter of 60mm. Moreover, the aluminium plate has thickness of 3mm, outside diameter of 64mm, and inside diameter of 40mm for all models.

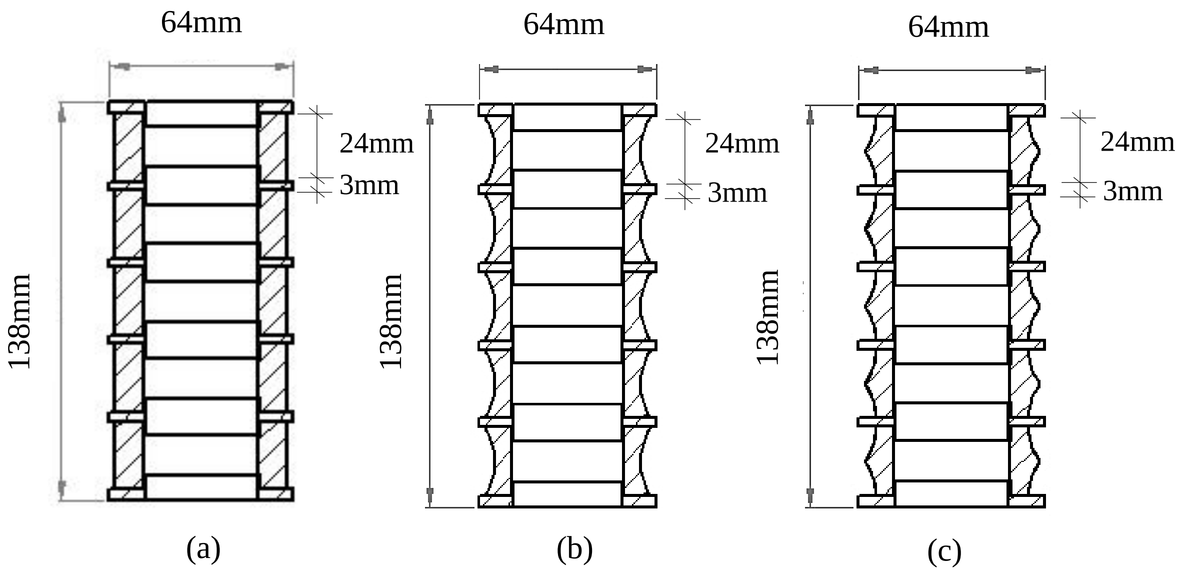


Figure 22 (a) Rubber shock absorber model-1; (b) Rubber shock absorber model-2; (c) Rubber shock absorber model-3

2.4.2 Hyperelastic Simulation

The natural rubber used in this study is assumed to be isotropic and incompressible material. The mechanical property including stiffness and the damping property of shock absorber with spring made of natural rubber is analysed by finite element method (FEM) using Abaqus® CAE since it is capable of Bergstrom Boyce model with ease of use. It is necessary to have the material parameters of strain energy function model to input in the simulation. Those material parameters can be calibrated directly from finite element software or from other commercial software like Hyperfit or Mcalibration software.

2.4.2.1 Material Calibration

Table 2 Compound formulation for rubber shock absorber

No.	Ingredients	Amount (Phr.)
1	NR (STR5L)	100
2	ZnO	5
3	Wingstay L	1
4	Steric acid	1.5
5	Carbon black (CBN330)	50
6	Paraffinic Oil	2
7	MBT	1
8	6PPD	1.5
9	MTQ	1.5
10	Sulfur	2

Rubber ingredients used in the design of rubber shock absorber are listed in table 2. The content of carbon black N330 is modified to be 50 phr. and two anti-degradants such as 6PPD and MTQ are added in the compound.

In this hyperelastic simulation, Yeoh material model (Eq.16) is chosen to be used because of its good fit for the large strain with less experimental mode [Shahzada, M., 2015]. The material parameters of hyperelastic Yeoh are obtained by using Mcalibration® software developed by Veryst Engineering®, LLC. This software is very potential to calibrate various models of material constitutive with the less requirement of the material tested data [Bergström, J.S., 2019; Veryst Engineering, LLC, 2019]. Due to the limitation of the testing equipment and the actual requirement, the only uniaxial compression test is performed. Material testing is followed by the ASTM D575 for three rubber specimens. The experiment data used in the calibration are averaged. Figure 23 shows material parameter calibration of the Yeoh model using Mcalibration software with the coefficient of determination R^2 = 0.997. The material parameters of the Yeoh model are listed in table 3.

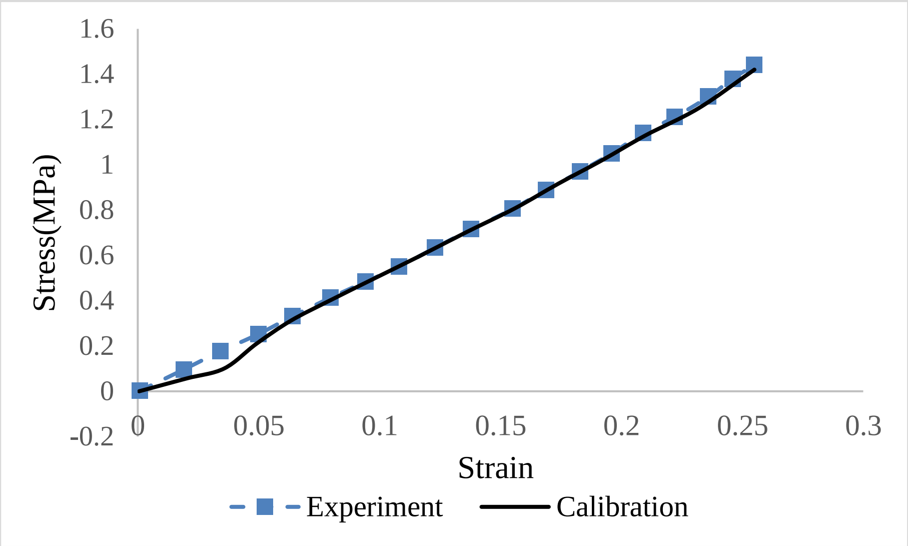


Figure 23 Material parameters calibration for Yeoh-hyperelastic model

Table 3 Material parameters of Yeoh model

Model	Material Parameter		
Yeoh (hyperelasticity)	C10 = 0.40 D1= 0	C20 = 0.18 D2 = 0	C30 = 0.023 D3 = 0

Aluminium 7075-T651 used in the finite element analysis of three models of natural rubber shock absorber has the mass density $\rho = 2.81 \times 10^3$ Kg/m^3, elastic modulus $E = 70 \times 10^3$ MPa, and Poisson's ratio $\nu = 0.32$ [“7075-T6 Aluminium”, 2019].

2.4.2.2 Simulation of Stiffness of Rubber Shock Absorber

Rubber pads of each model are interacted with aluminium plates by surface-to-surface contact (standard) with a friction coefficient μ= 0.8 [Smith, R. H., 2008]. The bottom and the top aluminium plate are bonded to the upper and lower rigid body by tie constraints. The two dimensional (2D) axisymmetric structure of the shock absorber made of natural rubber is fixed at the lower side and compressed at the top side 20mm using a displacement control method with the general static analysis. The geometry of rubber pads and aluminium plates are discretized into a 4-node bilinear axisymmetric quadrilateral, hybrid, constant pressure (CAX4H). Model-1, figure 24(a), contains 545 elements and 1183 nodes. Model-2, figure 24(b), has 430 elements and 943 nodes. Model-3, figure 24(c), comprises 385 elements and 853 nodes. The simulation is used as a geometric nonlinearity approximation to the total stiffness matrix.

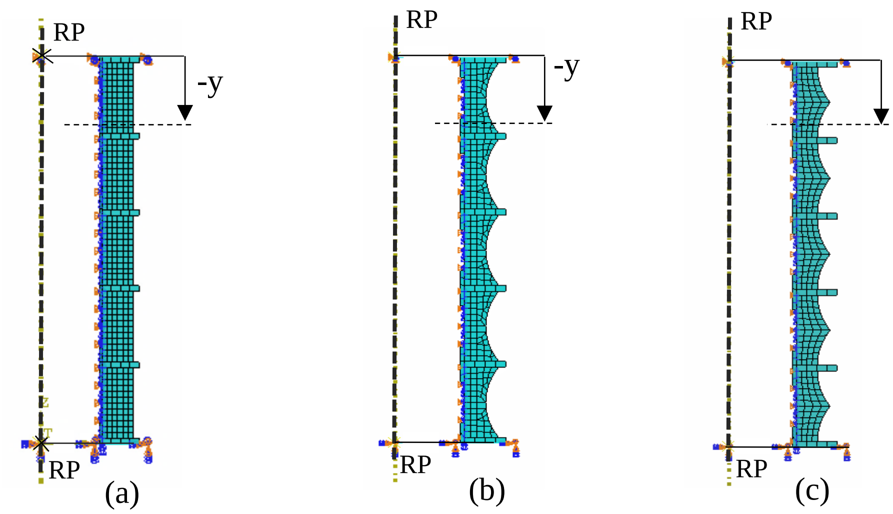


Figure 24 Boundary condition of rubber shock absorber model-1(a), model-2(b), and model-3 (c) for hyperelastic simulation

2.4.3 Non-Linear Viscoelastic Simulation

2.4.3.1 Material Calibration

The Bergstrom Boyceis used in this simulation since it responds to the property of natural rubber, non-linear viscoelasticity and it is also built in ABAQUS software. Material parameters of the BB model are calibrated using Mcalibration® software. The vulcanized rubber specimens with diameter of 28 mm and height of 12 mm are performed load-unloading test at two different strain rates (-0.1/s and -1.0/s) under 25% of compression strain using Instron® 8872 (25kN). Experimental data averaged from three rubber specimens are used for the calibration of material parameters of Yeoh-Bergstrom Boyce model.

Figure 25 shows the material parameters of BB model calibrated using Mcalibration software with the coefficient of determination R^2 = 0.973 and table 4 shows the material parameters of Bergstrom Boyce Model.

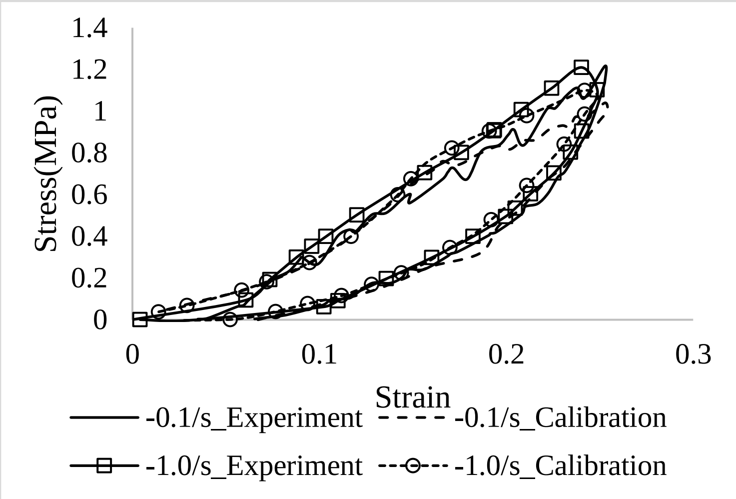


Figure 25 Material parameters calibration for non-linear viscoelastic constitutive model (BB model)

Table 4 Material parameters of BB model

Bergstrom Boyce Material Parameters (Yeoh-BB model)				
Yeoh model	C10 = 0.40	C20 = 0.18	C30 = 0.023	
	D1 = 0.0	D2 = 0.0	D3 = 0.0	
Power creep law	S = 0.40	A = 0.05	m = 6.50	C = -0.95

2.4.3.2 Simulation of Damping of Rubber Shock Absorber

The top and bottom end side of the structure of rubber shock absorber are boned using tie constraint. The rubber pads are connected to the aluminium plates by surface-to-surface contact (standard) with a friction coefficient μ= 0.8. The rubber shock absorber is modelled as a 2D axisymmetric structure. It is fixed at the bottom side and compressed at its top side 20 mm using a displacement control method with the dynamic implicit procedure. The simulation is used as a non-linear geometry approximation to the total stiffness matrix. The rubber pads and aluminium plates, in figure 26, are discretized into a 4-node bilinear axisymmetric quadrilateral, hybrid, constant pressure (CAX4H). There are 545 elements and 1183 nodes for rubber shock absorber model-1, 420 elements and 923 nodes for rubber shock absorber model-2 and 385 elements and 853 nodes for rubber shock absorber model-3. The simulation is used as a geometric nonlinearity approximation to the total stiffness matrix.

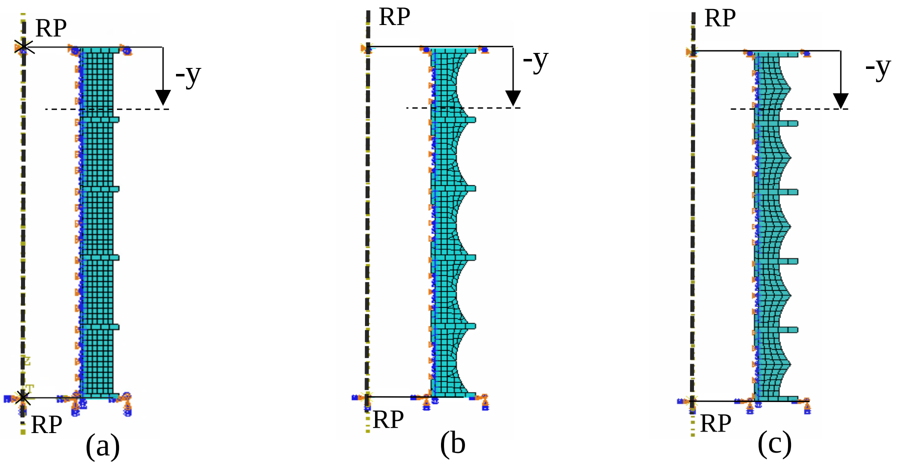


Figure 26 Boundary condition of rubber shock absorber model-1(a), model-2(b), and model-3 (c) for hyperelastic simulation

2.5 Damping Test for Prototype of Rubber Shock Absorber

The rubber pads are fabricated using a compression mould by the hydraulic hot press machine. The rubber compound is vulcanized 20 minutes under temperature 140°C. The stiffness property of the rubber shock absorber is tested using INSTRON® material testing machine as shown in figure 27. The rubber shock absorber is placed between two rigid grips where it is fixed at the lower side. The work piece is performed five cyclic loading before being compressed 20 mm using a displacement control method to prevent the Mullins effect. The forced is recorded until the test reaches the desired deformation.

On the other hand, the damping property of the rubber shock absorber is carried out using the test rig. Five specimens of the rubber pads are assembled with a dashpot of the motorcycle shock absorber whose hydraulic damping is already drained out. Each type of rubber shock absorber is performed a harmonic test using a test rig with a compressive frequency of 1Hz. The test is repeated three times for all types of rubber shock absorber.

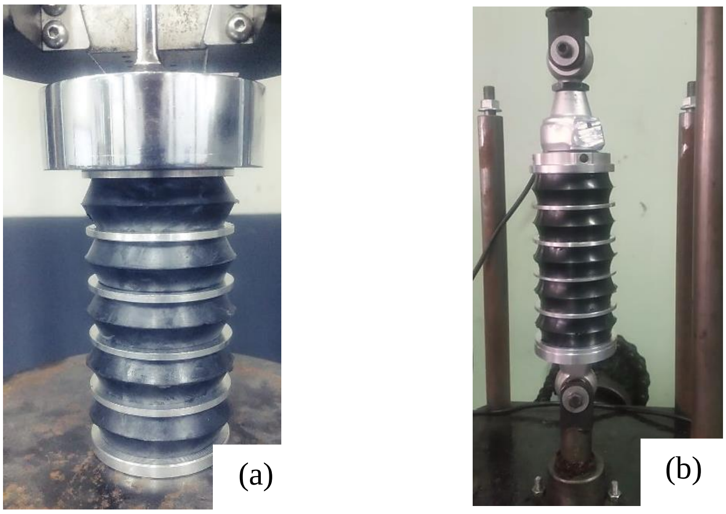


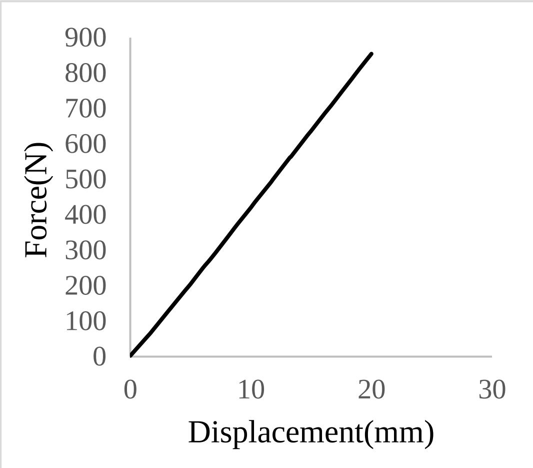
Figure 27 (a) Rubber shock absorber model-3 under compression test; (b) Rubber shock absorber model-3 under harmonic force test

2.6 Fatigue Test for Rubber Shock Absorber

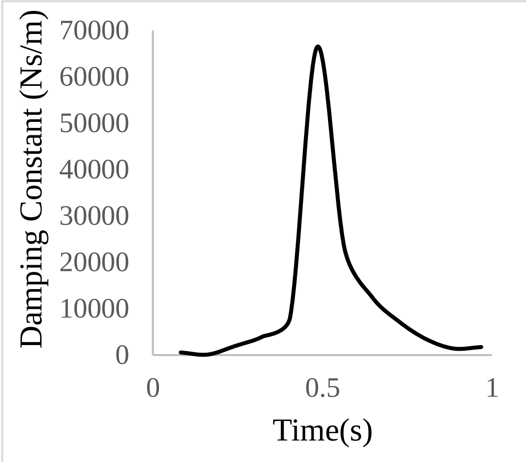
The fatigue test of rubber shock absorber is carried out using the test rig. The shock absorber is compressed under a harmonic force with the frequency of 1Hz for 10 hours at the room temperature. The IR sensor is used to capture the surface temperature of the rubber shock absorber during testing. The temperature of each rubber pad is recorded for every 15 minutes.

CHAPTER 3
RESULTS AND DISCUSSIONS

3.1 Commercial Shock Absorber Testing



(a)



(b)

Figure 28 (a) Force vs displacement of the commercial shock absorber from compression test using Instron® machine; (b) Damping vs time from harmonic test using the test rig

Figure 28(a) represent a force and displacement relationship of the steel coil spring from the static compression test. The unit of the force is represented in Newton (N) and the displacement unit is shown in mm. The spring stiffness K is equal to 42,597 N/m. Figure 28(b) illustrates the damping constant of the commercial shock absorber. The damping value is averaged from 60 cycles of damping test with the test rig. The highest peak is represented the damping characteristic when the shock absorber is reached its maximum compressive displacement, 20 mm. The maximum damping value of the commercial shock absorber at maximum compression is equal to 66,429 Ns/m.

3.2 Rubber Formulation

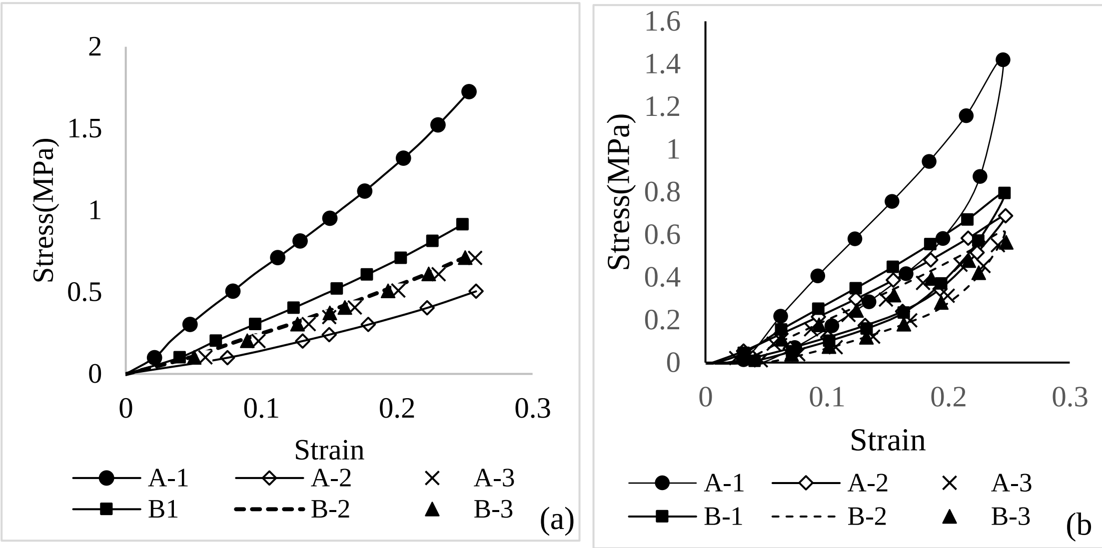


Figure 29 (a) Stress-strain relationship of different rubber compounds;
(b) Hysteresis loop of different rubber compounds

Figure 29(a) represents a stress-strain relationship of the rubber specimens of six different compounds from uniaxial compression test. Based on the result of 25% strain, the rubber specimen A-2 has the lowest stress. Specimen A-3, B-2, and B-3 show similar in stress but lower than specimen B-1. On the other hand, the stress in specimen B-1 is lower than specimen A-1. Figure 29(b) illustrates hysteresis loops of rubber specimen of six compounds from cyclic loading. The loops are represented in stress and strain relationship. Specimen A-1 has higher hysteresis loop than specimen B-1. Furthermore, the other specimens have the similar loop.

Table 5 shows the value of elastic modulus and hysteresis lost ratio of rubber specimen from six different compounds. The modulus of elasticity and hysteresis lost ratio of rubber specimen A-1 are 6.81 MPa and 0.43, rubber specimen A-2 are 2.21 MPa and 0.32, rubber specimen A-3 are 3.05 MPa and 0.37, rubber specimen B-1 are 3.90 MPa and 0.42, rubber specimen B-2 are 3.24 MPa and 0.40, and rubber specimen B-3 are 3.05 MPa and 0.36, respectively. In conclusion, rubber specimen A-1 has the highest modulus of elasticity and hysteresis lost ratio; nevertheless, A-2 has the lowest modulus of elastic and hysteresis lost ratio.

Table 5 Modulus of elasticity and hysteresis lost ratio for different rubber compounds

Compound	Modulus of elasticity (MPa)	Hysteresis loss ratio
A-1	6.81	0.43
A-2	2.21	0.32
A-3	3.05	0.37
B-1	3.90	0.42
B-2	3.24	0.40
B-3	3.05	0.36

In conclusion, rubber compound A-1 provides the better stiffness and damping property than other compounds. Therefore, the rubber compound A-1 is selected to be used in the design of the shock absorber made of natural rubber.

3.3 Hyperelastic Simulation

Figure 30 shows the result of 2D axisymmetric shock absorber made of natural rubber from the hyperelastic simulation for model-1 in figure 30(a), model-2 in figure 30(b), and model-3 in figure 30(c).The structure of shock absorber is illustrated in von mises stress.

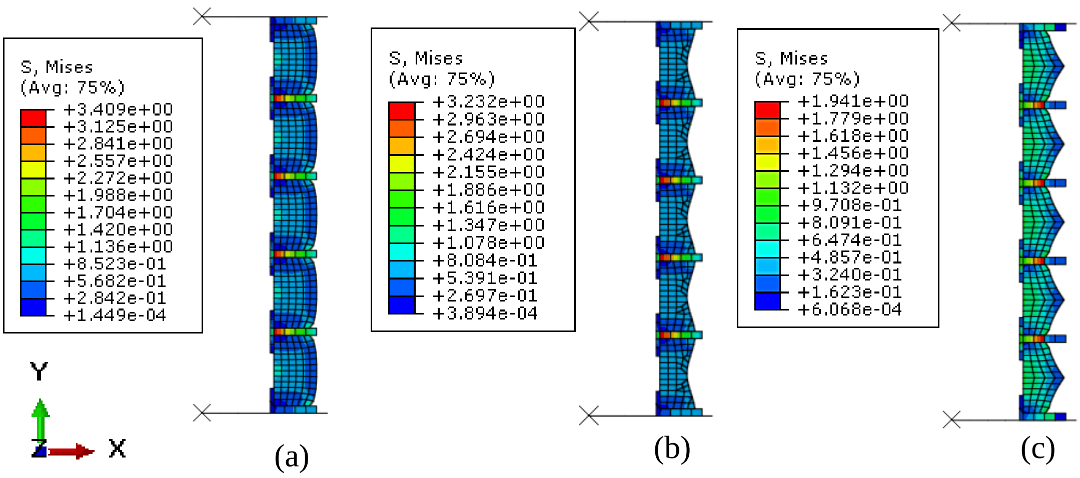


Figure 30 Rubber shock absorber model-1 (a), model-2 (b), and model-3(c) are represented in von mises stress

Table 6 Maximum Stress value of rubber shock absorber from hyperelastic simulation

	Von mises (MPa)	S11(MPa)	S22(MPa)	S33(MPa)
Model-1	3.40	1.03	2.56	1.18
Model-2	3.23	0.49	2.70	1.02
Model-3	1.94	0.15	1.23	0.56

Table 6 represents the maximum stress value of rubber shock absorber from the hyperelastic simulation in the unit of MPa. Each model is shown in von mises stress, x direction stress (S11), y direction stress (S22), z direction stress (S33). In overall, the shock absorber model-1 has the highest stress and this is followed by model-2 and model-3.

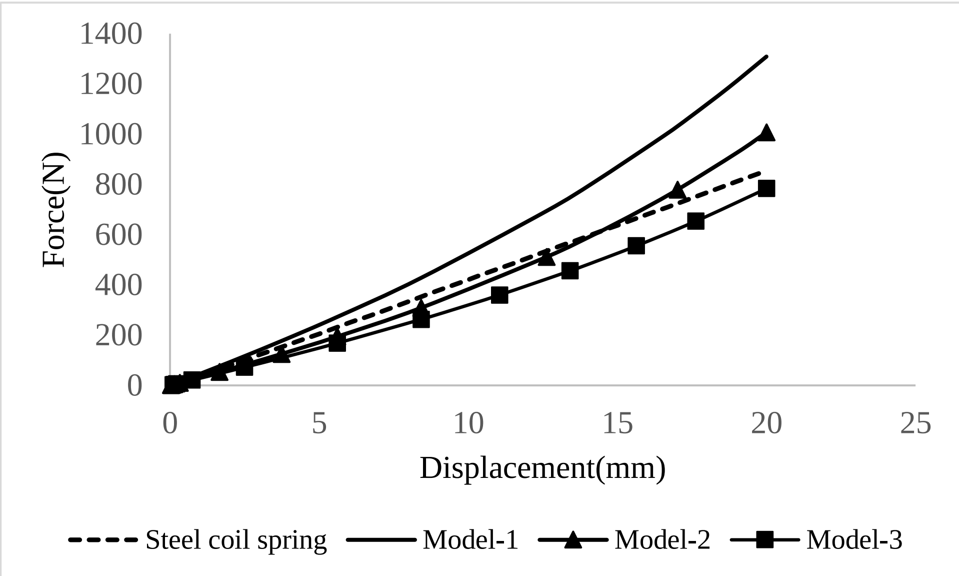


Figure 31 Force and displacement relationship of three models of rubber shock absorber from hyperelastic simulation

Figure 31 illustrates a force and displacement relationship of three different rubber shock absorber from hyperelastic simulation. Rubber shock absorber model-1 shows the highest stiffness modulus and this followed by model-2 and model-3. Table 7 lists a stiffness property of rubber shock absorber calculated from the simulation. The stiffness coefficient of rubber shock absorber model-1 is 65,444N/m, model-2 is 50,338N/m and model-3 is 39,170N/m.

Table 7 Stiffness coefficient of three models of rubber shock absorber

Rubber Shock Absorber	Stiffness (N/m)
Model-1	65,444
Model-2	50,338
Model-3	39,170

3.4 Non-linear Viscoelastic Simulation

2D axisymmetric structure of shock absorber made of natural rubber from the non-linear viscoelastic simulation is illustrated in figure 32(a) for model-1, figure 32(b) for model-2, and figure 32(c) for model-3.

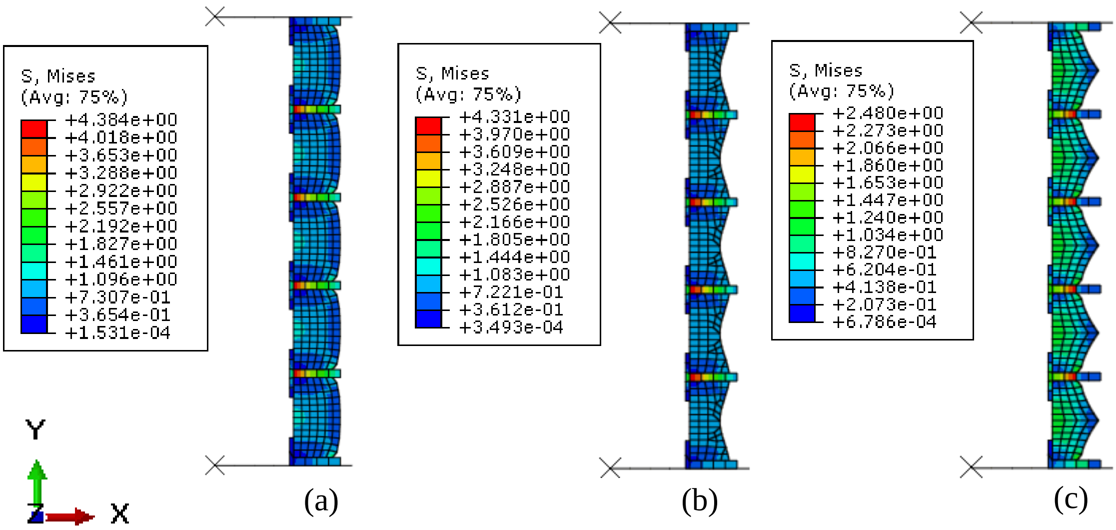


Figure 32 Rubber shock absorber model-1 (a), model-2 (b), and model-3 (c) from non-linear viscoelastic simulation

Table 8 Max. Stress value of rubber shock absorber from non-linear viscoelastic simulation

	Von mises (MPa)	S11(MPa)	S22(MPa)	S33(MPa)
Model-1	4.38	1.32	3.28	1.52
Model-2	4.33	0.65	3.62	1.33
Model-3	2.48	0.12	1.60	0.71

Table 8 represents the maximum stress value of rubber shock absorber from the non-linear viscoelastic simulation in the unit of MPa. Each model is shown in von mises stress, x direction stress (S11), y direction stress (S22), and z direction stress (S33). In generally, the rubber shock absorber model-1 and model-2 have higher stress than model-3.

Figure 33 represents the damping property of the rubber shock absorber from the non-linear viscoelastic simulation. The result shows that the rubber shock absorber model-1 has the highest damping value and this is followed by the rubber shock absorber model-2 and model-3, respectively.

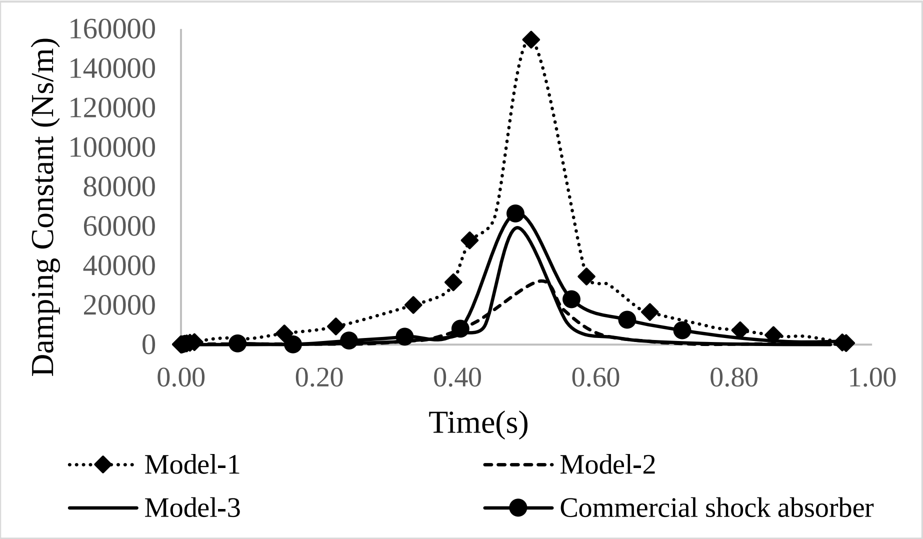


Figure 33 Damping and time relationship of rubber shock absorber from non-linear viscoelastic simulation

Table 9 Damping coefficient of three models of rubber shock absorber

Rubber Shock Absorber	Damping (Ns/m)
Model-1	154,595
Model-2	32,169
Model-3	59,256

Table 9 list the damping value of the rubber shock absorber for three different models. The damping value for the rubber shock absorber model-1 is 154,595Ns/m, model-2 is 32,169Ns/m, and model-3 is 59,256Ns/m. Rubber shock absorber model-1 has the biggest damping value while rubber shock absorber model-2 has the lowest damping value.

Table 10 Percentage of different in stiffness value of each type of shock absorber made of natural rubber from the commercial shock absorber

Rubber shock absorber	Stiffness difference (%)	Damping difference (%)
Model-1	54	133
Model-2	18	52
Model-3	8	11

Table 10 shows the percentage of different in stiffness and damping property between each rubber shock absorber and the commercial shock absorber. The rubber shock absorber model-1 has the percentage of different from the commercial shock absorber about 54% in stiffness and about 133% in damping coefficient. On the other hand, the rubber shock absorber model-2 is different around 18% in stiffness and 52% in damping value from the commercial shock absorber. Nevertheless, the stiffness and damping coefficient of rubber shock absorber model-3 are different from the commercial shock absorber about 8% and 11%, respectively.

According to the result in table 10, the rubber shock absorber model-3 provides a closed result to the commercial shock absorber than rubber shock absorber model-1 and model-2. For this reason, rubber shock absorber model-3 is selected as a prototype to be fabricated.

3.5 Prototype Testing

3.5.1 Stiffness Property

Figure 31 represents the force and displacement relationship of rubber shock absorber model-3 from simulation and experiment compared with the result of testing of the steel coil spring. From the experiment result, the stiffness coefficient of rubber shock absorber model-3 is 38,652N/m and the steel coil spring is 42,597 N/m. The percentage of error between experiment and simulation of rubber shock absorber model-3 is about 15%. The different of rubber shock absorber model-3 and the steel coil spring in stiffness is 9%.

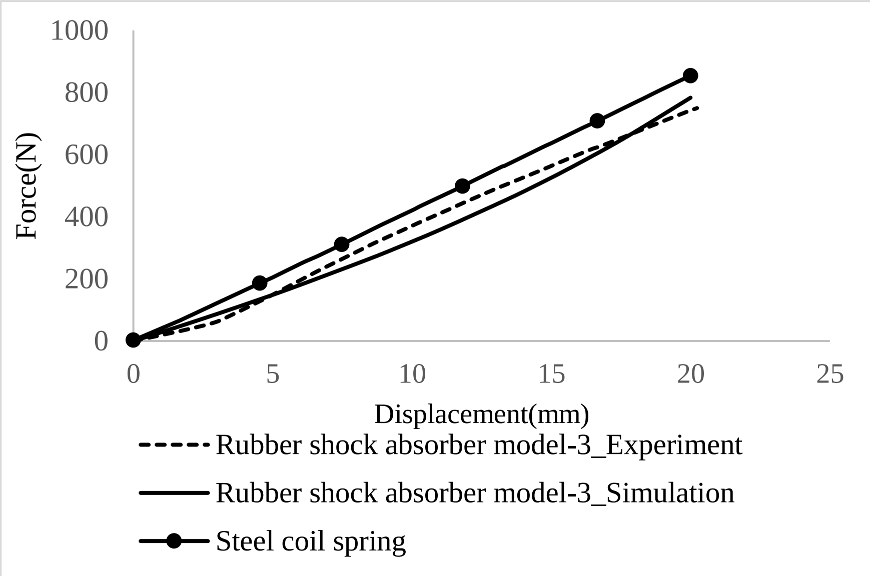


Figure 34 Force and displacement relationship of rubber shock absorber from simulation and experiment along with the steel coil spring

3.5.2 Damping Property

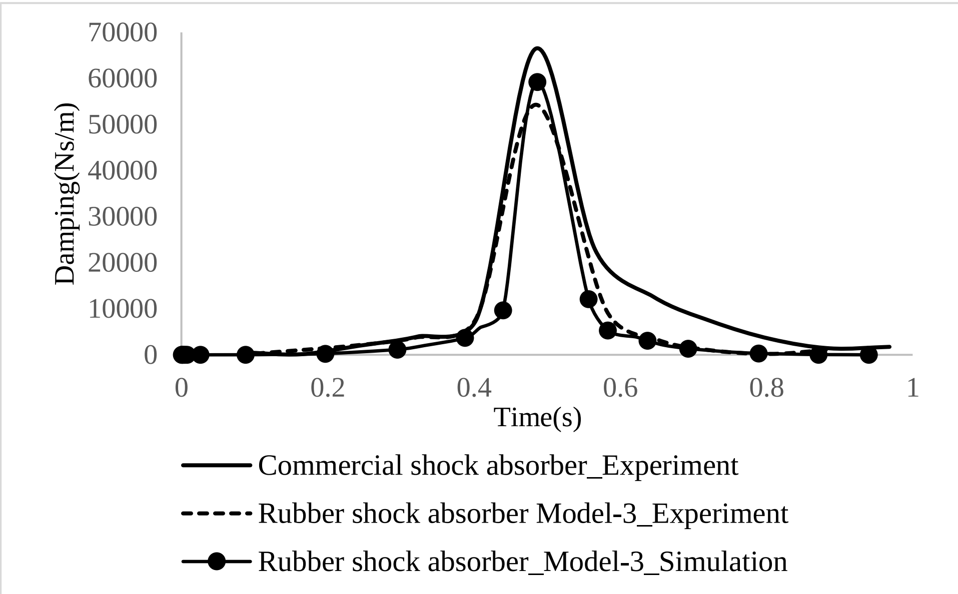
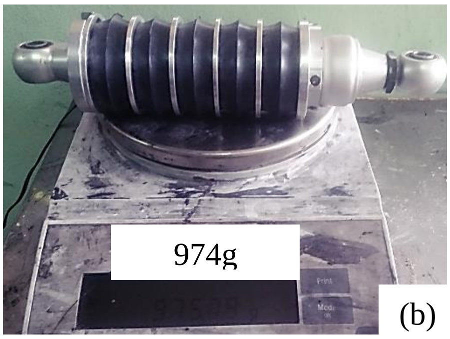


Figure 35 Damping and time relationship of rubber shock absorber from simulation and experiment along with the commercial shock absorber from testing

Figure 35 shows the damping property of the rubber shock absorber model-3 from simulation and testing compared with the result of testing of the commercial shock absorber. From the experiment, the rubber shock absorber model-3 has the damping constant of 54,286Ns/m and the commercial absorber has the damping constant of 66,429Ns/m. The percentage of error between simulation and experiment of the rubber shock absorber model-3 is about 19%. The percentage of different between rubber shock absorber model-3 and the commercial shock absorber in damping coefficient is about 11%.

Figure 36 shows the weight of the commercial shock absorber and the rubber shock absorber model-3. The commercial shock absorber has the weight of about 1,307g and the rubber shock absorber model-3 has the weight of about 974 g. The rubber shock absorber model-3 is lighter than the commercial shock absorber about 25%.

(a)



(b)

Figure 36 (a) Weight of the commercial shock absorber; (b) Weight of the rubber shock absorber model-3

Table 11 Stiffness and damping to weight ratio of the commercial shock absorber

	Commercial shock absorber	Rubber shock absorber model-3
Stiffness to weight ratio(N.g^{-1}/m)	33	40
Damping to weight ratio(Ns.g^{-1}/m)	51	56

Table 11 shows the stiffness to weight ratio and the damping to weight ratio of the commercial shock absorber and the rubber shock absorber model-3. The stiffness value to weight ratio for the commercial shock absorb is about 32 N.g^{-1}/m and for the rubber shock absorber model-3 is about 40 $N.g^{-1}/m$. In addition, the damping value to the weight ratio for the commercial shock absorber is around 51 $Ns.g^{-1}/m$ and for the rubber shock absorber model-3 is about 56 $Ns.g^{-1}/m$.

3.5.3 Fatigue Test

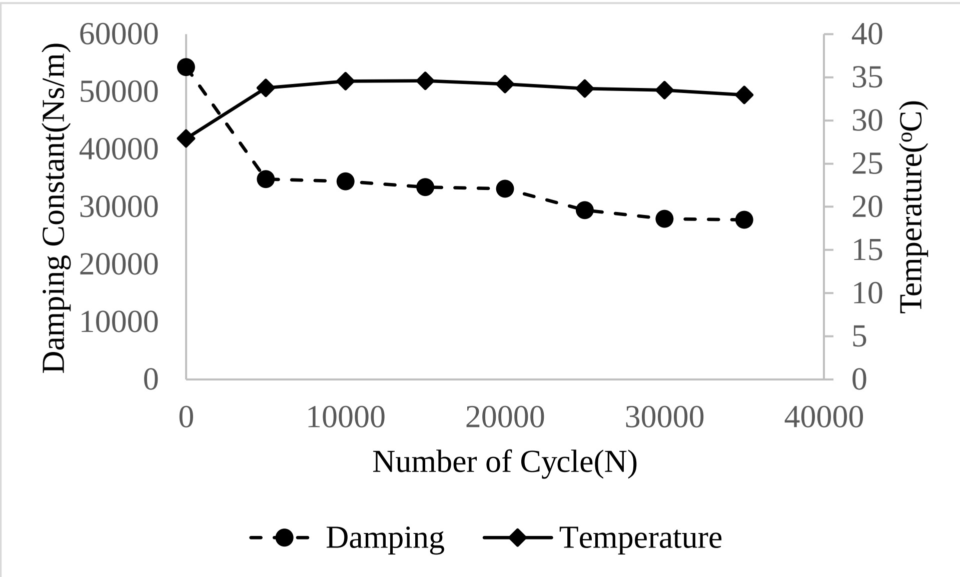


Figure 37 Relationship of damping and temperature subjected to fatigue load

Figure 37 represents the damping and temperature relationship with the number of cyclic loading when the rubber shock absorber is subjected to the fatigue load. The result shows that the damping value decreases exponentially between the 1st cycle and 5,000th cycle. After that, the damping value becomes smaller. Furthermore, the temperature gets higher between 1st cycle and 5,000th cycle and then it drops down very slowly.

In conclusion, the damping property and temperature change with the number of cyclic loading especially at the first stage of fatigue load.

CHAPTER 4
CONCLUSIONS

The aim of this research is to design a light-weight shock absorber made of natural rubber for the motorcycle. Based on the result of experiment, the weight of the shock absorber made of natural rubber is lower than the commercial shock absorber about 25%. The damping property and stiffness property of rubber shock absorber and the commercial shock absorber shows in good agreement.

The rubber material is formulated to get the desired mechanical properties. According to the material experiment, the compound A-1 provide better mechanical properties compared to the other compounds. Therefore, the rubber compound A-1 is selected to be used in the design of the shock absorber made of natural rubber. Three rubber shock absorbers are designed and simulated using finite element analysis. The rubber shock absorber model-3 shows the good results in stiffness and damping property with the commercial shock absorber than the other models. Therefore, the rubber shock absorber model-3 is selected as a prototype to be fabricated. The results show a good agreement between experiment and simulation.

The future research should be studied the improvement for the fatigue life of the rubber shock absorber. The rubber shock absorber should be tested with different frequencies until it is cracked. The rubber shock absorber should be applied in the real motorcycle.

The shock absorber made of natural rubber provides some advantages such as:

- It has a lower weight than the commercial shock absorber.
- It is easy to install and maintain. When any rubber pad is broken, it can be replaced just a single piece.
- Since the rubber pad is freely assembled, it can be used in different models of motorcycle.
- Its stiffness and damping property can be changed according to the actual needs by modification the rubber compound.

In conclusion, the rubber shock absorber shows some benefits compared to the commercial shock absorber. It is practical and can be replaced in some cases for the existing shock absorber.

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APPENDIX 1

Displacement of the Eccentric Cam's Follower

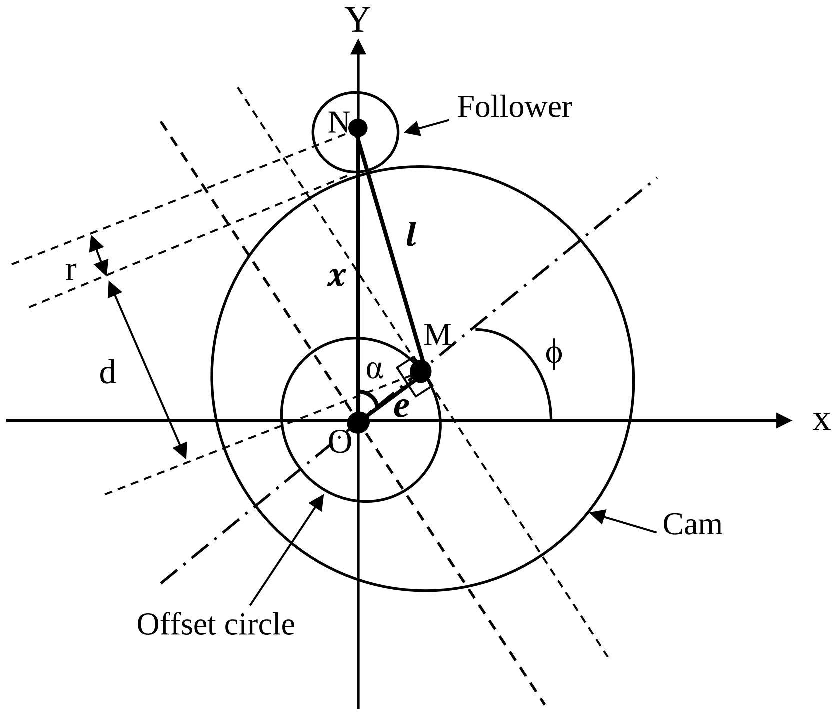

Figure 1. Nomenclature of eccentric cam at an angle

Definition:

- M : a center of a cam,
- O : a center of an offset circle (it's offset e = 10mm from the center of the cam),
- N : a center of a follower,
- e : an eccentricity,
- l : a rod from a center of the cam to a center of the follower,
- d : a radius of the Cam,
- r : a radius of the follower,
- x : a displacement of the follower from the center of offset circle,
- α : an angle of the offset circle from the vertical axe,
- ϕ : an angle of the offset circle from the horizontal axe.

Position of the follower with respect to the offset circle:

In Δ MON of Figure 1, we have:

$$l^2 = x^2 + e^2 - 2x.e.cos\alpha\ , \qquad \textit{(cosine's law)} \qquad (1)$$

$$l^2 - e^2 + (e.cos\alpha)^2 = x^2 - 2x.e.cos\alpha + (e.cos\alpha)^2,\ \textit{[we add}: (e.cos\alpha)^2\textit{]} \qquad (2)$$

$$l^2 - e^2 + (e.cos\alpha)^2 = (x - e.cos\alpha)^2, \qquad (3)$$

$$\Rightarrow\ x = e.cos\alpha + \sqrt{l^2 - e^2 + (e.cos\alpha)^2} \qquad (4)$$

$$x = e.cos\alpha + \sqrt{l^2 - e^2(1 - cos^2\alpha)} \qquad (5)$$

We can say,

$$x = e.\cos\left(\frac{\pi}{2} - \phi\right) + \sqrt{l^2 - e^2[1 - cos^2\left(\frac{\pi}{2} - \phi\right)]}\ ,\ \left(\alpha = \frac{\pi}{2} - \phi\right) \qquad (6)$$

$$x = e.\sin(\phi) + \sqrt{l^2 - e^2[1 - sin^2(\phi)]} \qquad (7)$$

$$\Leftrightarrow\ x(t) = e.\sin(\omega t) + \sqrt{l^2 - e^2[1 - sin^2(\omega t)]}\ ,\ (\phi = \omega t) \qquad (8)$$

At $\text{time}(t) = 0$, the cam is at the position of angle $\phi = -90$ degree (Fig.2) and the position of the follower is $x = 0$ (mm).

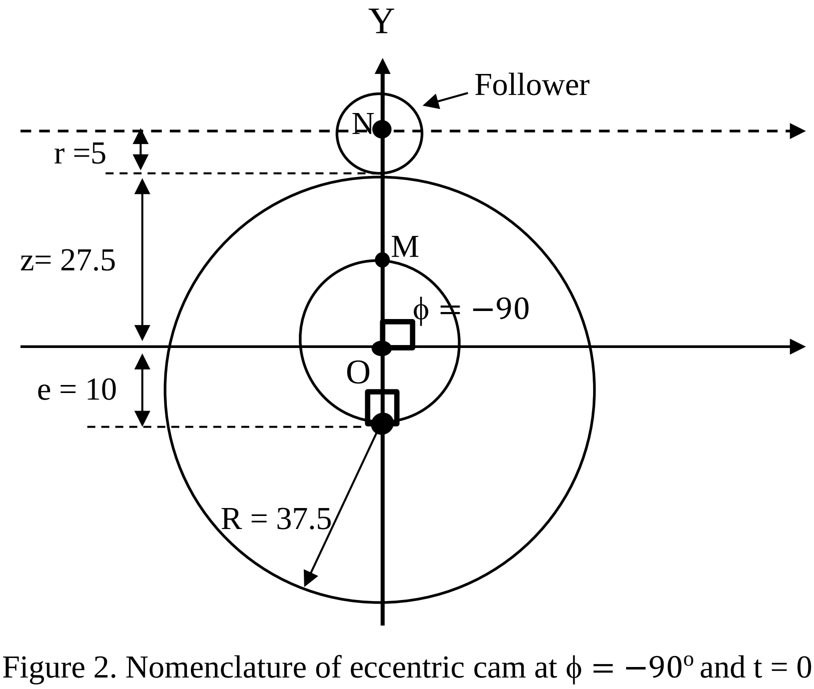

Figure 2. Nomenclature of eccentric cam at $\phi = -90^{o}$ and t = 0.

So, the position of the follower from the center of the offset circle will be,

$$x(t) = e.\sin\left(\omega t - \frac{\pi}{2}\right) + \sqrt{l^2 - e^2\left[1 - sin^2\left(\omega t - \frac{\pi}{2}\right)\right]} - 32.5(\mathrm{mm}) \tag{9}$$

Where,

$e = 10mm,$

$l = d + r = 42.5mm, (d = 37.5mm, r = 5mm)$

Therefore,

$$x(t) = 10\sin\left(2\pi t - \frac{\pi}{2}\right) + \sqrt{42.5^2 - 10^2\left[1 - sin^2\left(2\pi t - \frac{\pi}{2}\right)\right]} - 32.5\ (\mathrm{mm}) \tag{10}$$

$$x'(t) = \frac{20\pi\cos\left(2\pi t - \frac{\pi}{2}\right) + \frac{1}{2}(400\pi\cos\left(2\pi t - \frac{\pi}{2}\right)\sin\left(2\pi t - \frac{\pi}{2}\right)}{\sqrt{42.5^2 - 10^2(1 - sin^2\left(2\pi t - \frac{\pi}{2}\right)}}(mm/s) \tag{11}$$

APPENDIX 2

Damping Constant Calculation

At time (t) = 0.484s

Velocity Calculation

$$x'(t) = v(t) \quad = \frac{20\pi \cos\left(2\pi t - \frac{\pi}{2}\right) + \frac{1}{2}(400\pi \cos\left(2\pi t - \frac{\pi}{2}\right) \sin\left(2\pi t - \frac{\pi}{2}\right)}{\sqrt{42.5^2 - 10^2(1 - sin^2\left(2\pi t - \frac{\pi}{2}\right)}}$$

$$v(= \frac{20\pi \cos\left(2\pi(0.48 \ldots) - \frac{\pi}{2}\right) + \frac{1}{2}(400\pi \cos\left(2\pi(0.48 \ldots) - \frac{\pi}{2}\right) \sin\left(2\pi(0.48 \ldots) - \frac{\pi}{2}\right)}{\sqrt{42.5^2 - 10^2(1 - sin^2\left(2\pi(0.48 \ldots) - \frac{\pi}{2}\right)}}$$

$$= 6.15\text{mm/s}$$

Damping Calculation

$$Damping\ Coefficient: D\ (t) \quad = \frac{F(t) - kx(t)}{v(t)} = \frac{1104.5384 - 38.652 \times 19.94}{6.15} = 54{,}286\text{Ns}/m$$

Commercial Shock Absorber

Harmonic test (damping property)					
Time (s)	Force (N)	Velocity (mm/s)	Stiffness K(N/mm)	X (mm)	Damping (Ns/m)
0.07974	37.5144	3.02E+01	38.652	0.956780528	1.77E+01
0.16098	201.6448	5.33E+01	38.652	3.840017455	9.99E+02
0.2422	453.642	6.28E+01	38.652	8.319791738	2.10E+03
0.32112	729.8452	5.67E+01	38.652	13.35356749	3.77E+03
0.40316	973.8456	3.59E+01	38.652	17.8191231	7.94E+03
0.4844	1104.5384	6.15E+00	38.652	19.94073286	5.43E+04
0.58126	1007.9104	-3.07E+01	38.652	18.44277203	9.61E+03
0.6516	746.2504	-5.12E+01	38.652	15.00768964	3.25E+03
0.72426	464.618	-6.20E+01	38.652	10.44840388	9.80E+02
0.80548	202.664	-5.91E+01	38.652	5.532025633	1.89E+02
0.8844	32.0852	-4.17E+01	38.652	2.001754125	1.09E+03
0.96566	81.4772	-1.35E+01	38.652	0.177910715	5.55E+03

APPENDIX 3

INP file for Simulation of Shock Absorber Made of Natural Rubber

1. INP file for Hyperelastic Simulation of Rubber Shock Absorber Model-1

```
*Heading
** Job name: Job-1 Model name:
Model-1
** Generated by: Abaqus/CAE 6.13-1
*Preprint, echo=NO, model=NO,
history=NO, contact=NO
**
** PARTS
**
*Part, name=Rigid-bot
*End Part
**
*Part, name=Rigid-top
*End Part
**
*Part, name="Rubber pad"
*End Part
**
*Part, name=Steel-1
*End Part
**
*Part, name=Steel-6
*End Part
**
*Part, name=Steel_middle
*End Part
**
**
** ASSEMBLY
**
*Assembly, name=Assembly
**
*Instance, name="Rubber pad-1",
part="Rubber pad"
          0.,           2.,           0.
*Node
      1,          25.,          12.
      2,          25.,          24.
      3,          20.,          24.
 ------------------------------
     91,    28.333334,           2.
*Element, type=CAX4H
 1,  1, 10, 52, 23
 2, 10, 11, 53, 52
 3, 11, 12, 54, 53
 ---------------------
72, 91, 46,  9, 47
*Nset, nset=_PickedSet6, internal,
generate
  1,  91,   1
*Elset, elset=_PickedSet6, internal,
generate
  1,  72,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet6,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-2",
part="Rubber pad"
          0.,          28.,           0.
*Node
      1,          25.,          12.
      2,          25.,          24.
      3,          20.,          24.
--------------------------------------
     91,    28.333334,           2.
*Element, type=CAX4H
 1,  1, 10, 52, 23
 2, 10, 11, 53, 52
 3, 11, 12, 54, 53
 ----------------------------------------------
72, 91, 46,  9, 47
*Nset, nset=_PickedSet6, internal,
generate
  1,  91,   1
*Elset, elset=_PickedSet6, internal,
generate
```

```
  1,  72,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet6,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-3",
part="Rubber pad"
         0.,          54.,           0.
*Node
      1,          25.,          12.
      2,          25.,          24.
      3,          20.,          24.
-------------------------------------
     91,    28.333334,           2.
*Element, type=CAX4H
 1,  1, 10, 52, 23
 2, 10, 11, 53, 52
 3, 11, 12, 54, 53
--------------------------------------
72, 91, 46,  9, 47
*Nset, nset=_PickedSet6, internal,
generate
  1,  91,   1
*Elset, elset=_PickedSet6, internal,
generate
  1,  72,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet6,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-4",
part="Rubber pad"
         0.,          80.,           0.
*Node
      1,          25.,          12.
      2,          25.,          24.
      3,          20.,          24.
      -------------------------------
     91,    28.333334,           2.
*Element, type=CAX4H
 1,  1, 10, 52, 23
 2, 10, 11, 53, 52
 3, 11, 12, 54, 53
-------------------------------------
72, 91, 46,  9, 47
*Nset, nset=_PickedSet6, internal,
generate
  1,  91,   1
*Elset, elset=_PickedSet6, internal,
generate
  1,  72,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet6,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-5",
part="Rubber pad"
         0.,         106.,           0.
*Node
      1,          25.,          12.
      2,          25.,          24.
      3,          20.,          24.
----------------------------------------
     91,    28.333334,           2.
*Element, type=CAX4H
 1,  1, 10, 52, 23
 2, 10, 11, 53, 52
 3, 11, 12, 54, 53
----------------------------------------------
72, 91, 46,  9, 47
*Nset, nset=_PickedSet6, internal,
generate
  1,  91,   1
*Elset, elset=_PickedSet6, internal,
generate
  1,  72,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet6,
material=Rubber-55
,
*End Instance
**
*Instance, name=Rigid-top-1,
part=Rigid-top
         0.,         132.,           0.
*Node
      1,           0.,           0.
      2,           5.,           0.
      3,          10.,           0.
      -------------------------------------------
```

```
     8,          35.,           0.
*Element, type=RAX2
1, 1, 2
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
*Node
     9,           0.,           0.,           0.
*Nset, nset=Rigid-top-1-RefPt_, internal
9,
*End Instance
**
*Instance, name=Rigid-bot-1,
part=Rigid-bot
*Node
     1,           0.,           0.
     2,           5.,           0.
     3,          10.,           0.
     4,          15.,           0.
     5,          20.,           0.
     6,          25.,           0.
     7,          30.,           0.
     8,          35.,           0.
*Element, type=RAX2
1, 1, 2
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
*Node
     9,           0.,           0.,           0.
*Nset, nset=Rigid-bot-1-RefPt_, internal
9,
*End Instance
**
*Instance, name=Steel_2,
part=Steel_middle
          0.,          26.,           0.
*Node
     1,          20.,           7.
     2,          19.,           7.
----------------------------------
     20,          23.,           2.
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
---------------------------------
 9, 18, 17, 14, 13
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_3,
part=Steel_middle
          0.,          52.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
--------------------------------
     20,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
-----------------------------
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_4,
part=Steel_middle
          0.,          78.,           0.
*Node
```

```
     1,         20.,          2.
     2,         20.,          0.
     3,         23.,          2.
-------------------------------------
    20,         20.,        -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_5,
part=Steel_middle
         0.,        104.,          0.
*Node
     1,         20.,          2.
     2,         20.,          0.
     3,         23.,          2.
-------------------------------------
    20,         20.,        -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
---------------------------
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel-1, part=Steel-1
*Node
     1,         20.,          2.
     2,         20.,          0.
     3,         23.,          2.
-----------------------------------
    14,         19.,         3.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  2,  1, 14, 11
6,  1, 12, 13, 14
*Nset, nset=_PickedSet2, internal,
generate
  1,  14,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  6,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel-6, part=Steel-6
         0.,        130.,          0.
*Node
     1,         20.,          2.
     2,         20.,          0.
     3,         23.,          2.
----------------------------------
    16,         20.,        -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  1, 12, 14,  2
6,  2, 14, 15, 16
7, 16, 15, 13, 11
```

```
*Nset, nset=_PickedSet2, internal,
generate
  1,  16,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  7,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Nset, nset=_PickedSet96, internal,
instance=Rigid-bot-1, generate
 1,  8,  1
*Elset, elset=_PickedSet96, internal,
instance=Rigid-bot-1, generate
 1,  7,  1
*Nset, nset=_PickedSet117, internal,
instance=Rigid-top-1
 9,
*Nset, nset=_PickedSet118, internal,
instance=Rigid-top-1, generate
 1,  8,  1
*Elset, elset=_PickedSet118, internal,
instance=Rigid-top-1, generate
 1,  7,  1
*Nset, nset=_PickedSet119, internal,
instance=Rigid-bot-1
 9,
*Nset, nset=_PickedSet120, internal,
instance=Rigid-bot-1, generate
 1,  8,  1
*Elset, elset=_PickedSet120, internal,
instance=Rigid-bot-1, generate
 1,  7,  1
*Nset, nset=_PickedSet123, internal,
instance=Rigid-top-1, generate
 1,  8,  1
*Elset, elset=_PickedSet123, internal,
instance=Rigid-top-1, generate
 1,  7,  1
*Nset, nset=_PickedSet174, internal,
instance="Rubber pad-1"
  3,  4,  8, 17, 18, 19, 20, 21, 38, 39, 40,
41, 42
*Nset, nset=_PickedSet174, internal,
instance="Rubber pad-2"
  3,  4,  8, 17, 18, 19, 20, 21, 38, 39, 40,
41, 42
*Nset, nset=_PickedSet174, internal,
instance="Rubber pad-3"
  3,  4,  8, 17, 18, 19, 20, 21, 38, 39, 40,
41, 42
*Nset, nset=_PickedSet174, internal,
instance="Rubber pad-4"
  3,  4,  8, 17, 18, 19, 20, 21, 38, 39, 40,
41, 42
*Nset, nset=_PickedSet174, internal,
instance=Steel_4
 12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet174, internal,
instance="Rubber pad-5"
  3,  4,  8, 17, 18, 19, 20, 21, 38, 39, 40,
41, 42
*Nset, nset=_PickedSet174, internal,
instance=Steel_2, generate
  2,  12,   2
*Nset, nset=_PickedSet174, internal,
instance=Steel-1
 11, 13, 14
*Nset, nset=_PickedSet174, internal,
instance=Steel_3
 12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet174, internal,
instance=Steel_5
 12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet174, internal,
instance=Steel-6, generate
 12,  15,   1
*Elset, elset=_PickedSet174, internal,
instance="Rubber pad-1"
 13, 14, 15, 16, 17, 18, 49, 50, 51, 52,
53, 54
*Elset, elset=_PickedSet174, internal,
instance="Rubber pad-2"
 13, 14, 15, 16, 17, 18, 49, 50, 51, 52,
53, 54
*Elset, elset=_PickedSet174, internal,
instance="Rubber pad-3"
 13, 14, 15, 16, 17, 18, 49, 50, 51, 52,
53, 54
*Elset, elset=_PickedSet174, internal,
instance="Rubber pad-4"
 13, 14, 15, 16, 17, 18, 49, 50, 51, 52,
53, 54
```

```
*Elset, elset=_PickedSet174, internal,
instance=Steel_4, generate
 5,  9,  1
*Elset, elset=_PickedSet174, internal,
instance="Rubber pad-5"
 13, 14, 15, 16, 17, 18, 49, 50, 51, 52,
53, 54
*Elset, elset=_PickedSet174, internal,
instance=Steel_2, generate
 1,  5,  1
*Elset, elset=_PickedSet174, internal,
instance=Steel-1
 5, 6
*Elset, elset=_PickedSet174, internal,
instance=Steel_3, generate
 5,  9,  1
*Elset, elset=_PickedSet174, internal,
instance=Steel_5, generate
 5,  9,  1
*Elset, elset=_PickedSet174, internal,
instance=Steel-6, generate
 5,  7,  1
*Elset, elset=_R1-bot_S2, internal,
instance="Rubber pad-1", generate
 60,  72,   6
*Elset, elset=_R1-bot_S4, internal,
instance="Rubber pad-1", generate
 37,  49,   6
*Surface, type=ELEMENT, name=R1-
bot
_R1-bot_S2, S2
_R1-bot_S4, S4
*Elset, elset=_R1-top_S2, internal,
instance="Rubber pad-1", generate
  6,  18,   6
*Elset, elset=_R1-top_S4, internal,
instance="Rubber pad-1", generate
 19,  31,   6
*Surface, type=ELEMENT, name=R1-
top
_R1-top_S2, S2
_R1-top_S4, S4
*Elset, elset=_R2-bot_S2, internal,
instance="Rubber pad-2", generate
 60,  72,   6
*Elset, elset=_R2-bot_S4, internal,
instance="Rubber pad-2", generate
 37,  49,   6
*Surface, type=ELEMENT, name=R2-
bot
_R2-bot_S2, S2
_R2-bot_S4, S4
*Elset, elset=_R2-top_S2, internal,
instance="Rubber pad-2", generate
  6,  18,   6
*Elset, elset=_R2-top_S4, internal,
instance="Rubber pad-2", generate
 19,  31,   6
*Surface, type=ELEMENT, name=R2-
top
_R2-top_S2, S2
_R2-top_S4, S4
*Elset, elset=_R3-bot_S2, internal,
instance="Rubber pad-3", generate
 60,  72,   6
*Elset, elset=_R3-bot_S4, internal,
instance="Rubber pad-3", generate
 37,  49,   6
*Surface, type=ELEMENT, name=R3-
bot
_R3-bot_S2, S2
_R3-bot_S4, S4
*Elset, elset=_R3-top_S2, internal,
instance="Rubber pad-3", generate
  6,  18,   6
*Elset, elset=_R3-top_S4, internal,
instance="Rubber pad-3", generate
 19,  31,   6
*Surface, type=ELEMENT, name=R3-
top
_R3-top_S2, S2
_R3-top_S4, S4
*Elset, elset=_R4-bot_S2, internal,
instance="Rubber pad-4", generate
 60,  72,   6
*Elset, elset=_R4-bot_S4, internal,
instance="Rubber pad-4", generate
 37,  49,   6
*Surface, type=ELEMENT, name=R4-
bot
_R4-bot_S2, S2
_R4-bot_S4, S4
*Elset, elset=_R4-top_S2, internal,
instance="Rubber pad-4", generate
  6,  18,   6
```

```
*Elset, elset=_R4-top_S4, internal,
instance="Rubber pad-4", generate
 19,  31,   6
*Surface, type=ELEMENT, name=R4-
top
_R4-top_S2, S2
_R4-top_S4, S4
*Elset, elset=_R5-bot_S2, internal,
instance="Rubber pad-5", generate
 60,  72,   6
*Elset, elset=_R5-bot_S4, internal,
instance="Rubber pad-5", generate
 37,  49,   6
*Surface, type=ELEMENT, name=R5-
bot
_R5-bot_S2, S2
_R5-bot_S4, S4
*Elset, elset=_R5-top_S2, internal,
instance="Rubber pad-5", generate
  6,  18,   6
*Elset, elset=_R5-top_S4, internal,
instance="Rubber pad-5", generate
 19,  31,   6
*Surface, type=ELEMENT, name=R5-
top
_R5-top_S2, S2
_R5-top_S4, S4
*Elset, elset=_Rigid-bot_SNEG,
internal, instance=Rigid-bot-1, generate
 1,  7,  1
*Surface, type=ELEMENT,
name=Rigid-bot
_Rigid-bot_SNEG, SNEG
*Elset, elset=_Rigid-top_SPOS,
internal, instance=Rigid-top-1, generate
 1,  7,  1
*Surface, type=ELEMENT,
name=Rigid-top
_Rigid-top_SPOS, SPOS
*Elset, elset=_S1_bot_S2, internal,
instance=Steel-1, generate
 1,  4,  1
*Elset, elset=_S1_bot_S4, internal,
instance=Steel-1
 5,
*Surface, type=ELEMENT,
name=S1_bot
_S1_bot_S2, S2
_S1_bot_S4, S4
*Elset, elset=_S1_top_S1, internal,
instance=Steel-1
 6,
*Elset, elset=_S1_top_S4, internal,
instance=Steel-1, generate
 1,  4,  1
*Surface, type=ELEMENT,
name=S1_top
_S1_top_S1, S1
_S1_top_S4, S4
*Elset, elset=_S2-top_S4, internal,
instance=Steel_2
 1, 2, 6, 7, 8, 9
*Surface, type=ELEMENT, name=S2-
top
_S2-top_S4, S4
*Elset, elset=_S2_bot_S2, internal,
instance=Steel_2, generate
 6,  9,  1
*Elset, elset=_S2_bot_S4, internal,
instance=Steel_2
 4, 5
*Surface, type=ELEMENT,
name=S2_bot
_S2_bot_S2, S2
_S2_bot_S4, S4
*Elset, elset=_S3-bot_S2, internal,
instance=Steel_3, generate
 1,  4,  1
*Elset, elset=_S3-bot_S4, internal,
instance=Steel_3
 8, 9
*Surface, type=ELEMENT, name=S3-
bot
_S3-bot_S2, S2
_S3-bot_S4, S4
*Elset, elset=_S3-top_S4, internal,
instance=Steel_3, generate
 1,  6,  1
*Surface, type=ELEMENT, name=S3-
top
_S3-top_S4, S4
*Elset, elset=_S4-bot_S2, internal,
instance=Steel_4, generate
 1,  4,  1
*Elset, elset=_S4-bot_S4, internal,
instance=Steel_4
```

8, 9
*Surface, type=ELEMENT, name=S4-bot
_S4-bot_S2, S2
_S4-bot_S4, S4
*Elset, elset=_S4-top_S4, internal, instance=Steel_4, generate
1, 6, 1
*Surface, type=ELEMENT, name=S4-top
_S4-top_S4, S4
*Elset, elset=_S5-bot_S2, internal, instance=Steel_5, generate
1, 4, 1
*Elset, elset=_S5-bot_S4, internal, instance=Steel_5
8, 9
*Surface, type=ELEMENT, name=S5-bot
_S5-bot_S2, S2
_S5-bot_S4, S4
*Elset, elset=_S5-top_S4, internal, instance=Steel_5, generate
1, 6, 1
*Surface, type=ELEMENT, name=S5-top
_S5-top_S4, S4
*Elset, elset=_S6-bot_S2, internal, instance=Steel-6, generate
1, 4, 1
*Elset, elset=_S6-bot_S4, internal, instance=Steel-6
6, 7
*Surface, type=ELEMENT, name=S6-bot
_S6-bot_S2, S2
_S6-bot_S4, S4
*Elset, elset=_S6-top_S1, internal, instance=Steel-6
5,
*Elset, elset=_S6-top_S4, internal, instance=Steel-6, generate
1, 4, 1
*Surface, type=ELEMENT, name=S6-top
_S6-top_S1, S1
_S6-top_S4, S4
** Constraint: Constraint-11
*Tie, name=Constraint-11, adjust=yes, type=SURFACE TO SURFACE
S6-top, Rigid-top
** Constraint: Constraint-12
*Tie, name=Constraint-12, adjust=yes, type=SURFACE TO SURFACE
S1_bot, Rigid-bot
** Constraint: Rigid body
*Rigid Body, ref node=_PickedSet117, elset=_PickedSet118
** Constraint: Rigid body-bot
*Rigid Body, ref node=_PickedSet119, elset=_PickedSet120
*End Assembly
*Amplitude, name=Amp-1
0., 0.000214577, 0.898, 1.508784, 1., 1.676917, 1.84, 3.049886
2., 3.331685, 2.719, 4.531372, 3., 4.990602, 3.63, 6.038129
4., 6.679118, 4.48, 7.483423, 5., 8.327878, 5.369, 8.929956
6., 10.00321, 6.214, 10.36071, 7., 11.66673, 7.085, 11.80775
7.95, 13.23564, 8., 13.32452, 8.818, 14.6849, 9., 14.99463
9.698, 16.14583, 10., 16.66722, 10.531, 17.55829, 11., 18.33884
11.406, 19.00816, 12., 19.98798
**
** MATERIALS
**
*Material, name=Aluminum
*Density
2.81e-09,
*Elastic
70000., 0.32
*Material, name=Rubber-55
*Density
1.18e-09,
*Hyperelastic, yeoh
0.5, 0.18, 0.023, 0., 0., 0.

```
**
** INTERACTION PROPERTIES
**
*Surface Interaction, name=IntProp-1
1.,
*Friction, slip tolerance=1e-05
 0.8,
**
** BOUNDARY CONDITIONS
**
** Name: BC-X Type:
Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet174, XSYMM
** Name: BC-bot Type:
Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet96, ENCASTRE
** Name: comp Type:
Displacement/Rotation
*Boundary
_PickedSet123, 1, 1
_PickedSet123, 2, 2
_PickedSet123, 6, 6
**
** INTERACTIONS
**
** Interaction: Int-1
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R1-bot, S1_top
** Interaction: Int-2
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R1-top, S2_bot
** Interaction: Int-3
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R2-bot, S2-top
** Interaction: Int-4
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R2-top, S3-bot
** Interaction: Int-5
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R3-bot, S3-top
** Interaction: Int-6
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R3-top, S4-bot
** Interaction: Int-7
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R4-bot, S4-top
** Interaction: Int-8
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R4-top, S5-bot
** Interaction: Int-9
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R5-bot, S5-top
** Interaction: Int-10
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R5-top, S6-bot
** ----------------------------------------------
**
** STEP: Compression
**
*Step, name=Compression,
nlgeom=YES, inc=1000000
*Static, stabilize=0.0002, allsdtol=0.05,
continue=NO
0.0001, 12., 1e-09, 12.
**
** BOUNDARY CONDITIONS
**
** Name: BC-X Type:
Symmetry/Antisymmetry/Encastre
*Boundary, op=NEW
_PickedSet174, XSYMM
** Name: BC-bot Type:
Symmetry/Antisymmetry/Encastre
*Boundary, op=NEW
_PickedSet96, ENCASTRE
** Name: comp Type:
Displacement/Rotation
*Boundary, op=NEW
_PickedSet123, 1, 1
_PickedSet123, 2, 2, -20.
_PickedSet123, 6, 6
**
** OUTPUT REQUESTS
**
```

```
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
RF, RT, U, UT, V, VT
*Element Output, directions=YES
E, LE, MISES, NE, S
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
```

2. INP File for Hyperelastic Simulation of Rubber Shock Absorber Model-2

```
*Heading
** Job name: Job-1 Model name:
Model-1
** Generated by: Abaqus/CAE 6.13-1
*Preprint, echo=NO, model=NO,
history=NO, contact=NO
**
** PARTS
**
*Part, name=Rigid-bot
*End Part
**
*Part, name=Rigid-top
*End Part
**
*Part, name="Rubber pad"
*End Part
**
*Part, name=Steel-1
*End Part
**
*Part, name=Steel-6
*End Part
**
*Part, name=Steel_middle
*End Part
**
**
** ASSEMBLY
**
*Assembly, name=Assembly
**
*Instance, name="Rubber pad-1",
part="Rubber pad"
         0.,          2.,          0.
*Node
      1,         20.,         12.
      2,   23.8023567,         12.
      3,   23.8023567,         24.
--------------------------------------------
     70,    25.773077,   1.85084665
*Element, type=CAX4H
 1,  1, 10, 47, 21
 2, 10,  2, 11, 47
 3, 21, 47, 48, 20
-----------------------------------------
53, 46, 68, 69, 45
*Element, type=CAX3H
40, 67, 42, 43
41, 69, 30, 66
*Nset, nset=_PickedSet3, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet3, internal,
generate
  1,  53,   1
*Nset, nset=_PickedSet4, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet4, internal,
generate
  1,  53,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet3,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-2",
part="Rubber pad"
         0.,         28.,          0.
*Node
      1,         20.,         12.
      2,   23.8023567,         12.
      3,   23.8023567,         24.
----------------------------------------------
53, 46, 68, 69, 45
*Element, type=CAX3H
```

```
40, 67, 42, 43
41, 69, 30, 66
*Nset, nset=_PickedSet3, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet3, internal,
generate
  1,  53,   1
*Nset, nset=_PickedSet4, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet4, internal,
generate
  1,  53,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet3,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-3",
part="Rubber pad"
          0.,          54.,           0.
*Node
      1,          20.,          12.
      2,   23.8023567,          12.
      3,   23.8023567,          24.
  --------------------------------------
     70,    25.773077,   1.85084665
*Element, type=CAX4H
 1,  1, 10, 47, 21
 2, 10,  2, 11, 47
 3, 21, 47, 48, 20
----------------------------------------------
53, 46, 68, 69, 45
*Element, type=CAX3H
40, 67, 42, 43
41, 69, 30, 66
*Nset, nset=_PickedSet3, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet3, internal,
generate
  1,  53,   1
*Nset, nset=_PickedSet4, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet4, internal,
generate
  1,  53,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet3,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-4",
part="Rubber pad"
          0.,          80.,           0.
*Node
      1,          20.,          12.
      2,   23.8023567,          12.
      3,   23.8023567,          24.
-----------------------------------------
     70,    25.773077,   1.85084665
*Element, type=CAX4H
 1,  1, 10, 47, 21
 2, 10,  2, 11, 47
 3, 21, 47, 48, 20
-----------------------------------
53, 46, 68, 69, 45
*Element, type=CAX3H
40, 67, 42, 43
41, 69, 30, 66
*Nset, nset=_PickedSet3, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet3, internal,
generate
  1,  53,   1
*Nset, nset=_PickedSet4, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet4, internal,
generate
  1,  53,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet3,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-5",
part="Rubber pad"
          0.,         106.,           0.
```

```
*Node
     1,          20.,          12.
     2,   23.8023567,          12.
     3,   23.8023567,          24.
-----------------------------------------
    70,    25.773077,   1.85084665
*Element, type=CAX4H
 1,  1, 10, 47, 21
 2, 10,  2, 11, 47
 3, 21, 47, 48, 20
 ---------------------------------------------
53, 46, 68, 69, 45
*Element, type=CAX3H
40, 67, 42, 43
41, 69, 30, 66
*Nset, nset=_PickedSet3, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet3, internal,
generate
  1,  53,   1
*Nset, nset=_PickedSet4, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet4, internal,
generate
  1,  53,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet3,
material=Rubber-55
,
*End Instance
**
*Instance, name=Rigid-top-1,
part=Rigid-top
         0.,         132.,           0.
*Node
     1,           0.,           0.
     2,           5.,           0.
     3,          10.,           0.
     4,          15.,           0.
     5,          20.,           0.
     6,          25.,           0.
     7,          30.,           0.
     8,          35.,           0.
*Element, type=RAX2
1, 1, 2
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
*Node
     9,           0.,           0.,           0.
*Nset, nset=Rigid-top-1-RefPt_, internal
9,
*End Instance
**
*Instance, name=Rigid-bot-1,
part=Rigid-bot
*Node
     1,           0.,           0.
     2,           5.,           0.
     3,          10.,           0.
     4,          15.,           0.
     5,          20.,           0.
     6,          25.,           0.
     7,          30.,           0.
     8,          35.,           0.
*Element, type=RAX2
1, 1, 2
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
*Node
     9,           0.,           0.,           0.
*Nset, nset=Rigid-bot-1-RefPt_, internal
9,
*End Instance
**
*Instance, name=Steel_2,
part=Steel_middle
         0.,          26.,           0.
*Node
     1,          20.,           7.
     2,          19.,           7.
     3,          20.,          4.5
---------------------------------
    19,          26.,           2.
    20,          23.,           2.
*Element, type=CAX4R
1,  1,  2,  4,  3
```

```
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  9, 10, 12, 11
 6,  5,  7, 15, 20
 7, 20, 15, 16, 19
 8, 19, 16, 17, 18
 9, 18, 17, 14, 13
*Nset, nset=_PickedSet2, internal, generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal, generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2, material=Aluminum
,
*End Instance
**
*Instance, name=Steel_3, part=Steel_middle
          0.,          52.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
      ----------------------------
     20,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
-------------------------------
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal, generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal, generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2, material=Aluminum
,
*End Instance
**
*Instance, name=Steel_4, part=Steel_middle
          0.,          78.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
      --------------------------------
     20,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
--------------------------------------
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal, generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal, generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2, material=Aluminum
,
*End Instance
**
*Instance, name=Steel_5, part=Steel_middle
          0.,         104.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
------------------------------------
     20,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal, generate
```

```
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel-1, part=Steel-1
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
------------------------------------------------
     14,          19.,          3.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  2,  1, 14, 11
6,  1, 12, 13, 14
*Nset, nset=_PickedSet2, internal,
generate
  1,  14,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  6,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel-6, part=Steel-6
          0.,         130.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
----------------------------------------
     16,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  1, 12, 14,  2
6,  2, 14, 15, 16
7, 16, 15, 13, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  16,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  7,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Nset, nset=_PickedSet96, internal,
instance=Rigid-bot-1, generate
 1,  8,  1
*Elset, elset=_PickedSet96, internal,
instance=Rigid-bot-1, generate
 1,  7,  1
*Nset, nset=_PickedSet117, internal,
instance=Rigid-top-1
 9,
*Nset, nset=_PickedSet118, internal,
instance=Rigid-top-1, generate
 1,  8,  1
*Elset, elset=_PickedSet118, internal,
instance=Rigid-top-1, generate
 1,  7,  1
*Nset, nset=_PickedSet119, internal,
instance=Rigid-bot-1
 9,
*Nset, nset=_PickedSet120, internal,
instance=Rigid-bot-1, generate
 1,  8,  1
*Elset, elset=_PickedSet120, internal,
instance=Rigid-bot-1, generate
 1,  7,  1
*Nset, nset=_PickedSet123, internal,
instance=Rigid-top-1, generate
 1,  8,  1
*Elset, elset=_PickedSet123, internal,
instance=Rigid-top-1, generate
 1,  7,  1
*Nset, nset=_PickedSet162, internal,
instance="Rubber pad-1"
```

1, 4, 5, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26
*Nset, nset=_PickedSet162, internal, instance="Rubber pad-2"
1, 4, 5, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26
*Nset, nset=_PickedSet162, internal, instance="Rubber pad-3"
1, 4, 5, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26
*Nset, nset=_PickedSet162, internal, instance="Rubber pad-4"
1, 4, 5, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26
*Nset, nset=_PickedSet162, internal, instance=Steel_4
12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet162, internal, instance="Rubber pad-5"
1, 4, 5, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26
*Nset, nset=_PickedSet162, internal, instance=Steel_2, generate
2, 12, 2
*Nset, nset=_PickedSet162, internal, instance=Steel-1
11, 13, 14
*Nset, nset=_PickedSet162, internal, instance=Steel_3
12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet162, internal, instance=Steel_5
12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet162, internal, instance=Steel-6, generate
12, 15, 1
*Elset, elset=_PickedSet162, internal, instance="Rubber pad-1"
1, 3, 5, 7, 9, 11, 14, 16, 18, 20, 22, 24
*Elset, elset=_PickedSet162, internal, instance="Rubber pad-2"
1, 3, 5, 7, 9, 11, 14, 16, 18, 20, 22, 24
*Elset, elset=_PickedSet162, internal, instance="Rubber pad-3"
1, 3, 5, 7, 9, 11, 14, 16, 18, 20, 22, 24
*Elset, elset=_PickedSet162, internal, instance="Rubber pad-4"
1, 3, 5, 7, 9, 11, 14, 16, 18, 20, 22, 24
*Elset, elset=_PickedSet162, internal, instance=Steel_4, generate
5, 9, 1
*Elset, elset=_PickedSet162, internal, instance="Rubber pad-5"
1, 3, 5, 7, 9, 11, 14, 16, 18, 20, 22, 24
*Elset, elset=_PickedSet162, internal, instance=Steel_2, generate
1, 5, 1
*Elset, elset=_PickedSet162, internal, instance=Steel-1
5, 6
*Elset, elset=_PickedSet162, internal, instance=Steel_3, generate
5, 9, 1
*Elset, elset=_PickedSet162, internal, instance=Steel_5, generate
5, 9, 1
*Elset, elset=_PickedSet162, internal, instance=Steel-6, generate
5, 7, 1
*Elset, elset=_R1-bot_S1, internal, instance="Rubber pad-1", generate
49, 51, 1
*Elset, elset=_R1-bot_S3, internal, instance="Rubber pad-1"
23, 24
*Surface, type=ELEMENT, name=R1-bot
_R1-bot_S1, S1
_R1-bot_S3, S3
*Elset, elset=_R1-top_S2, internal, instance="Rubber pad-1"
29,
*Elset, elset=_R1-top_S3, internal, instance="Rubber pad-1"
11, 12, 31
*Elset, elset=_R1-top_S4, internal, instance="Rubber pad-1"
32,
*Surface, type=ELEMENT, name=R1-top
_R1-top_S2, S2

_R1-top_S3, S3
_R1-top_S4, S4
*Elset, elset=_R2-bot_S1, internal, instance="Rubber pad-2", generate
 49, 51,   1
*Elset, elset=_R2-bot_S3, internal, instance="Rubber pad-2"
 23, 24
*Surface, type=ELEMENT, name=R2-bot
_R2-bot_S1, S1
_R2-bot_S3, S3
*Elset, elset=_R2-top_S2, internal, instance="Rubber pad-2"
 29,
*Elset, elset=_R2-top_S3, internal, instance="Rubber pad-2"
 11, 12, 31
*Elset, elset=_R2-top_S4, internal, instance="Rubber pad-2"
 32,
*Surface, type=ELEMENT, name=R2-top
_R2-top_S2, S2
_R2-top_S3, S3
_R2-top_S4, S4
*Elset, elset=_R3-bot_S1, internal, instance="Rubber pad-3", generate
 49, 51,   1
*Elset, elset=_R3-bot_S3, internal, instance="Rubber pad-3"
 23, 24
*Surface, type=ELEMENT, name=R3-bot
_R3-bot_S1, S1
_R3-bot_S3, S3
*Elset, elset=_R3-top_S2, internal, instance="Rubber pad-3"
 29,
*Elset, elset=_R3-top_S3, internal, instance="Rubber pad-3"
 11, 12, 31
*Elset, elset=_R3-top_S4, internal, instance="Rubber pad-3"
 32,
*Surface, type=ELEMENT, name=R3-top
_R3-top_S2, S2
_R3-top_S3, S3
_R3-top_S4, S4
*Elset, elset=_R4-bot_S1, internal, instance="Rubber pad-4", generate
 49, 51,   1
*Elset, elset=_R4-bot_S3, internal, instance="Rubber pad-4"
 23, 24
*Surface, type=ELEMENT, name=R4-bot
_R4-bot_S1, S1
_R4-bot_S3, S3
*Elset, elset=_R4-top_S2, internal, instance="Rubber pad-4"
 29,
*Elset, elset=_R4-top_S3, internal, instance="Rubber pad-4"
 11, 12, 31
*Elset, elset=_R4-top_S4, internal, instance="Rubber pad-4"
 32,
*Surface, type=ELEMENT, name=R4-top
_R4-top_S2, S2
_R4-top_S3, S3
_R4-top_S4, S4
*Elset, elset=_R5-bot_S1, internal, instance="Rubber pad-5", generate
 49, 51,   1
*Elset, elset=_R5-bot_S3, internal, instance="Rubber pad-5"
 23, 24
*Surface, type=ELEMENT, name=R5-bot
_R5-bot_S1, S1
_R5-bot_S3, S3
*Elset, elset=_R5-top_S2, internal, instance="Rubber pad-5"
 29,
*Elset, elset=_R5-top_S3, internal, instance="Rubber pad-5"
 11, 12, 31
*Elset, elset=_R5-top_S4, internal, instance="Rubber pad-5"
 32,
*Surface, type=ELEMENT, name=R5-top
_R5-top_S2, S2

_R5-top_S3, S3
_R5-top_S4, S4
*Elset, elset=_Rigid-bot_SNEG, internal, instance=Rigid-bot-1, generate
 1, 7, 1
*Surface, type=ELEMENT, name=Rigid-bot
_Rigid-bot_SNEG, SNEG
*Elset, elset=_Rigid-top_SPOS, internal, instance=Rigid-top-1, generate
 1, 7, 1
*Surface, type=ELEMENT, name=Rigid-top
_Rigid-top_SPOS, SPOS
*Elset, elset=_S1_bot_S2, internal, instance=Steel-1, generate
 1, 4, 1
*Elset, elset=_S1_bot_S4, internal, instance=Steel-1
 5,
*Surface, type=ELEMENT, name=S1_bot
_S1_bot_S2, S2
_S1_bot_S4, S4
*Elset, elset=_S1_top_S1, internal, instance=Steel-1
 6,
*Elset, elset=_S1_top_S4, internal, instance=Steel-1, generate
 1, 4, 1
*Surface, type=ELEMENT, name=S1_top
_S1_top_S1, S1
_S1_top_S4, S4
*Elset, elset=_S2-top_S4, internal, instance=Steel_2
 1, 2, 6, 7, 8, 9
*Surface, type=ELEMENT, name=S2-top
_S2-top_S4, S4
*Elset, elset=_S2_bot_S2, internal, instance=Steel_2, generate
 6, 9, 1
*Elset, elset=_S2_bot_S4, internal, instance=Steel_2
 4, 5
*Surface, type=ELEMENT, name=S2_bot
_S2_bot_S2, S2
_S2_bot_S4, S4
*Elset, elset=_S3-bot_S2, internal, instance=Steel_3, generate
 1, 4, 1
*Elset, elset=_S3-bot_S4, internal, instance=Steel_3
 8, 9
*Surface, type=ELEMENT, name=S3-bot
_S3-bot_S2, S2
_S3-bot_S4, S4
*Elset, elset=_S3-top_S4, internal, instance=Steel_3, generate
 1, 6, 1
*Surface, type=ELEMENT, name=S3-top
_S3-top_S4, S4
*Elset, elset=_S4-bot_S2, internal, instance=Steel_4, generate
 1, 4, 1
*Elset, elset=_S4-bot_S4, internal, instance=Steel_4
 8, 9
*Surface, type=ELEMENT, name=S4-bot
_S4-bot_S2, S2
_S4-bot_S4, S4
*Elset, elset=_S4-top_S4, internal, instance=Steel_4, generate
 1, 6, 1
*Surface, type=ELEMENT, name=S4-top
_S4-top_S4, S4
*Elset, elset=_S5-bot_S2, internal, instance=Steel_5, generate
 1, 4, 1
*Elset, elset=_S5-bot_S4, internal, instance=Steel_5
 8, 9
*Surface, type=ELEMENT, name=S5-bot
_S5-bot_S2, S2
_S5-bot_S4, S4
*Elset, elset=_S5-top_S4, internal, instance=Steel_5, generate
 1, 6, 1

*Surface, type=ELEMENT, name=S5-top
_S5-top_S4, S4
*Elset, elset=_S6-bot_S2, internal, instance=Steel-6, generate
 1, 4, 1
*Elset, elset=_S6-bot_S4, internal, instance=Steel-6
 6, 7
*Surface, type=ELEMENT, name=S6-bot
_S6-bot_S2, S2
_S6-bot_S4, S4
*Elset, elset=_S6-top_S1, internal, instance=Steel-6
 5,
*Elset, elset=_S6-top_S4, internal, instance=Steel-6, generate
 1, 4, 1
*Surface, type=ELEMENT, name=S6-top
_S6-top_S1, S1
_S6-top_S4, S4
** Constraint: Constraint-11
*Tie, name=Constraint-11, adjust=yes, type=SURFACE TO SURFACE
S6-top, Rigid-top
** Constraint: Constraint-12
*Tie, name=Constraint-12, adjust=yes, type=SURFACE TO SURFACE
S1_bot, Rigid-bot
** Constraint: Rigid body
*Rigid Body, ref node=_PickedSet117, elset=_PickedSet118
** Constraint: Rigid body-bot
*Rigid Body, ref node=_PickedSet119, elset=_PickedSet120
*End Assembly
*Amplitude, name=Amp-1
 0., 0.000214577, 0.898, 1.508784, 1., 1.676917, 1.84, 3.049886
 2., 3.331685, 2.719, 4.531372, 3., 4.990602, 3.63, 6.038129
 4., 6.679118, 4.48, 7.483423, 5., 8.327878, 5.369, 8.929956
 6., 10.00321, 6.214, 10.36071, 7., 11.66673, 7.085, 11.80775
 7.95, 13.23564, 8., 13.32452, 8.818, 14.6849, 9., 14.99463
 9.698, 16.14583, 10., 16.66722, 10.531, 17.55829, 11., 18.33884
 11.406, 19.00816, 12., 19.98798
**
** MATERIALS
**
*Material, name=Aluminum
*Density
 2.81e-09,
*Elastic
70000., 0.32
*Material, name=Rubber-55
*Density
 1.18e-09,
*Hyperelastic, yeoh
 0.5, 0.18, 0.023,   0.,   0.,   0.
**
** INTERACTION PROPERTIES
**
*Surface Interaction, name=IntProp-1
1.,
*Friction, slip tolerance=1e-05
 0.8,
**
** BOUNDARY CONDITIONS
**
** Name: BC-X Type: Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet162, XSYMM
** Name: BC-bot Type: Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet96, ENCASTRE
** Name: comp Type: Displacement/Rotation
*Boundary
_PickedSet123, 1, 1
_PickedSet123, 2, 2
_PickedSet123, 6, 6

```
**
** INTERACTIONS
**
** Interaction: Int-1
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R1-bot, S1_top
** Interaction: Int-2
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R1-top, S2_bot
** Interaction: Int-3
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R2-bot, S2-top
** Interaction: Int-4
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R2-top, S3-bot
** Interaction: Int-5
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R3-bot, S3-top
** Interaction: Int-6
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R3-top, S4-bot
** Interaction: Int-7
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R4-bot, S4-top
** Interaction: Int-8
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R4-top, S5-bot
** Interaction: Int-9
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R5-bot, S5-top
** Interaction: Int-10
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R5-top, S6-bot
** ---------------------------------------------
-------------------
**
** STEP: Compression
**
*Step, name=Compression,
nlgeom=YES, inc=1000000
*Static, stabilize=0.0002, allsdtol=0.05,
continue=NO
0.0001, 12., 1e-09, 12.
**
** BOUNDARY CONDITIONS
**
** Name: BC-X Type:
Symmetry/Antisymmetry/Encastre
*Boundary, op=NEW
_PickedSet162, XSYMM
** Name: BC-bot Type:
Symmetry/Antisymmetry/Encastre
*Boundary, op=NEW
_PickedSet96, ENCASTRE
** Name: comp Type:
Displacement/Rotation
*Boundary, op=NEW
_PickedSet123, 1, 1
_PickedSet123, 2, 2, -20.
_PickedSet123, 6, 6
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
RF, RT, U, UT, V, VT
*Element Output, directions=YES
E, LE, MISES, NE, S
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
```

3. INP File for Hyperelastic Simulation of Rubber Shock Absorber Model-3

```
*Heading
** Job name: Job-1 Model name:
Model-1
** Generated by: Abaqus/CAE 6.13-1
```

```
*Preprint, echo=NO, model=NO,
history=NO, contact=NO
**
** PARTS
**
*Part, name=Rigid-bot
*End Part
**
*Part, name=Rigid-top
*End Part
**
*Part, name="Rubber pad"
*End Part
**
*Part, name=Steel-1
*End Part
**
*Part, name=Steel-6
*End Part
**
*Part, name=Steel_middle
*End Part
**
**
** ASSEMBLY
**
*Assembly, name=Assembly
**
*Instance, name="Rubber pad-1",
part="Rubber pad"
        0.,          2.,          0.
*Node
     1,         30.,         12.
     2,         20.,         12.
     3,         20.,          0.
-----------------------------------------
    65,   24.7561264,   21.9060879
*Element, type=CAX4H
 1,  1,  7, 36, 22
 2,  7,  8, 37, 36
 3,  8,  9, 38, 37
 -----------------------------------
48, 65, 27,  5, 28
*Nset, nset=_PickedSet5, internal,
generate
  1,  65,   1
*Elset, elset=_PickedSet5, internal,
generate
  1,  48,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet5,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-2",
part="Rubber pad"
        0.,         28.,          0.
*Node
     1,         30.,         12.
     2,         20.,         12.
     3,         20.,          0.
     --
    65,   24.7561264,   21.9060879
*Element, type=CAX4H
 1,  1,  7, 36, 22
 2,  7,  8, 37, 36
 3,  8,  9, 38, 37
 ---------------------------------------
48, 65, 27,  5, 28
*Nset, nset=_PickedSet5, internal,
generate
  1,  65,   1
*Elset, elset=_PickedSet5, internal,
generate
  1,  48,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet5,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-3",
part="Rubber pad"
        0.,         54.,          0.
*Node
     1,         30.,         12.
     2,         20.,         12.
     3,         20.,          0.
-----------------------------------------
    65,   24.7561264,   21.9060879
*Element, type=CAX4H
 1,  1,  7, 36, 22
 2,  7,  8, 37, 36
 3,  8,  9, 38, 37
 ------------------------------------
```

```
48, 65, 27,  5, 28
*Nset, nset=_PickedSet5, internal,
generate
  1,  65,   1
*Elset, elset=_PickedSet5, internal,
generate
  1,  48,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet5,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-4",
part="Rubber pad"
          0.,          80.,           0.
*Node
      1,          30.,          12.
      2,          20.,          12.
      3,          20.,           0.
----------------------------------
     65,   24.7561264,   21.9060879
*Element, type=CAX4H
 1,  1,  7, 36, 22
 2,  7,  8, 37, 36
 3,  8,  9, 38, 37
 4,  9,  2, 10, 38
-----------------------------------------
     65,   24.7561264,   21.9060879
*Element, type=CAX4H
 1,  1,  7, 36, 22
 2,  7,  8, 37, 36
 3,  8,  9, 38, 37
-----------------------------------------
48, 65, 27,  5, 28
*Nset, nset=_PickedSet5, internal,
generate
  1,  65,   1
*Elset, elset=_PickedSet5, internal,
generate
  1,  48,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet5,
material=Rubber-55
,
*End Instance
**
```

```
*Instance, name=Rigid-top-1,
part=Rigid-top
          0.,         132.,           0.
*Node
      1,           0.,           0.
      2,           5.,           0.
      3,          10.,           0.
      4,          15.,           0.
      5,          20.,           0.
      6,          25.,           0.
      7,          30.,           0.
      8,          35.,           0.
*Element, type=RAX2
1, 1, 2
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
*Node
      9,           0.,           0.,           0.
*Nset, nset=Rigid-top-1-RefPt_, internal
9,
*End Instance
**
*Instance, name=Rigid-bot-1,
part=Rigid-bot
*Node
      1,           0.,           0.
      2,           5.,           0.
      3,          10.,           0.
      4,          15.,           0.
      5,          20.,           0.
      6,          25.,           0.
      7,          30.,           0.
      8,          35.,           0.
*Element, type=RAX2
1, 1, 2
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
*Node
      9,           0.,           0.,           0.
*Nset, nset=Rigid-bot-1-RefPt_, internal
```

```
9,
*End Instance
**
*Instance, name=Steel_2,
part=Steel_middle
         0.,          26.,           0.
*Node
      1,          20.,           7.
      2,          19.,           7.
      3,          20.,          4.5
--------------------------------------------
     20,          23.,           2.
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  9, 10, 12, 11
 6,  5,  7, 15, 20
 7, 20, 15, 16, 19
 8, 19, 16, 17, 18
 9, 18, 17, 14, 13
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_3,
part=Steel_middle
         0.,          52.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
      --------------------------------------------
     20,          20.,          -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_4,
part=Steel_middle
         0.,          78.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
-----------------------------------------------
     20,          20.,          -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
```

```
*Instance, name=Steel_5,
part=Steel_middle
         0.,        104.,          0.
*Node
      1,         20.,          2.
      2,         20.,          0.
      3,         23.,          2.
------------------------------------
     20,         20.,        -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel-1, part=Steel-1
*Node
      1,         20.,          2.
      2,         20.,          0.
      3,         23.,          2.
      -------------------------------------------
     14,         19.,          3.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  2,  1, 14, 11
6,  1, 12, 13, 14
*Nset, nset=_PickedSet2, internal,
generate
  1,  14,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  6,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel-6, part=Steel-6
         0.,        130.,          0.
*Node
      1,         20.,          2.
      2,         20.,          0.
      3,         23.,          2.
-------------------------------------------
     16,         20.,        -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  1, 12, 14,  2
6,  2, 14, 15, 16
7, 16, 15, 13, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  16,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  7,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Nset, nset=_PickedSet96, internal,
instance=Rigid-bot-1, generate
 1,  8,  1
*Elset, elset=_PickedSet96, internal,
instance=Rigid-bot-1, generate
 1,  7,  1
*Nset, nset=_PickedSet117, internal,
instance=Rigid-top-1
 9,
*Nset, nset=_PickedSet118, internal,
instance=Rigid-top-1, generate
```

```
 1,  8,  1
*Elset, elset=_PickedSet118, internal, instance=Rigid-top-1, generate
 1,  7,  1
*Nset, nset=_PickedSet119, internal, instance=Rigid-bot-1
 9,
*Nset, nset=_PickedSet120, internal, instance=Rigid-bot-1, generate
 1,  8,  1
*Elset, elset=_PickedSet120, internal, instance=Rigid-bot-1, generate
 1,  7,  1
*Nset, nset=_PickedSet123, internal, instance=Rigid-top-1, generate
 1,  8,  1
*Elset, elset=_PickedSet123, internal, instance=Rigid-top-1, generate
 1,  7,  1
*Nset, nset=_PickedSet174, internal, instance="Rubber pad-1"
  2,  3,  6, 10, 11, 12, 13, 14, 31, 32, 33, 34, 35
*Nset, nset=_PickedSet174, internal, instance="Rubber pad-2"
  2,  3,  6, 10, 11, 12, 13, 14, 31, 32, 33, 34, 35
*Nset, nset=_PickedSet174, internal, instance="Rubber pad-3"
  2,  3,  6, 10, 11, 12, 13, 14, 31, 32, 33, 34, 35
*Nset, nset=_PickedSet174, internal, instance="Rubber pad-4"
  2,  3,  6, 10, 11, 12, 13, 14, 31, 32, 33, 34, 35
*Nset, nset=_PickedSet174, internal, instance=Steel_4
 12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet174, internal, instance="Rubber pad-5"
  2,  3,  6, 10, 11, 12, 13, 14, 31, 32, 33, 34, 35
*Nset, nset=_PickedSet174, internal, instance=Steel_2, generate
  2,  12,   2
*Nset, nset=_PickedSet174, internal, instance=Steel-1
 11, 13, 14
*Nset, nset=_PickedSet174, internal, instance=Steel_3
 12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet174, internal, instance=Steel_5
 12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet174, internal, instance=Steel-6, generate
 12,  15,   1
*Elset, elset=_PickedSet174, internal, instance="Rubber pad-1"
  4,  8, 12, 16, 20, 24, 25, 29, 33, 37, 41, 45
*Elset, elset=_PickedSet174, internal, instance="Rubber pad-2"
  4,  8, 12, 16, 20, 24, 25, 29, 33, 37, 41, 45
*Elset, elset=_PickedSet174, internal, instance="Rubber pad-3"
  4,  8, 12, 16, 20, 24, 25, 29, 33, 37, 41, 45
*Elset, elset=_PickedSet174, internal, instance="Rubber pad-4"
  4,  8, 12, 16, 20, 24, 25, 29, 33, 37, 41, 45
*Elset, elset=_PickedSet174, internal, instance=Steel_4, generate
 5,  9,  1
*Elset, elset=_PickedSet174, internal, instance="Rubber pad-5"
  4,  8, 12, 16, 20, 24, 25, 29, 33, 37, 41, 45
*Elset, elset=_PickedSet174, internal, instance=Steel_2, generate
 1,  5,  1
*Elset, elset=_PickedSet174, internal, instance=Steel-1
 5, 6
*Elset, elset=_PickedSet174, internal, instance=Steel_3, generate
 5,  9,  1
*Elset, elset=_PickedSet174, internal, instance=Steel_5, generate
 5,  9,  1
*Elset, elset=_PickedSet174, internal, instance=Steel-6, generate
 5,  7,  1
```

```
*Elset, elset=_R1-bot_S3, internal,
instance="Rubber pad-1", generate
 21,  24,   1
*Surface, type=ELEMENT, name=R1-
bot
_R1-bot_S3, S3
*Elset, elset=_R1-top_S3, internal,
instance="Rubber pad-1", generate
 45,  48,   1
*Surface, type=ELEMENT, name=R1-
top
_R1-top_S3, S3
*Elset, elset=_R2-bot_S3, internal,
instance="Rubber pad-2", generate
 21,  24,   1
*Surface, type=ELEMENT, name=R2-
bot
_R2-bot_S3, S3
*Elset, elset=_R2-top_S3, internal,
instance="Rubber pad-2", generate
 45,  48,   1
*Surface, type=ELEMENT, name=R2-
top
_R2-top_S3, S3
*Elset, elset=_R3-bot_S3, internal,
instance="Rubber pad-3", generate
 21,  24,   1
*Surface, type=ELEMENT, name=R3-
bot
_R3-bot_S3, S3
*Elset, elset=_R3-top_S3, internal,
instance="Rubber pad-3", generate
 45,  48,   1
*Surface, type=ELEMENT, name=R3-
top
_R3-top_S3, S3
*Elset, elset=_R4-bot_S3, internal,
instance="Rubber pad-4", generate
 21,  24,   1
*Surface, type=ELEMENT, name=R4-
bot
_R4-bot_S3, S3
*Elset, elset=_R4-top_S3, internal,
instance="Rubber pad-4", generate
 45,  48,   1
*Surface, type=ELEMENT, name=R4-
top
_R4-top_S3, S3
*Elset, elset=_R5-bot_S3, internal,
instance="Rubber pad-5", generate
 21,  24,   1
*Surface, type=ELEMENT, name=R5-
bot
_R5-bot_S3, S3
*Elset, elset=_R5-top_S3, internal,
instance="Rubber pad-5", generate
 45,  48,   1
*Surface, type=ELEMENT, name=R5-
top
_R5-top_S3, S3
*Elset, elset=_Rigid-bot_SNEG,
internal, instance=Rigid-bot-1, generate
 1,  7,  1
*Surface, type=ELEMENT,
name=Rigid-bot
_Rigid-bot_SNEG, SNEG
*Elset, elset=_Rigid-top_SPOS,
internal, instance=Rigid-top-1, generate
 1,  7,  1
*Surface, type=ELEMENT,
name=Rigid-top
_Rigid-top_SPOS, SPOS
*Elset, elset=_S1_bot_S2, internal,
instance=Steel-1, generate
 1,  4,  1
*Elset, elset=_S1_bot_S4, internal,
instance=Steel-1
 5,
*Surface, type=ELEMENT,
name=S1_bot
_S1_bot_S2, S2
_S1_bot_S4, S4
*Elset, elset=_S1_top_S1, internal,
instance=Steel-1
 6,
*Elset, elset=_S1_top_S4, internal,
instance=Steel-1, generate
 1,  4,  1
*Surface, type=ELEMENT,
name=S1_top
_S1_top_S1, S1
_S1_top_S4, S4
*Elset, elset=_S2-top_S4, internal,
instance=Steel_2
 1, 2, 6, 7, 8, 9
```

```
*Surface, type=ELEMENT, name=S2-
top
_S2-top_S4, S4
*Elset, elset=_S2_bot_S2, internal,
instance=Steel_2, generate
 6,  9,  1
*Elset, elset=_S2_bot_S4, internal,
instance=Steel_2
 4, 5
*Surface, type=ELEMENT,
name=S2_bot
_S2_bot_S2, S2
_S2_bot_S4, S4
*Elset, elset=_S3-bot_S2, internal,
instance=Steel_3, generate
 1,  4,  1
*Elset, elset=_S3-bot_S4, internal,
instance=Steel_3
 8, 9
*Surface, type=ELEMENT, name=S3-
bot
_S3-bot_S2, S2
_S3-bot_S4, S4
*Elset, elset=_S3-top_S4, internal,
instance=Steel_3, generate
 1,  6,  1
*Surface, type=ELEMENT, name=S3-
top
_S3-top_S4, S4
*Elset, elset=_S4-bot_S2, internal,
instance=Steel_4, generate
 1,  4,  1
*Elset, elset=_S4-bot_S4, internal,
instance=Steel_4
 8, 9
*Surface, type=ELEMENT, name=S4-
bot
_S4-bot_S2, S2
_S4-bot_S4, S4
*Elset, elset=_S4-top_S4, internal,
instance=Steel_4, generate
 1,  6,  1
*Surface, type=ELEMENT, name=S4-
top
_S4-top_S4, S4
*Elset, elset=_S5-bot_S2, internal,
instance=Steel_5, generate
 1,  4,  1
*Elset, elset=_S5-bot_S4, internal,
instance=Steel_5
 8, 9
*Surface, type=ELEMENT, name=S5-
bot
_S5-bot_S2, S2
_S5-bot_S4, S4
*Elset, elset=_S5-top_S4, internal,
instance=Steel_5, generate
 1,  6,  1
*Surface, type=ELEMENT, name=S5-
top
_S5-top_S4, S4
*Elset, elset=_S6-bot_S2, internal,
instance=Steel-6, generate
 1,  4,  1
*Elset, elset=_S6-bot_S4, internal,
instance=Steel-6
 6, 7
*Surface, type=ELEMENT, name=S6-
bot
_S6-bot_S2, S2
_S6-bot_S4, S4
*Elset, elset=_S6-top_S1, internal,
instance=Steel-6
 5,
*Elset, elset=_S6-top_S4, internal,
instance=Steel-6, generate
 1,  4,  1
*Surface, type=ELEMENT, name=S6-
top
_S6-top_S1, S1
_S6-top_S4, S4
** Constraint: Constraint-11
*Tie, name=Constraint-11, adjust=yes,
type=SURFACE TO SURFACE
S6-top, Rigid-top
** Constraint: Constraint-12
*Tie, name=Constraint-12, adjust=yes,
type=SURFACE TO SURFACE
S1_bot, Rigid-bot
** Constraint: Rigid body
*Rigid Body, ref node=_PickedSet117,
elset=_PickedSet118
** Constraint: Rigid body-bot
*Rigid Body, ref node=_PickedSet119,
elset=_PickedSet120
*End Assembly
```

```
*Amplitude, name=Amp-1
          0.,    0.000214577,          0.898,
1.508784,             1.,       1.676917,
1.84,       3.049886
          2.,       3.331685,          2.719,
4.531372,             3.,       4.990602,
3.63,       6.038129
          4.,       6.679118,           4.48,
7.483423,             5.,       8.327878,
5.369,       8.929956
          6.,       10.00321,          6.214,
10.36071,             7.,       11.66673,
7.085,       11.80775
        7.95,       13.23564,             8.,
13.32452,          8.818,        14.6849,
9.,       14.99463
       9.698,       16.14583,            10.,
16.66722,         10.531,       17.55829,
11.,       18.33884
      11.406,       19.00816,            12.,
19.98798
**
** MATERIALS
**
*Material, name=Aluminum
*Density
 2.81e-09,
*Elastic
70000., 0.32
*Material, name=Rubber-55
*Density
 1.18e-09,
*Hyperelastic, yeoh
 0.5,  0.18, 0.023,    0.,    0.,    0.
**
** INTERACTION PROPERTIES
**
*Surface Interaction, name=IntProp-1
1.,
*Friction, slip tolerance=1e-05
 0.8,
**
** BOUNDARY CONDITIONS
**
** Name: BC-X Type:
Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet174, XSYMM
** Name: BC-bot Type:
Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet96, ENCASTRE
** Name: comp Type:
Displacement/Rotation
*Boundary
_PickedSet123, 1, 1
_PickedSet123, 2, 2
_PickedSet123, 6, 6
**
** INTERACTIONS
**
** Interaction: Int-1
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R1-bot, S1_top
** Interaction: Int-2
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R1-top, S2_bot
** Interaction: Int-3
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R2-bot, S2-top
** Interaction: Int-4
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R2-top, S3-bot
** Interaction: Int-5
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R3-bot, S3-top
** Interaction: Int-6
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R3-top, S4-bot
** Interaction: Int-7
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R4-bot, S4-top
** Interaction: Int-8
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R4-top, S5-bot
** Interaction: Int-9
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
```

R5-bot, S5-top
** Interaction: Int-10
*Contact Pair, interaction=IntProp-1, type=SURFACE TO SURFACE
R5-top, S6-bot
** --
**
** STEP: Compression
**
*Step, name=Compression, nlgeom=YES, inc=1000000
*Static, stabilize=0.0002, allsdtol=0.05, continue=NO
0.0001, 12., 1e-09, 12.
**
** BOUNDARY CONDITIONS
**
** Name: BC-X Type: Symmetry/Antisymmetry/Encastre
*Boundary, op=NEW
_PickedSet174, XSYMM
** Name: BC-bot Type: Symmetry/Antisymmetry/Encastre
*Boundary, op=NEW
_PickedSet96, ENCASTRE
** Name: comp Type: Displacement/Rotation
*Boundary, op=NEW
_PickedSet123, 1, 1
_PickedSet123, 2, 2, -20.
_PickedSet123, 6, 6
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
RF, RT, U, UT, V, VT
*Element Output, directions=YES
E, LE, MISES, NE, S
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step

4. INP File for Non-linear Viscoelastic Simulation of NR Shock Absorber Model-1

*Heading
** Job name: Job-1 Model name: Model-1
** Generated by: Abaqus/CAE 6.13-1
*Preprint, echo=NO, model=NO, history=NO, contact=NO
**
** PARTS
**
*Part, name=Rigid-bot
*End Part
**
*Part, name=Rigid-top
*End Part
**
*Part, name="Rubber pad"
*End Part
**
*Part, name=Steel-1
*End Part
**
*Part, name=Steel-6
*End Part
**
*Part, name=Steel_middle
*End Part
**
**
** ASSEMBLY
**
*Assembly, name=Assembly
**
*Instance, name="Rubber pad-1", part="Rubber pad"
0., 2., 0.
*Node
1, 25., 12.
2, 25., 24.
3, 20., 24.
---------------------------------------.
91, 28.333334, 2.
*Element, type=CAX4H

```
 1,  1, 10, 52, 23
 2, 10, 11, 53, 52
 3, 11, 12, 54, 53
------------------------------------------
72, 91, 46,  9, 47
*Nset, nset=_PickedSet6, internal,
generate
  1,  91,   1
*Elset, elset=_PickedSet6, internal,
generate
  1,  72,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet6,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-2",
part="Rubber pad"
          0.,          28.,           0.
*Node
      1,          25.,          12.
      2,          25.,          24.
      3,          20.,          24.
--------------------------------------
     91,    28.333334,           2.
*Element, type=CAX4H
 1,  1, 10, 52, 23
 2, 10, 11, 53, 52
 3, 11, 12, 54, 53
-----------------------------------------
72, 91, 46,  9, 47
*Nset, nset=_PickedSet6, internal,
generate
  1,  91,   1
*Elset, elset=_PickedSet6, internal,
generate
  1,  72,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet6,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-3",
part="Rubber pad"
          0.,          54.,           0.
*Node
      1,          25.,          12.
      2,          25.,          24.
      3,          20.,          24.
----------------------------------------
     91,    28.333334,           2.
*Element, type=CAX4H
 1,  1, 10, 52, 23
 2, 10, 11, 53, 52
 3, 11, 12, 54, 53
 4, 12, 13, 55, 54
 -------------------------------------------
72, 91, 46,  9, 47
*Nset, nset=_PickedSet6, internal,
generate
  1,  91,   1
*Elset, elset=_PickedSet6, internal,
generate
  1,  72,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet6,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-4",
part="Rubber pad"
          0.,          80.,           0.
*Node
      1,          25.,          12.
      2,          25.,          24.
      3,          20.,          24.
      4,          20.,          12.
----------------------------------------------
     91,    28.333334,           2.
*Element, type=CAX4H
 1,  1, 10, 52, 23
 2, 10, 11, 53, 52
 3, 11, 12, 54, 53
-------------------------------------------
72, 91, 46,  9, 47
*Nset, nset=_PickedSet6, internal,
generate
  1,  91,   1
*Elset, elset=_PickedSet6, internal,
generate
  1,  72,   1
** Section: Rubber-55
```

```
*Solid Section, elset=_PickedSet6,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-5",
part="Rubber pad"
         0.,         106.,           0.
*Node
      1,          25.,          12.
      2,          25.,          24.
      3,          20.,          24.
      4,          20.,          12.
-----------------------------------------
     91,    28.333334,           2.
*Element, type=CAX4H
 1,  1, 10, 52, 23
 2, 10, 11, 53, 52
 3, 11, 12, 54, 53
-------------------------------------
72, 91, 46,  9, 47
*Nset, nset=_PickedSet6, internal,
generate
  1,  91,   1
*Elset, elset=_PickedSet6, internal,
generate
  1,  72,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet6,
material=Rubber-55
,
*End Instance
**
*Instance, name=Rigid-top-1,
part=Rigid-top
         0.,         132.,           0.
*Node
      1,           0.,          0.
      2,           5.,          0.
      3,          10.,          0.
      ----------------------------------
      8,          35.,          0.
*Element, type=RAX2
1, 1, 2
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
*Node
      9,           0.,           0.,           0.
*Nset, nset=Rigid-top-1-RefPt_, internal
9,
*End Instance
**
*Instance, name=Rigid-bot-1,
part=Rigid-bot
*Node
      1,           0.,          0.
      2,           5.,          0.
      3,          10.,          0.
      4,          15.,          0.
      5,          20.,          0.
      6,          25.,          0.
      7,          30.,          0.
      8,          35.,          0.
*Element, type=RAX2
1, 1, 2
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
*Node
      9,           0.,           0.,           0.
*Nset, nset=Rigid-bot-1-RefPt_, internal
9,
*End Instance
**
*Instance, name=Steel_2,
part=Steel_middle
         0.,          26.,           0.
*Node
      1,          20.,          7.
      2,          19.,          7.
      3,          20.,         4.5
-------------------------------------
     20,          23.,           2.
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  9, 10, 12, 11
```

```
 6,  5,  7, 15, 20
 7, 20, 15, 16, 19
 8, 19, 16, 17, 18
 9, 18, 17, 14, 13
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_3,
part=Steel_middle
         0.,          52.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
------------------------------------
     20,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_4,
part=Steel_middle
         0.,          78.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
-------------------------------------
     20,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_5,
part=Steel_middle
         0.,         104.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
--------------------------------------
     20,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
```

```
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel-1, part=Steel-1
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
----------------------------------------------
     14,          19.,          3.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  2,  1, 14, 11
6,  1, 12, 13, 14
*Nset, nset=_PickedSet2, internal,
generate
  1,  14,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  6,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel-6, part=Steel-6
          0.,         130.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
-----------------------------------------
     16,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  1, 12, 14,  2
6,  2, 14, 15, 16
7, 16, 15, 13, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  16,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  7,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Nset, nset=_PickedSet96, internal,
instance=Rigid-bot-1, generate
 1,  8,  1
*Elset, elset=_PickedSet96, internal,
instance=Rigid-bot-1, generate
 1,  7,  1
*Nset, nset=_PickedSet117, internal,
instance=Rigid-top-1
 9,
*Nset, nset=_PickedSet118, internal,
instance=Rigid-top-1, generate
 1,  8,  1
*Elset, elset=_PickedSet118, internal,
instance=Rigid-top-1, generate
 1,  7,  1
*Nset, nset=_PickedSet119, internal,
instance=Rigid-bot-1
 9,
*Nset, nset=_PickedSet120, internal,
instance=Rigid-bot-1, generate
 1,  8,  1
*Elset, elset=_PickedSet120, internal,
instance=Rigid-bot-1, generate
 1,  7,  1
*Nset, nset=_PickedSet123, internal,
instance=Rigid-top-1, generate
 1,  8,  1
```

*Elset, elset=_PickedSet123, internal, instance=Rigid-top-1, generate
1, 7, 1
*Nset, nset=_PickedSet174, internal, instance="Rubber pad-1"
3, 4, 8, 17, 18, 19, 20, 21, 38, 39, 40, 41, 42
*Nset, nset=_PickedSet174, internal, instance="Rubber pad-2"
3, 4, 8, 17, 18, 19, 20, 21, 38, 39, 40, 41, 42
*Nset, nset=_PickedSet174, internal, instance="Rubber pad-3"
3, 4, 8, 17, 18, 19, 20, 21, 38, 39, 40, 41, 42
*Nset, nset=_PickedSet174, internal, instance="Rubber pad-4"
3, 4, 8, 17, 18, 19, 20, 21, 38, 39, 40, 41, 42
*Nset, nset=_PickedSet174, internal, instance=Steel_4
12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet174, internal, instance="Rubber pad-5"
3, 4, 8, 17, 18, 19, 20, 21, 38, 39, 40, 41, 42
*Nset, nset=_PickedSet174, internal, instance=Steel_2, generate
2, 12, 2
*Nset, nset=_PickedSet174, internal, instance=Steel-1
11, 13, 14
*Nset, nset=_PickedSet174, internal, instance=Steel_3
12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet174, internal, instance=Steel_5
12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet174, internal, instance=Steel-6, generate
12, 15, 1
*Elset, elset=_PickedSet174, internal, instance="Rubber pad-1"
13, 14, 15, 16, 17, 18, 49, 50, 51, 52, 53, 54
*Elset, elset=_PickedSet174, internal, instance="Rubber pad-2"
13, 14, 15, 16, 17, 18, 49, 50, 51, 52, 53, 54
*Elset, elset=_PickedSet174, internal, instance="Rubber pad-3"
13, 14, 15, 16, 17, 18, 49, 50, 51, 52, 53, 54
*Elset, elset=_PickedSet174, internal, instance="Rubber pad-4"
13, 14, 15, 16, 17, 18, 49, 50, 51, 52, 53, 54
*Elset, elset=_PickedSet174, internal, instance=Steel_4, generate
5, 9, 1
*Elset, elset=_PickedSet174, internal, instance="Rubber pad-5"
13, 14, 15, 16, 17, 18, 49, 50, 51, 52, 53, 54
*Elset, elset=_PickedSet174, internal, instance=Steel_2, generate
1, 5, 1
*Elset, elset=_PickedSet174, internal, instance=Steel-1
5, 6
*Elset, elset=_PickedSet174, internal, instance=Steel_3, generate
5, 9, 1
*Elset, elset=_PickedSet174, internal, instance=Steel_5, generate
5, 9, 1
*Elset, elset=_PickedSet174, internal, instance=Steel-6, generate
5, 7, 1
*Elset, elset=_R1-bot_S2, internal, instance="Rubber pad-1", generate
60, 72, 6
*Elset, elset=_R1-bot_S4, internal, instance="Rubber pad-1", generate
37, 49, 6
*Surface, type=ELEMENT, name=R1-bot
_R1-bot_S2, S2
_R1-bot_S4, S4
*Elset, elset=_R1-top_S2, internal, instance="Rubber pad-1", generate
6, 18, 6
*Elset, elset=_R1-top_S4, internal, instance="Rubber pad-1", generate
19, 31, 6

*Surface, type=ELEMENT, name=R1-top
_R1-top_S2, S2
_R1-top_S4, S4
*Elset, elset=_R2-bot_S2, internal, instance="Rubber pad-2", generate
60, 72, 6
*Elset, elset=_R2-bot_S4, internal, instance="Rubber pad-2", generate
37, 49, 6
*Surface, type=ELEMENT, name=R2-bot
_R2-bot_S2, S2
_R2-bot_S4, S4
*Elset, elset=_R2-top_S2, internal, instance="Rubber pad-2", generate
6, 18, 6
*Elset, elset=_R2-top_S4, internal, instance="Rubber pad-2", generate
19, 31, 6
*Surface, type=ELEMENT, name=R2-top
_R2-top_S2, S2
_R2-top_S4, S4
*Elset, elset=_R3-bot_S2, internal, instance="Rubber pad-3", generate
60, 72, 6
*Elset, elset=_R3-bot_S4, internal, instance="Rubber pad-3", generate
37, 49, 6
*Surface, type=ELEMENT, name=R3-bot
_R3-bot_S2, S2
_R3-bot_S4, S4
*Elset, elset=_R3-top_S2, internal, instance="Rubber pad-3", generate
6, 18, 6
*Elset, elset=_R3-top_S4, internal, instance="Rubber pad-3", generate
19, 31, 6
*Surface, type=ELEMENT, name=R3-top
_R3-top_S2, S2
_R3-top_S4, S4
*Elset, elset=_R4-bot_S2, internal, instance="Rubber pad-4", generate
60, 72, 6
*Elset, elset=_R4-bot_S4, internal, instance="Rubber pad-4", generate
37, 49, 6
*Surface, type=ELEMENT, name=R4-bot
_R4-bot_S2, S2
_R4-bot_S4, S4
*Elset, elset=_R4-top_S2, internal, instance="Rubber pad-4", generate
6, 18, 6
*Elset, elset=_R4-top_S4, internal, instance="Rubber pad-4", generate
19, 31, 6
*Surface, type=ELEMENT, name=R4-top
_R4-top_S2, S2
_R4-top_S4, S4
*Elset, elset=_R5-bot_S2, internal, instance="Rubber pad-5", generate
60, 72, 6
*Elset, elset=_R5-bot_S4, internal, instance="Rubber pad-5", generate
37, 49, 6
*Surface, type=ELEMENT, name=R5-bot
_R5-bot_S2, S2
_R5-bot_S4, S4
*Elset, elset=_R5-top_S2, internal, instance="Rubber pad-5", generate
6, 18, 6
*Elset, elset=_R5-top_S4, internal, instance="Rubber pad-5", generate
19, 31, 6
*Surface, type=ELEMENT, name=R5-top
_R5-top_S2, S2
_R5-top_S4, S4
*Elset, elset=_Rigid-bot_SNEG, internal, instance=Rigid-bot-1, generate
1, 7, 1
*Surface, type=ELEMENT, name=Rigid-bot
_Rigid-bot_SNEG, SNEG
*Elset, elset=_Rigid-top_SPOS, internal, instance=Rigid-top-1, generate
1, 7, 1
*Surface, type=ELEMENT, name=Rigid-top

```
_Rigid-top_SPOS, SPOS
*Elset, elset=_S1_bot_S2, internal,
instance=Steel-1, generate
 1,  4,  1
*Elset, elset=_S1_bot_S4, internal,
instance=Steel-1
 5,
*Surface, type=ELEMENT,
name=S1_bot
_S1_bot_S2, S2
_S1_bot_S4, S4
*Elset, elset=_S1_top_S1, internal,
instance=Steel-1
 6,
*Elset, elset=_S1_top_S4, internal,
instance=Steel-1, generate
 1,  4,  1
*Surface, type=ELEMENT,
name=S1_top
_S1_top_S1, S1
_S1_top_S4, S4
*Elset, elset=_S2-top_S4, internal,
instance=Steel_2
 1, 2, 6, 7, 8, 9
*Surface, type=ELEMENT, name=S2-
top
_S2-top_S4, S4
*Elset, elset=_S2_bot_S2, internal,
instance=Steel_2, generate
 6,  9,  1
*Elset, elset=_S2_bot_S4, internal,
instance=Steel_2
 4, 5
*Surface, type=ELEMENT,
name=S2_bot
_S2_bot_S2, S2
_S2_bot_S4, S4
*Elset, elset=_S3-bot_S2, internal,
instance=Steel_3, generate
 1,  4,  1
*Elset, elset=_S3-bot_S4, internal,
instance=Steel_3
 8, 9
*Surface, type=ELEMENT, name=S3-
bot
_S3-bot_S2, S2
_S3-bot_S4, S4
*Elset, elset=_S3-top_S4, internal,
instance=Steel_3, generate
 1,  6,  1
*Surface, type=ELEMENT, name=S3-
top
_S3-top_S4, S4
*Elset, elset=_S4-bot_S2, internal,
instance=Steel_4, generate
 1,  4,  1
*Elset, elset=_S4-bot_S4, internal,
instance=Steel_4
 8, 9
*Surface, type=ELEMENT, name=S4-
bot
_S4-bot_S2, S2
_S4-bot_S4, S4
*Elset, elset=_S4-top_S4, internal,
instance=Steel_4, generate
 1,  6,  1
*Surface, type=ELEMENT, name=S4-
top
_S4-top_S4, S4
*Elset, elset=_S5-bot_S2, internal,
instance=Steel_5, generate
 1,  4,  1
*Elset, elset=_S5-bot_S4, internal,
instance=Steel_5
 8, 9
*Surface, type=ELEMENT, name=S5-
bot
_S5-bot_S2, S2
_S5-bot_S4, S4
*Elset, elset=_S5-top_S4, internal,
instance=Steel_5, generate
 1,  6,  1
*Surface, type=ELEMENT, name=S5-
top
_S5-top_S4, S4
*Elset, elset=_S6-bot_S2, internal,
instance=Steel-6, generate
 1,  4,  1
*Elset, elset=_S6-bot_S4, internal,
instance=Steel-6
 6, 7
*Surface, type=ELEMENT, name=S6-
bot
_S6-bot_S2, S2
_S6-bot_S4, S4
```

*Elset, elset=_S6-top_S1, internal, instance=Steel-6
 5,
*Elset, elset=_S6-top_S4, internal, instance=Steel-6, generate
 1, 4, 1
*Surface, type=ELEMENT, name=S6-top
_S6-top_S1, S1
_S6-top_S4, S4
** Constraint: Constraint-11
*Tie, name=Constraint-11, adjust=yes, type=SURFACE TO SURFACE
S6-top, Rigid-top
** Constraint: Constraint-12
*Tie, name=Constraint-12, adjust=yes, type=SURFACE TO SURFACE
S1_bot, Rigid-bot
** Constraint: Rigid body
*Rigid Body, ref node=_PickedSet117, elset=_PickedSet118
** Constraint: Rigid body-bot
*Rigid Body, ref node=_PickedSet119, elset=_PickedSet120
*End Assembly
*Amplitude, name=Amp-1
 0., 0., 0.080898611, 0.984682058, 0.161111111, 3.846112527, 0.241928056, 8.302932109
 0.322565333, 13.44386606, 0.4030805, 17.81571041, 0.483334, 19.93236806, 0.564539111, 19.00552873
 0.644873889, 15.39526582, 0.724782556, 10.41474067, 0.805296889, 5.541951209, 0.885933556, 1.949490444
 0.966361556, 0.170719294
**
** MATERIALS
**
*Material, name=Aluminum
*Density
 2.81e-09,
*Elastic
70000., 0.32
*Material, name=Rubber-55
*Density
 1.18e-09,
*Hyperelastic, yeoh, moduli=LONG TERM
 0.5, 0.18, 0.023,   0.,   0.,   0.
*Hysteresis
 1.45, 0.04, 8.25, -0.95
**
** INTERACTION PROPERTIES
**
*Surface Interaction, name=IntProp-1
1.,
*Friction, slip tolerance=1e-05
 0.8,
**
** BOUNDARY CONDITIONS
**
** Name: BC-X Type: Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet174, XSYMM
** Name: BC-bot Type: Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet96, ENCASTRE
** Name: comp Type: Displacement/Rotation
*Boundary
_PickedSet123, 1, 1
_PickedSet123, 2, 2
_PickedSet123, 6, 6
**
** INTERACTIONS
**
** Interaction: Int-1
*Contact Pair, interaction=IntProp-1, type=SURFACE TO SURFACE
R1-bot, S1_top
** Interaction: Int-2
*Contact Pair, interaction=IntProp-1, type=SURFACE TO SURFACE
R1-top, S2_bot
** Interaction: Int-3
*Contact Pair, interaction=IntProp-1, type=SURFACE TO SURFACE
R2-bot, S2-top
** Interaction: Int-4

```
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R2-top, S3-bot
** Interaction: Int-5
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R3-bot, S3-top
** Interaction: Int-6
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R3-top, S4-bot
** Interaction: Int-7
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R4-bot, S4-top
** Interaction: Int-8
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R4-top, S5-bot
** Interaction: Int-9
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R5-bot, S5-top
** Interaction: Int-10
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R5-top, S6-bot
** --------------------------------------------
-------------------
**
** STEP: Compression
**
*Step, name=Compression,
nlgeom=YES, inc=1000000
*Dynamic,application=QUASI-
STATIC,initial=NO
1e-05,1.,1e-09
**
** BOUNDARY CONDITIONS
**
** Name: comp Type:
Displacement/Rotation
*Boundary, amplitude=Amp-1
_PickedSet123, 1, 1
_PickedSet123, 2, 2, -1.
_PickedSet123, 6, 6
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field, frequency=1
*Node Output
RF, RT, U, UT, V, VT
*Element Output, directions=YES
E, LE, MISES, NE, S
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history,
variable=PRESELECT, frequency=1
*End Step
```

5. INP File for Non-linear Viscoelastic Simulation of NR Shock Absorber Model-2

```
*Heading
** Job name: Job-1 Model name:
Model-1
** Generated by: Abaqus/CAE 6.13-1
*Preprint, echo=NO, model=NO,
history=NO, contact=NO
**
** PARTS
**
*Part, name=Rigid-bot
*End Part
**
*Part, name=Rigid-top
*End Part
**
*Part, name="Rubber pad"
*End Part
**
*Part, name=Steel-1
*End Part
**
*Part, name=Steel-6
*End Part
**
*Part, name=Steel_middle
*End Part
**
```

```
**
** ASSEMBLY
**
*Assembly, name=Assembly
**
*Instance, name="Rubber pad-1",
part="Rubber pad"
          0.,           2.,           0.
*Node
      1,          20.,          12.
      2,   23.8023567,          12.
      3,   23.8023567,          24.
      ----------------------------------------
     70,    25.773077,   1.85084665
*Element, type=CAX4H
 1,  1, 10, 47, 21
 2, 10,  2, 11, 47
 3, 21, 47, 48, 20
 ----------------------------------------
53, 46, 68, 69, 45
*Element, type=CAX3H
40, 67, 42, 43
41, 69, 30, 66
*Nset, nset=_PickedSet3, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet3, internal,
generate
  1,  53,   1
*Nset, nset=_PickedSet4, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet4, internal,
generate
  1,  53,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet3,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-2",
part="Rubber pad"
          0.,          28.,           0.
*Node
      1,          20.,          12.
      2,   23.8023567,          12.
      3,   23.8023567,          24.
----------------------------------------------
     70,    25.773077,   1.85084665
*Element, type=CAX4H
 1,  1, 10, 47, 21
 2, 10,  2, 11, 47
 3, 21, 47, 48, 20
----------------------------------------
53, 46, 68, 69, 45
*Element, type=CAX3H
40, 67, 42, 43
41, 69, 30, 66
*Nset, nset=_PickedSet3, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet3, internal,
generate
  1,  53,   1
*Nset, nset=_PickedSet4, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet4, internal,
generate
  1,  53,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet3,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-3",
part="Rubber pad"
          0.,          54.,           0.
*Node
      1,          20.,          12.
      2,   23.8023567,          12.
      3,   23.8023567,          24.
      ----------------------------------------
     70,    25.773077,   1.85084665
*Element, type=CAX4H
 1,  1, 10, 47, 21
 2, 10,  2, 11, 47
 3, 21, 47, 48, 20
----------------------------------------------
53, 46, 68, 69, 45
*Element, type=CAX3H
40, 67, 42, 43
41, 69, 30, 66
```

```
*Nset, nset=_PickedSet3, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet3, internal,
generate
  1,  53,   1
*Nset, nset=_PickedSet4, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet4, internal,
generate
  1,  53,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet3,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-4",
part="Rubber pad"
          0.,          80.,           0.
*Node
      1,          20.,          12.
      2,   23.8023567,          12.
      3,   23.8023567,          24.
--------------------------------------------
     70,    25.773077,   1.85084665
*Element, type=CAX4H
 1,  1, 10, 47, 21
 2, 10,  2, 11, 47
 3, 21, 47, 48, 20
 -----------------------------------------
53, 46, 68, 69, 45
*Element, type=CAX3H
40, 67, 42, 43
41, 69, 30, 66
*Nset, nset=_PickedSet3, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet3, internal,
generate
  1,  53,   1
*Nset, nset=_PickedSet4, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet4, internal,
generate
  1,  53,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet3,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-5",
part="Rubber pad"
          0.,         106.,           0.
*Node
      1,          20.,          12.
      2,   23.8023567,          12.
      3,   23.8023567,          24.
----------------------------------------
     70,    25.773077,   1.85084665
*Element, type=CAX4H
 1,  1, 10, 47, 21
 2, 10,  2, 11, 47
 3, 21, 47, 48, 20
 -------------------------------------
53, 46, 68, 69, 45
*Element, type=CAX3H
40, 67, 42, 43
41, 69, 30, 66
*Nset, nset=_PickedSet3, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet3, internal,
generate
  1,  53,   1
*Nset, nset=_PickedSet4, internal,
generate
  1,  70,   1
*Elset, elset=_PickedSet4, internal,
generate
  1,  53,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet3,
material=Rubber-55
,
*End Instance
**
*Instance, name=Rigid-top-1,
part=Rigid-top
          0.,         132.,           0.
*Node
      1,           0.,           0.
      2,           5.,           0.
```

```
     3,         10.,          0.
------------------------------------
     8,         35.,          0.
*Element, type=RAX2
1, 1, 2
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
*Node
     9,          0.,          0.,          0.
*Nset, nset=Rigid-top-1-RefPt_, internal
9,
*End Instance
**
*Instance, name=Rigid-bot-1,
part=Rigid-bot
*Node
     1,          0.,          0.
     2,          5.,          0.
     3,         10.,          0.
-------------------------------------
     8,         35.,          0.
*Element, type=RAX2
1, 1, 2
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
*Node
     9,          0.,          0.,          0.
*Nset, nset=Rigid-bot-1-RefPt_, internal
9,
*End Instance
**
*Instance, name=Steel_2,
part=Steel_middle
         0.,         26.,          0.
*Node
     1,         20.,          7.
     2,         19.,          7.
     3,         20.,         4.5
-----------------------------------
    20,         23.,          2.
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  9, 10, 12, 11
 6,  5,  7, 15, 20
 7, 20, 15, 16, 19
 8, 19, 16, 17, 18
 9, 18, 17, 14, 13
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_3,
part=Steel_middle
         0.,         52.,          0.
*Node
     1,         20.,          2.
     2,         20.,          0.
     3,         23.,          2.
--------------------------------------
    20,         20.,        -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
```

```
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_4,
part=Steel_middle
         0.,          78.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
------------------------------------------
     20,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_5,
part=Steel_middle
         0.,         104.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
----------------------------------------
     20,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel-1, part=Steel-1
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
-----------------------------------------
     14,          19.,          3.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  2,  1, 14, 11
6,  1, 12, 13, 14
*Nset, nset=_PickedSet2, internal,
generate
  1,  14,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  6,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel-6, part=Steel-6
         0.,         130.,           0.
*Node
```

```
      1,          20.,           2.
     2,          20.,           0.
     3,          23.,           2.
---------------------------------------
    16,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  1, 12, 14,  2
6,  2, 14, 15, 16
7, 16, 15, 13, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  16,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  7,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Nset, nset=_PickedSet96, internal,
instance=Rigid-bot-1, generate
 1,  8,  1
*Elset, elset=_PickedSet96, internal,
instance=Rigid-bot-1, generate
 1,  7,  1
*Nset, nset=_PickedSet117, internal,
instance=Rigid-top-1
 9,
*Nset, nset=_PickedSet118, internal,
instance=Rigid-top-1, generate
 1,  8,  1
*Elset, elset=_PickedSet118, internal,
instance=Rigid-top-1, generate
 1,  7,  1
*Nset, nset=_PickedSet119, internal,
instance=Rigid-bot-1
 9,
*Nset, nset=_PickedSet120, internal,
instance=Rigid-bot-1, generate
 1,  8,  1
*Elset, elset=_PickedSet120, internal,
instance=Rigid-bot-1, generate
 1,  7,  1
*Nset, nset=_PickedSet123, internal,
instance=Rigid-top-1, generate
 1,  8,  1
*Elset, elset=_PickedSet123, internal,
instance=Rigid-top-1, generate
 1,  7,  1
*Nset, nset=_PickedSet162, internal,
instance="Rubber pad-1"
  1,  4,  5, 17, 18, 19, 20, 21, 22, 23, 24,
25, 26
*Nset, nset=_PickedSet162, internal,
instance="Rubber pad-2"
  1,  4,  5, 17, 18, 19, 20, 21, 22, 23, 24,
25, 26
*Nset, nset=_PickedSet162, internal,
instance="Rubber pad-3"
  1,  4,  5, 17, 18, 19, 20, 21, 22, 23, 24,
25, 26
*Nset, nset=_PickedSet162, internal,
instance="Rubber pad-4"
  1,  4,  5, 17, 18, 19, 20, 21, 22, 23, 24,
25, 26
*Nset, nset=_PickedSet162, internal,
instance=Steel_4
 12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet162, internal,
instance="Rubber pad-5"
  1,  4,  5, 17, 18, 19, 20, 21, 22, 23, 24,
25, 26
*Nset, nset=_PickedSet162, internal,
instance=Steel_2, generate
  2,  12,   2
*Nset, nset=_PickedSet162, internal,
instance=Steel-1
 11, 13, 14
*Nset, nset=_PickedSet162, internal,
instance=Steel_3
 12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet162, internal,
instance=Steel_5
 12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet162, internal,
instance=Steel-6, generate
 12,  15,   1
*Elset, elset=_PickedSet162, internal,
instance="Rubber pad-1"
```

 1, 3, 5, 7, 9, 11, 14, 16, 18, 20, 22,
24
*Elset, elset=_PickedSet162, internal,
instance="Rubber pad-2"
 1, 3, 5, 7, 9, 11, 14, 16, 18, 20, 22,
24
*Elset, elset=_PickedSet162, internal,
instance="Rubber pad-3"
 1, 3, 5, 7, 9, 11, 14, 16, 18, 20, 22,
24
*Elset, elset=_PickedSet162, internal,
instance="Rubber pad-4"
 1, 3, 5, 7, 9, 11, 14, 16, 18, 20, 22,
24
*Elset, elset=_PickedSet162, internal,
instance=Steel_4, generate
 5, 9, 1
*Elset, elset=_PickedSet162, internal,
instance="Rubber pad-5"
 1, 3, 5, 7, 9, 11, 14, 16, 18, 20, 22,
24
*Elset, elset=_PickedSet162, internal,
instance=Steel_2, generate
 1, 5, 1
*Elset, elset=_PickedSet162, internal,
instance=Steel-1
 5, 6
*Elset, elset=_PickedSet162, internal,
instance=Steel_3, generate
 5, 9, 1
*Elset, elset=_PickedSet162, internal,
instance=Steel_5, generate
 5, 9, 1
*Elset, elset=_PickedSet162, internal,
instance=Steel-6, generate
 5, 7, 1
*Elset, elset=_R1-bot_S1, internal,
instance="Rubber pad-1", generate
 49, 51, 1
*Elset, elset=_R1-bot_S3, internal,
instance="Rubber pad-1"
 23, 24
*Surface, type=ELEMENT, name=R1-
bot
_R1-bot_S1, S1
_R1-bot_S3, S3
*Elset, elset=_R1-top_S2, internal,
instance="Rubber pad-1"
 29,
*Elset, elset=_R1-top_S3, internal,
instance="Rubber pad-1"
 11, 12, 31
*Elset, elset=_R1-top_S4, internal,
instance="Rubber pad-1"
 32,
*Surface, type=ELEMENT, name=R1-
top
_R1-top_S2, S2
_R1-top_S3, S3
_R1-top_S4, S4
*Elset, elset=_R2-bot_S1, internal,
instance="Rubber pad-2", generate
 49, 51, 1
*Elset, elset=_R2-bot_S3, internal,
instance="Rubber pad-2"
 23, 24
*Surface, type=ELEMENT, name=R2-
bot
_R2-bot_S1, S1
_R2-bot_S3, S3
*Elset, elset=_R2-top_S2, internal,
instance="Rubber pad-2"
 29,
*Elset, elset=_R2-top_S3, internal,
instance="Rubber pad-2"
 11, 12, 31
*Elset, elset=_R2-top_S4, internal,
instance="Rubber pad-2"
 32,
*Surface, type=ELEMENT, name=R2-
top
_R2-top_S2, S2
_R2-top_S3, S3
_R2-top_S4, S4
*Elset, elset=_R3-bot_S1, internal,
instance="Rubber pad-3", generate
 49, 51, 1
*Elset, elset=_R3-bot_S3, internal,
instance="Rubber pad-3"
 23, 24
*Surface, type=ELEMENT, name=R3-
bot
_R3-bot_S1, S1
_R3-bot_S3, S3
*Elset, elset=_R3-top_S2, internal,
instance="Rubber pad-3"

```
 29,
*Elset, elset=_R3-top_S3, internal,
instance="Rubber pad-3"
 11, 12, 31
*Elset, elset=_R3-top_S4, internal,
instance="Rubber pad-3"
 32,
*Surface, type=ELEMENT, name=R3-
top
_R3-top_S2, S2
_R3-top_S3, S3
_R3-top_S4, S4
*Elset, elset=_R4-bot_S1, internal,
instance="Rubber pad-4", generate
 49,  51,   1
*Elset, elset=_R4-bot_S3, internal,
instance="Rubber pad-4"
 23, 24
*Surface, type=ELEMENT, name=R4-
bot
_R4-bot_S1, S1
_R4-bot_S3, S3
*Elset, elset=_R4-top_S2, internal,
instance="Rubber pad-4"
 29,
*Elset, elset=_R4-top_S3, internal,
instance="Rubber pad-4"
 11, 12, 31
*Elset, elset=_R4-top_S4, internal,
instance="Rubber pad-4"
 32,
*Surface, type=ELEMENT, name=R4-
top
_R4-top_S2, S2
_R4-top_S3, S3
_R4-top_S4, S4
*Elset, elset=_R5-bot_S1, internal,
instance="Rubber pad-5", generate
 49,  51,   1
*Elset, elset=_R5-bot_S3, internal,
instance="Rubber pad-5"
 23, 24
*Surface, type=ELEMENT, name=R5-
bot
_R5-bot_S1, S1
_R5-bot_S3, S3
*Elset, elset=_R5-top_S2, internal,
instance="Rubber pad-5"
 29,
*Elset, elset=_R5-top_S3, internal,
instance="Rubber pad-5"
 11, 12, 31
*Elset, elset=_R5-top_S4, internal,
instance="Rubber pad-5"
 32,
*Surface, type=ELEMENT, name=R5-
top
_R5-top_S2, S2
_R5-top_S3, S3
_R5-top_S4, S4
*Elset, elset=_Rigid-bot_SNEG,
internal, instance=Rigid-bot-1, generate
 1,  7,  1
*Surface, type=ELEMENT,
name=Rigid-bot
_Rigid-bot_SNEG, SNEG
*Elset, elset=_Rigid-top_SPOS,
internal, instance=Rigid-top-1, generate
 1,  7,  1
*Surface, type=ELEMENT,
name=Rigid-top
_Rigid-top_SPOS, SPOS
*Elset, elset=_S1_bot_S2, internal,
instance=Steel-1, generate
 1,  4,  1
*Elset, elset=_S1_bot_S4, internal,
instance=Steel-1
 5,
*Surface, type=ELEMENT,
name=S1_bot
_S1_bot_S2, S2
_S1_bot_S4, S4
*Elset, elset=_S1_top_S1, internal,
instance=Steel-1
 6,
*Elset, elset=_S1_top_S4, internal,
instance=Steel-1, generate
 1,  4,  1
*Surface, type=ELEMENT,
name=S1_top
_S1_top_S1, S1
_S1_top_S4, S4
*Elset, elset=_S2-top_S4, internal,
instance=Steel_2
 1, 2, 6, 7, 8, 9
```

*Surface, type=ELEMENT, name=S2-top
_S2-top_S4, S4
*Elset, elset=_S2_bot_S2, internal, instance=Steel_2, generate
6, 9, 1
*Elset, elset=_S2_bot_S4, internal, instance=Steel_2
4, 5
*Surface, type=ELEMENT, name=S2_bot
_S2_bot_S2, S2
_S2_bot_S4, S4
*Elset, elset=_S3-bot_S2, internal, instance=Steel_3, generate
1, 4, 1
*Elset, elset=_S3-bot_S4, internal, instance=Steel_3
8, 9
*Surface, type=ELEMENT, name=S3-bot
_S3-bot_S2, S2
_S3-bot_S4, S4
*Elset, elset=_S3-top_S4, internal, instance=Steel_3, generate
1, 6, 1
*Surface, type=ELEMENT, name=S3-top
_S3-top_S4, S4
*Elset, elset=_S4-bot_S2, internal, instance=Steel_4, generate
1, 4, 1
*Elset, elset=_S4-bot_S4, internal, instance=Steel_4
8, 9
*Surface, type=ELEMENT, name=S4-bot
_S4-bot_S2, S2
_S4-bot_S4, S4
*Elset, elset=_S4-top_S4, internal, instance=Steel_4, generate
1, 6, 1
*Surface, type=ELEMENT, name=S4-top
_S4-top_S4, S4
*Elset, elset=_S5-bot_S2, internal, instance=Steel_5, generate
1, 4, 1
*Elset, elset=_S5-bot_S4, internal, instance=Steel_5
8, 9
*Surface, type=ELEMENT, name=S5-bot
_S5-bot_S2, S2
_S5-bot_S4, S4
*Elset, elset=_S5-top_S4, internal, instance=Steel_5, generate
1, 6, 1
*Surface, type=ELEMENT, name=S5-top
_S5-top_S4, S4
*Elset, elset=_S6-bot_S2, internal, instance=Steel-6, generate
1, 4, 1
*Elset, elset=_S6-bot_S4, internal, instance=Steel-6
6, 7
*Surface, type=ELEMENT, name=S6-bot
_S6-bot_S2, S2
_S6-bot_S4, S4
*Elset, elset=_S6-top_S1, internal, instance=Steel-6
5,
*Elset, elset=_S6-top_S4, internal, instance=Steel-6, generate
1, 4, 1
*Surface, type=ELEMENT, name=S6-top
_S6-top_S1, S1
_S6-top_S4, S4
** Constraint: Constraint-10
*Tie, name=Constraint-10, adjust=yes, type=SURFACE TO SURFACE
R5-top, S6-bot
** Constraint: Constraint-11
*Tie, name=Constraint-11, adjust=yes, type=SURFACE TO SURFACE
S6-top, Rigid-top
** Constraint: Constraint-12
*Tie, name=Constraint-12, adjust=yes, type=SURFACE TO SURFACE
S1_bot, Rigid-bot
** Constraint: Rigid body
*Rigid Body, ref node=_PickedSet117, elset=_PickedSet118

```
** Constraint: Rigid body-bot
*Rigid Body, ref node=_PickedSet119,
elset=_PickedSet120
*End Assembly
*Amplitude, name=Amp-1
            0.,             0.,     0.080898611,
0.984682058,     0.161111111,
3.846112527,     0.241928056,
8.302932109
    0.322565333,     13.44386606,
0.4030805,     17.81571041,
0.483334,     19.93236806,
0.564539111,     19.00552873
    0.644873889,     15.39526582,
0.724782556,     10.41474067,
0.805296889,     5.541951209,
0.885933556,     1.949490444
    0.966361556,     0.170719294
**
** MATERIALS
**
*Material, name=Aluminum
*Density
 2.81e-09,
*Elastic
70000., 0.32
*Material, name=Rubber-55
*Density
 1.18e-09,
*Hyperelastic, yeoh, moduli=LONG
TERM
 0.5,  0.18, 0.023,    0.,    0.,    0.
*Hysteresis
 1.45,  0.04,  8.25, -0.95
**
** INTERACTION PROPERTIES
**
*Surface Interaction, name=IntProp-1
1.,
*Friction, slip tolerance=1e-05
 0.8,
**
** BOUNDARY CONDITIONS
**
** Name: BC-X Type:
Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet162, XSYMM
** Name: BC-bot Type:
Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet96, ENCASTRE
** Name: comp Type:
Displacement/Rotation
*Boundary
_PickedSet123, 1, 1
_PickedSet123, 2, 2
_PickedSet123, 6, 6
**
** INTERACTIONS
**
** Interaction: Int-1
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R1-bot, S1_top
** Interaction: Int-2
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R1-top, S2_bot
** Interaction: Int-3
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R2-bot, S2-top
** Interaction: Int-4
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R2-top, S3-bot
** Interaction: Int-5
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R3-bot, S3-top
** Interaction: Int-6
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R3-top, S4-bot
** Interaction: Int-7
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R4-bot, S4-top
** Interaction: Int-8
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R4-top, S5-bot
** Interaction: Int-9
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
```

```
R5-bot, S5-top
** ---------------------------------------------
-------------------
**
** STEP: Compression
**
*Step, name=Compression,
nlgeom=YES, inc=10000000
*Dynamic,application=QUASI-
STATIC,initial=NO
0.0001,1.,1e-09
**
** BOUNDARY CONDITIONS
**
** Name: comp Type:
Displacement/Rotation
*Boundary, amplitude=Amp-1
_PickedSet123, 1, 1
_PickedSet123, 2, 2, -1.
_PickedSet123, 6, 6
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field, frequency=1
*Node Output
RF, RT, U, UT, V, VT
*Element Output, directions=YES
E, LE, MISES, NE, S
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history,
variable=PRESELECT, frequency=1
*End Step
```

6. INP File for Non-linear Viscoelastic Simulation of NR Shock Absorber Model-3

```
*Heading
** Job name: Job-1 Model name:
Model-1
** Generated by: Abaqus/CAE 6.13-1
*Preprint, echo=NO, model=NO,
history=NO, contact=NO
**
** PARTS
**
*Part, name=Rigid-bot
*End Part
**
*Part, name=Rigid-top
*End Part
**
*Part, name="Rubber pad"
*End Part
**
*Part, name=Steel-1
*End Part
**
*Part, name=Steel-6
*End Part
**
*Part, name=Steel_middle
*End Part
**
**
** ASSEMBLY
**
*Assembly, name=Assembly
**
*Instance, name="Rubber pad-1",
part="Rubber pad"
        0.,          2.,          0.
*Node
     1,         30.,         12.
     2,         20.,         12.
     3,         20.,          0.
-------------------------------------
    65,   24.7561264,   21.9060879
*Element, type=CAX4H
 1,  1,  7, 36, 22
 2,  7,  8, 37, 36
 3,  8,  9, 38, 37
 -------------------------------------
48, 65, 27,  5, 28
*Nset, nset=_PickedSet5, internal,
generate
  1,  65,   1
```

```
*Elset, elset=_PickedSet5, internal,
generate
  1,  48,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet5,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-2",
part="Rubber pad"
          0.,          28.,           0.
*Node
      1,          30.,          12.
      2,          20.,          12.
      3,          20.,           0.
----------------------------------------
     65,   24.7561264,   21.9060879
*Element, type=CAX4H
 1,  1,  7, 36, 22
 2,  7,  8, 37, 36
 3,  8,  9, 38, 37
----------------------------------------
48, 65, 27,  5, 28
*Nset, nset=_PickedSet5, internal,
generate
  1,  65,   1
*Elset, elset=_PickedSet5, internal,
generate
  1,  48,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet5,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-3",
part="Rubber pad"
          0.,          54.,           0.
*Node
      1,          30.,          12.
      2,          20.,          12.
      3,          20.,           0.
----------------------------------------
     65,   24.7561264,   21.9060879
*Element, type=CAX4H
 1,  1,  7, 36, 22
 2,  7,  8, 37, 36
 3,  8,  9, 38, 37
----------------------------------------
48, 65, 27,  5, 28
*Nset, nset=_PickedSet5, internal,
generate
  1,  65,   1
*Elset, elset=_PickedSet5, internal,
generate
  1,  48,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet5,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-4",
part="Rubber pad"
          0.,          80.,           0.
*Node
      1,          30.,          12.
      2,          20.,          12.
      3,          20.,           0.
--------------------------------------------
     65,   24.7561264,   21.9060879
*Element, type=CAX4H
 1,  1,  7, 36, 22
 2,  7,  8, 37, 36
 3,  8,  9, 38, 37
----------------------------------------------
48, 65, 27,  5, 28
*Nset, nset=_PickedSet5, internal,
generate
  1,  65,   1
*Elset, elset=_PickedSet5, internal,
generate
  1,  48,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet5,
material=Rubber-55
,
*End Instance
**
*Instance, name="Rubber pad-5",
part="Rubber pad"
          0.,         106.,           0.
*Node
      1,          30.,          12.
      2,          20.,          12.
```

```
     3,          20.,           0.
---------------------------------------------
    65,   24.7561264,   21.9060879
*Element, type=CAX4H
 1,  1,  7, 36, 22
 2,  7,  8, 37, 36
 3,  8,  9, 38, 37
---------------------------------------------
48, 65, 27,  5, 28
*Nset, nset=_PickedSet5, internal,
generate
  1,  65,   1
*Elset, elset=_PickedSet5, internal,
generate
  1,  48,   1
** Section: Rubber-55
*Solid Section, elset=_PickedSet5,
material=Rubber-55
,
*End Instance
**
*Instance, name=Rigid-top-1,
part=Rigid-top
         0.,         132.,           0.
*Node
     1,           0.,           0.
     2,           5.,           0.
     3,          10.,           0.
-----------------------------------------------
     8,          35.,           0.
*Element, type=RAX2
1, 1, 2
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
*Node
     9,           0.,           0.,           0.
*Nset, nset=Rigid-top-1-RefPt_, internal
9,
*End Instance
**
*Instance, name=Rigid-bot-1,
part=Rigid-bot
*Node
     1,           0.,           0.
     2,           5.,           0.
     3,          10.,           0.
     4,          15.,           0.
     5,          20.,           0.
     6,          25.,           0.
     7,          30.,           0.
     8,          35.,           0.
*Element, type=RAX2
1, 1, 2
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
*Node
     9,           0.,           0.,           0.
*Nset, nset=Rigid-bot-1-RefPt_, internal
9,
*End Instance
**
*Instance, name=Steel_2,
part=Steel_middle
         0.,          26.,           0.
*Node
     1,          20.,           7.
     2,          19.,           7.
     3,          20.,          4.5
---------------------------------------
    20,          23.,           2.
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  9, 10, 12, 11
 6,  5,  7, 15, 20
 7, 20, 15, 16, 19
 8, 19, 16, 17, 18
 9, 18, 17, 14, 13
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
```

```
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_3,
part=Steel_middle
         0.,          52.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
-------------------------------------------------
--
     20,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_4,
part=Steel_middle
         0.,          78.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
      -----------------------------------------
     20,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel_5,
part=Steel_middle
         0.,         104.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
------------------------------------------
     20,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
 5, 13, 14, 15, 19
 6, 19, 15, 16,  1
 7,  1, 16, 17,  2
 8,  2, 17, 18, 20
 9, 20, 18, 12, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  20,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  9,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
```

```
,
*End Instance
**
*Instance, name=Steel-1, part=Steel-1
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
----------------------------------------
     14,          19.,           3.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  2,  1, 14, 11
6,  1, 12, 13, 14
*Nset, nset=_PickedSet2, internal,
generate
  1,  14,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  6,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Instance, name=Steel-6, part=Steel-6
          0.,         130.,           0.
*Node
      1,          20.,           2.
      2,          20.,           0.
      3,          23.,           2.
---------------------------------------------
     16,          20.,         -2.5
*Element, type=CAX4R
1,  1,  2,  4,  3
2,  3,  4,  6,  5
3,  5,  6,  8,  7
4,  7,  8, 10,  9
5,  1, 12, 14,  2
6,  2, 14, 15, 16
7, 16, 15, 13, 11
*Nset, nset=_PickedSet2, internal,
generate
  1,  16,   1
*Elset, elset=_PickedSet2, internal,
generate
 1,  7,  1
** Section: Aluminum
*Solid Section, elset=_PickedSet2,
material=Aluminum
,
*End Instance
**
*Nset, nset=_PickedSet96, internal,
instance=Rigid-bot-1, generate
 1,  8,  1
*Elset, elset=_PickedSet96, internal,
instance=Rigid-bot-1, generate
 1,  7,  1
*Nset, nset=_PickedSet117, internal,
instance=Rigid-top-1
 9,
*Nset, nset=_PickedSet118, internal,
instance=Rigid-top-1, generate
 1,  8,  1
*Elset, elset=_PickedSet118, internal,
instance=Rigid-top-1, generate
 1,  7,  1
*Nset, nset=_PickedSet119, internal,
instance=Rigid-bot-1
 9,
*Nset, nset=_PickedSet120, internal,
instance=Rigid-bot-1, generate
 1,  8,  1
*Elset, elset=_PickedSet120, internal,
instance=Rigid-bot-1, generate
 1,  7,  1
*Nset, nset=_PickedSet123, internal,
instance=Rigid-top-1, generate
 1,  8,  1
*Elset, elset=_PickedSet123, internal,
instance=Rigid-top-1, generate
 1,  7,  1
*Nset, nset=_PickedSet174, internal,
instance="Rubber pad-1"
  2,  3,  6, 10, 11, 12, 13, 14, 31, 32, 33,
34, 35
*Nset, nset=_PickedSet174, internal,
instance="Rubber pad-2"
  2,  3,  6, 10, 11, 12, 13, 14, 31, 32, 33,
34, 35
```

```
*Nset, nset=_PickedSet174, internal,
instance="Rubber pad-3"
  2,  3,  6, 10, 11, 12, 13, 14, 31, 32, 33,
34, 35
*Nset, nset=_PickedSet174, internal,
instance="Rubber pad-4"
  2,  3,  6, 10, 11, 12, 13, 14, 31, 32, 33,
34, 35
*Nset, nset=_PickedSet174, internal,
instance=Steel_4
 12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet174, internal,
instance="Rubber pad-5"
  2,  3,  6, 10, 11, 12, 13, 14, 31, 32, 33,
34, 35
*Nset, nset=_PickedSet174, internal,
instance=Steel_2, generate
  2,  12,   2
*Nset, nset=_PickedSet174, internal,
instance=Steel-1
 11, 13, 14
*Nset, nset=_PickedSet174, internal,
instance=Steel_3
 12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet174, internal,
instance=Steel_5
 12, 14, 15, 16, 17, 18
*Nset, nset=_PickedSet174, internal,
instance=Steel-6, generate
 12,  15,   1
*Elset, elset=_PickedSet174, internal,
instance="Rubber pad-1"
  4,  8, 12, 16, 20, 24, 25, 29, 33, 37, 41,
45
*Elset, elset=_PickedSet174, internal,
instance="Rubber pad-2"
  4,  8, 12, 16, 20, 24, 25, 29, 33, 37, 41,
45
*Elset, elset=_PickedSet174, internal,
instance="Rubber pad-3"
  4,  8, 12, 16, 20, 24, 25, 29, 33, 37, 41,
45
*Elset, elset=_PickedSet174, internal,
instance="Rubber pad-4"
  4,  8, 12, 16, 20, 24, 25, 29, 33, 37, 41,
45
*Elset, elset=_PickedSet174, internal,
instance=Steel_4, generate
 5,  9,  1
*Elset, elset=_PickedSet174, internal,
instance="Rubber pad-5"
  4,  8, 12, 16, 20, 24, 25, 29, 33, 37, 41,
45
*Elset, elset=_PickedSet174, internal,
instance=Steel_2, generate
 1,  5,  1
*Elset, elset=_PickedSet174, internal,
instance=Steel-1
 5, 6
*Elset, elset=_PickedSet174, internal,
instance=Steel_3, generate
 5,  9,  1
*Elset, elset=_PickedSet174, internal,
instance=Steel_5, generate
 5,  9,  1
*Elset, elset=_PickedSet174, internal,
instance=Steel-6, generate
 5,  7,  1
*Elset, elset=_R1-bot_S3, internal,
instance="Rubber pad-1", generate
 21,  24,   1
*Surface, type=ELEMENT, name=R1-
bot
_R1-bot_S3, S3
*Elset, elset=_R1-top_S3, internal,
instance="Rubber pad-1", generate
 45,  48,   1
*Surface, type=ELEMENT, name=R1-
top
_R1-top_S3, S3
*Elset, elset=_R2-bot_S3, internal,
instance="Rubber pad-2", generate
 21,  24,   1
*Surface, type=ELEMENT, name=R2-
bot
_R2-bot_S3, S3
*Elset, elset=_R2-top_S3, internal,
instance="Rubber pad-2", generate
 45,  48,   1
*Surface, type=ELEMENT, name=R2-
top
_R2-top_S3, S3
*Elset, elset=_R3-bot_S3, internal,
instance="Rubber pad-3", generate
 21,  24,   1
```

```
*Surface, type=ELEMENT, name=R3-
bot
_R3-bot_S3, S3
*Elset, elset=_R3-top_S3, internal,
instance="Rubber pad-3", generate
 45,  48,   1
*Surface, type=ELEMENT, name=R3-
top
_R3-top_S3, S3
*Elset, elset=_R4-bot_S3, internal,
instance="Rubber pad-4", generate
 21,  24,   1
*Surface, type=ELEMENT, name=R4-
bot
_R4-bot_S3, S3
*Elset, elset=_R4-top_S3, internal,
instance="Rubber pad-4", generate
 45,  48,   1
*Surface, type=ELEMENT, name=R4-
top
_R4-top_S3, S3
*Elset, elset=_R5-bot_S3, internal,
instance="Rubber pad-5", generate
 21,  24,   1
*Surface, type=ELEMENT, name=R5-
bot
_R5-bot_S3, S3
*Elset, elset=_R5-top_S3, internal,
instance="Rubber pad-5", generate
 45,  48,   1
*Surface, type=ELEMENT, name=R5-
top
_R5-top_S3, S3
*Elset, elset=_Rigid-bot_SNEG,
internal, instance=Rigid-bot-1, generate
 1,  7,  1
*Surface, type=ELEMENT,
name=Rigid-bot
_Rigid-bot_SNEG, SNEG
*Elset, elset=_Rigid-top_SPOS,
internal, instance=Rigid-top-1, generate
 1,  7,  1
*Surface, type=ELEMENT,
name=Rigid-top
_Rigid-top_SPOS, SPOS
*Elset, elset=_S1_bot_S2, internal,
instance=Steel-1, generate
 1,  4,  1
*Elset, elset=_S1_bot_S4, internal,
instance=Steel-1
 5,
*Surface, type=ELEMENT,
name=S1_bot
_S1_bot_S2, S2
_S1_bot_S4, S4
*Elset, elset=_S1_top_S1, internal,
instance=Steel-1
 6,
*Elset, elset=_S1_top_S4, internal,
instance=Steel-1, generate
 1,  4,  1
*Surface, type=ELEMENT,
name=S1_top
_S1_top_S1, S1
_S1_top_S4, S4
*Elset, elset=_S2-top_S4, internal,
instance=Steel_2
 1, 2, 6, 7, 8, 9
*Surface, type=ELEMENT, name=S2-
top
_S2-top_S4, S4
*Elset, elset=_S2_bot_S2, internal,
instance=Steel_2, generate
 6,  9,  1
*Elset, elset=_S2_bot_S4, internal,
instance=Steel_2
 4, 5
*Surface, type=ELEMENT,
name=S2_bot
_S2_bot_S2, S2
_S2_bot_S4, S4
*Elset, elset=_S3-bot_S2, internal,
instance=Steel_3, generate
 1,  4,  1
*Elset, elset=_S3-bot_S4, internal,
instance=Steel_3
 8, 9
*Surface, type=ELEMENT, name=S3-
bot
_S3-bot_S2, S2
_S3-bot_S4, S4
*Elset, elset=_S3-top_S4, internal,
instance=Steel_3, generate
 1,  6,  1
*Surface, type=ELEMENT, name=S3-
top
```

_S3-top_S4, S4
*Elset, elset=_S4-bot_S2, internal, instance=Steel_4, generate
 1, 4, 1
*Elset, elset=_S4-bot_S4, internal, instance=Steel_4
 8, 9
*Surface, type=ELEMENT, name=S4-bot
_S4-bot_S2, S2
_S4-bot_S4, S4
*Elset, elset=_S4-top_S4, internal, instance=Steel_4, generate
 1, 6, 1
*Surface, type=ELEMENT, name=S4-top
_S4-top_S4, S4
*Elset, elset=_S5-bot_S2, internal, instance=Steel_5, generate
 1, 4, 1
*Elset, elset=_S5-bot_S4, internal, instance=Steel_5
 8, 9
*Surface, type=ELEMENT, name=S5-bot
_S5-bot_S2, S2
_S5-bot_S4, S4
*Elset, elset=_S5-top_S4, internal, instance=Steel_5, generate
 1, 6, 1
*Surface, type=ELEMENT, name=S5-top
_S5-top_S4, S4
*Elset, elset=_S6-bot_S2, internal, instance=Steel-6, generate
 1, 4, 1
*Elset, elset=_S6-bot_S4, internal, instance=Steel-6
 6, 7
*Surface, type=ELEMENT, name=S6-bot
_S6-bot_S2, S2
_S6-bot_S4, S4
*Elset, elset=_S6-top_S1, internal, instance=Steel-6
 5,
*Elset, elset=_S6-top_S4, internal, instance=Steel-6, generate
 1, 4, 1
*Surface, type=ELEMENT, name=S6-top
_S6-top_S1, S1
_S6-top_S4, S4
** Constraint: Constraint-11
*Tie, name=Constraint-11, adjust=yes, type=SURFACE TO SURFACE
S6-top, Rigid-top
** Constraint: Constraint-12
*Tie, name=Constraint-12, adjust=yes, type=SURFACE TO SURFACE
S1_bot, Rigid-bot
** Constraint: Rigid body
*Rigid Body, ref node=_PickedSet117, elset=_PickedSet118
** Constraint: Rigid body-bot
*Rigid Body, ref node=_PickedSet119, elset=_PickedSet120
*End Assembly
*Amplitude, name=Amp-1
 0., 0., 0.082231094,
1.017259851, 0.162401132,
3.906311288, 0.243161282,
8.379455473
 0.323967189, 13.53121591,
0.404588083, 17.88004016,
0.484281874, 19.93983303,
0.56538052, 18.97999321
 0.64576254, 15.34460972,
0.725713094, 10.35481445,
0.806750395, 5.463355493,
0.887132233, 1.909103549
 0.96831852, 0.15144204
**
** MATERIALS
**
*Material, name=Aluminum
*Density
 2.81e-09,
*Elastic
70000., 0.32
*Material, name=Rubber-55
*Density
 1.18e-09,
*Hyperelastic, yeoh, moduli=LONG TERM
 0.5, 0.18, 0.023, 0., 0., 0.

```
*Hysteresis
 1.45,  0.04,  8.25, -0.95
**
** INTERACTION PROPERTIES
**
*Surface Interaction, name=IntProp-1
1.,
*Friction, slip tolerance=1e-05
 0.8,
**
** BOUNDARY CONDITIONS
**
** Name: BC-X Type:
Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet174, XSYMM
** Name: BC-bot Type:
Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet96, ENCASTRE
** Name: comp Type:
Displacement/Rotation
*Boundary
_PickedSet123, 1, 1
_PickedSet123, 2, 2
_PickedSet123, 6, 6
**
** INTERACTIONS
**
** Interaction: Int-1
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R1-bot, S1_top
** Interaction: Int-2
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R1-top, S2_bot
** Interaction: Int-3
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R2-bot, S2-top
** Interaction: Int-4
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R2-top, S3-bot
** Interaction: Int-5
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R3-bot, S3-top
** Interaction: Int-6
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R3-top, S4-bot
** Interaction: Int-7
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R4-bot, S4-top
** Interaction: Int-8
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R4-top, S5-bot
** Interaction: Int-9
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R5-bot, S5-top
** Interaction: Int-10
*Contact Pair, interaction=IntProp-1,
type=SURFACE TO SURFACE
R5-top, S6-bot
** ----------------------------------------
**
** STEP: Compression
**
*Step, name=Compression,
nlgeom=YES, inc=1000000
*Dynamic,application=QUASI-
STATIC,initial=NO
0.0001,1.,1e-09
**
** BOUNDARY CONDITIONS
**
** Name: comp Type:
Displacement/Rotation
*Boundary, amplitude=Amp-1
_PickedSet123, 1, 1
_PickedSet123, 2, 2, -1.
_PickedSet123, 6, 6
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field, frequency=1
*Node Output
```

```
RF, RT, U, UT, V, VT
*Element Output, directions=YES
E, EE, LE, MISES, NE, P, S
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history,
variable=PRESELECT, frequency=1
*End Step
```

VITAE

Name Mr. Veasna Mann

Student ID 6010120104

Educational Attainment

Degree	Name of Institution	Year of Graduation
Bachelor of Engineering	Institute of Technology of Cambodia	2011

Scholarship Awards during Enrolment

2017 Prince of Songkla University and Faculty of Engineering

2018 Research grant from Faculty of Engineering, number ENG-61-2-7-16-02395

List of Publication and Proceeding

International Conference:

2019 Mann, V., Dechwayukul, C., Thongruang, W., & Srewaradachpisal, S. (2019). The Study on Effect of Contact Surface Area to Solid Volume on the Mechanical Behavior of a Rubber Shock Absorber. 4th ICSTR Bangkok – International Conference on Science & Technology Research, 17-18 October 2019.