

ANALYSING IMPACT RESPONSE OF A RUBBER SHOCK ABSORBER USING EXPERIMENTAL DATA AND FINITE ELEMENT METHOD

E. Kutlu¹, C. Oysu², T. Sınmazçelik³

¹Kocaeli University, Asım Kocabıyık Vocational School, 41800, Hereke, Kocaeli, Turkey

²Kocaeli University, Dept. Mechatronics Engineering, 41380, Izmit, Kocaeli, Turkey

³Kocaeli University, Dept. Mechanical Engineering, 41380, Izmit, Kocaeli, Turkey

Abstract

In this study an experimental shock absorbing set-up was designed and constructed. After designing experimental shock absorbing set-up which suits standard impact testing, certain samples of rubber shock absorbers' tests were carried out. The whole impact was recorded by a high speed camera (HSC), and certain dimensions were measured via the software of same HSC, measured data were collected and analysed. Meanwhile, an explicit and transient dynamic finite element model was prepared in Abaqus and Ansys softwares. Analyses were carried out for same impact loads and speeds. The numerical results verified using experimental data. Explicit results of Abaqus has showed a better compliance with experiments.

Key words: rubber shock absorber, finite element modelling of rubber impact, experimental impact behaviour, abaqus, implicit analysis

1. INTRODUCTION

Rubber is widely used and considered with its both stiffening and damping nature. Rubber has currently found vast amount of application areas from tires to bumpers, seals to membranes, coatings to pipes, due to its damping characteristics, easiness in usage and comparative low price. Impact, which is considered mostly as an impulse in vibration mechanics, has to be damped within the systems in order to carry out the proper function continuously. Impact damping, shock absorption and cushioning are terms which are mostly dealing with same phenomenon under vibration systems. There are two different use of impact damping mechanisms in engineering systems; one is for suspension, other is for reducing severity of injury during crash. There appear two different concepts in damping, according to fracture or plastic deformation allowance of damping materials or not. While polystyrene or other plastic foams, thin walled plastics or metal members, sheet metals etc. serve as deformable or breakable components under shock loads to absorb impact energy, shock absorbers, on the other hand, which consists of spring, piston with small orifices and oil, serve as heat dissipating component to absorb impact energy. However, since it has both stiffening and damping, mostly frictional damping, characteristics, rubber is closely followed in many of the researches considering impact and tried to use in impact damping systems. Although rubber bumpers and springs are very inexpensive considered to shock absorbers and high ductile till failure considered to deformable shock absorbers like foams, rubber has also recoil effect (EDINE 2016). Huge amount of absorbed energy at impact is stored instead of dissipate as heat. This residual energy produces a rebound and may result in damage to the load or machinery itself. Therefore, more sophisticated rubber bumper designs should be studied and much more design samples should be prepared and tested for optimum selection for impact damping. Since different designed sample preparation and their tests requires considerable amount of investment and time, a valid Finite Element Model (FEM) generation is needed.

Besides, new material implementation for better shock absorption under relevant deformation rates is significantly considered in researchers and industry. However, material development, shock absorption manufacturing and design are different research areas, to answer the requirements from design, manufacturing and market and to choose correct material and design are rather difficult subjects. Since a good working simulation of material and design will reduce the design, mold, material and production expenditure and minimize the research and development time, a proper FEM constitution is crucial. By

optimizing the design, the upset during impact which is not easily traced or heat dissipation caused by repetitive loadings and its result - artificial aging which is very characteristic property of polymers and especially of elastomers can easily be discovered and improved by means of FEM. So, in this study, in order to implement a proper FEM constitution by comparing with the results derived from experiments, an experiment set-up which has a wide range of sample size testing capacity, impact speed and momentum capability was designed and manufactured. Therefore, elastomers, polymers and other materials having complex geometrical shapes can also be simulated and their virtual material behaviour might be obtained. Same studies can also be made reversely, so, a model can firstly be designed and simulated under constitutive FEM and collected materials requirements for that model can be demanded from material researchers.

In this paper, two parallel study has been carried out; one is to get experimental data from impact test of EPDM (ethylene propylene diene monomer (M-class)) rubber, the other to build FEM which is fully comply with test results. A special impact test set-up was designed in compliance with ASTM DIN3763 standard. The designed test set up was manufactured and samples were gathered from a rubber parts manufacturer. The observation of impact tests was fulfilled by a High Speed Camera (HSC) in 8000 fps. The captured images were collected and certain points on those measured in software of HSC and data collected and analysed in Excel. From time vs distance data, best fit curve (trendline) with R^2 higher than 0,998 is created. The equation of time vs distance trendline is based for future calculations.

Similar and relevant studies on this field have focused on, i.a. force-deformation response for vibration damping parts (R.K. Luo, W.X.WU, W.J. Mortel, 2000). Luo (2016) studied impact behaviour validation via quasi-static analysis and experimental data. High strain rate behaviour of latex and nitril rubber under shock waves in tensile direction is issued by J. Niemczura, K. Ravi-Chandar (2010). Dependence of strain rate to characteristics and properties of rubber reinforced plastic materials under varying impact speeds up to 1 m/s is studied both experimentally and finite element model by G. Dean, L. Wright (2002). Relatively high speed (up to 150 m/s) impact tests to rubber membranes were carried out, monitored and recorded by high speed cameras and simulated according to both quasi-static and high speed response (Aaron B. Albrecht, K. Ravi-Chandar 2014). E. Verron et al. (2010) investigated variation in volumetric change and the deformation of a hyperelastic structure of rubber material. G. Dean and B. Read (2000) tried to establish a model leading to calculate stress as a function of strain at high strain rates by extrapolation of stress-strain relations relatively at low strain rates. This model can be used for Finite Element Analysis to increase the accuracy of simulation. Duan, Y., Saigal, A., Greif, R. and Zimmerman, M.A., (2002) used the DSGZ model, a stress-strain constitutive model for polymers which gives stress as a function of strain, strain rate and temperature. In order to calculate the nine material coefficients used in DSGZ equation, one needs at least three compressive stress-strain curves at varying strain rates and temperatures. To obtain the material coefficients and study the mechanical behaviour, compressive as well as tensile tests under varying conditions were conducted. The impact modelling was performed using Abaqus/Explicit in conjunction with a user-defined subroutine, which executed the DSGZ constitutive relationship.

2. MECHANICAL DESIGN

Testing sample is selected according to its availability and usage. For this study, the basics of future researches were tried to be founded. Once a valid model is developed for basic sample, from aging of sample rubber to new types of elastomeric materials will be carried out using same impact set-up and improved version of set-up. Therefore, in the design of set-up and decision in sample selection, while mobility, modularity, compliance with impact test standards, rigidity, simplicity and robustness to several repeated impact tests were taken as design criteria for test set-up, availability in market, simplicity in design and material and usage in damping were taken as selection criteria for sample.

Certain speeds were caught in test set-up in free fall from certain heights. Overall friction during free fall was ignored and proved the negligence after test measurements.

There are 3 plates machined, made of Aluminium and Kestamid®. Bottom one has used as basement, middle is to carry the load, upper one is to hold the load and carrier at certain height for free fall. Linear

bearings and induced and chromate steel rods provided the frictionless (ignorable) sliding to catch free fall till impact. In order to implement relatively rigid basement according to rubber sample, the plate thickness has been chosen as 50mm. Orthogonality, offset and parallelism of linear bearing rods were kept in very limited tolerances for manufacturing. Planarity of plate is another concern. Below the figures 1-3 presents the drawing and design of mechanism and its parts.

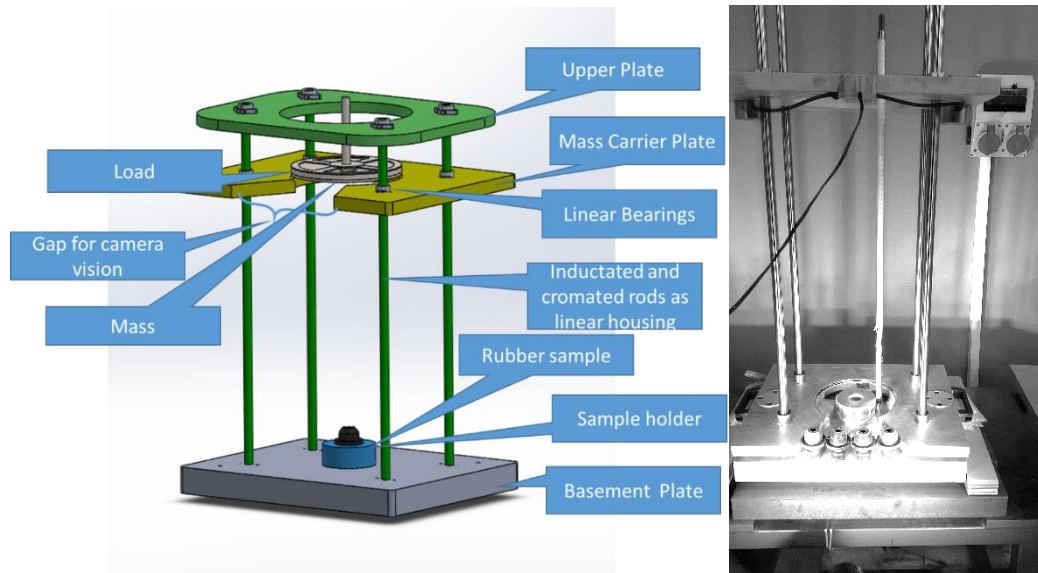


Figure 1. Mechanical Design of Experiment Set-up

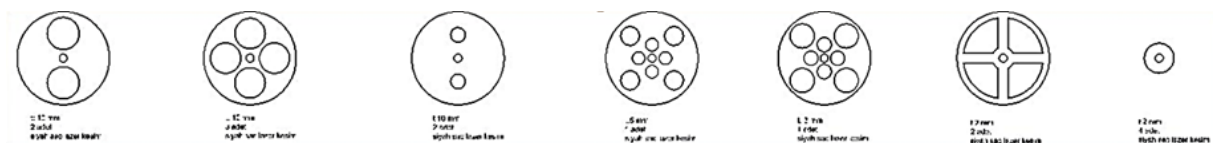


Figure 2. Different Loads for tests

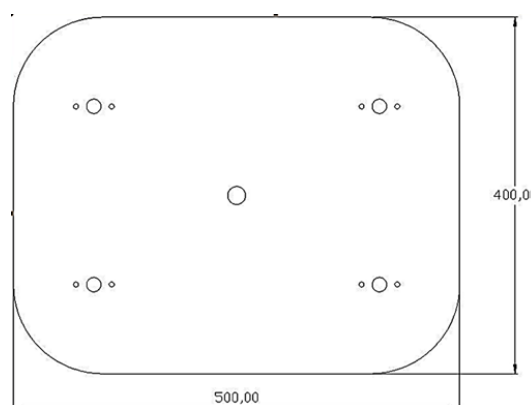


Figure 3. Basement – made of aluminium

Sample is an isolator of the radiator of an automobile, made of EPDM Rubber SAE J200 M3BA is subjected to impact loading created by freefall via experimental set-up. Below figure4 shows the design of isolator.

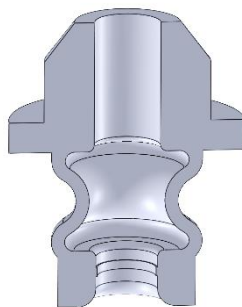


Figure 4. Test Sample

3. EXPERIMENTS

The impact speed in the experiment is customized according to the standard “ASTM D 3763 – 02 Standard Test Method for High Speed Puncture Properties of Plastics Using Load and Displacement Sensors”. Some suggested speeds are 2.5, 25, 125, 200, and 250 m/min according to ASTM D3763-02. The following tables are showing theoretical calculations for drop test.

V	V = Velocity of the falling weight@impact = Impact Speed						
Amplitude	Unit						
200	m/min	from ASTM D3763-02 10.4.1	for single test				
2,5	m/min	from ASTM D3763-02 10.4.2	for multiple tests				
25	m/min						
125	m/min						
200	m/min						
250	m/min						
Assumption for drop							
1. g: 9,81 m/s2							
2. Neglect friction in bearings and air friction							
Impact Speed V _{impact}		Impact Speed V _{impact}		Drop Height (h)		Time pass till impact (t _{drop})	
Amplitude	Unit	Amplitude	Unit	Amplitude	Unit	Amplitude	Unit
2,5	m/min	0,04	m/s	0,009	cm	0,004	s
25	m/min	0,42	m/s	0,885	cm	0,042	s
125	m/min	2,08	m/s	22,122	cm	0,212	s
200	m/min	3,33	m/s	56,632	cm	0,340	s
250	m/min	4,17	m/s	88,487	cm	0,425	s

Table 1. Standard impact speeds and relevant drop heights and time

Impact Speed V_{impact}		Impact Speed V_{impact}		Stopping dist.:5 mm --> t_{stop} (time) & a (acc.)				Stopping dist.:10 mm --> t_{stop} (time) & a (acc.)				Stopping dist.:15 mm --> t_{stop} (time) & a (acc.)				(Max) Force generated during first stroke, mass :		(Max) Force generated during first stroke, mass : 10kg	
				5	mm	Amplitude	Unit	10	mm	Amplitude	Unit	15	mm	Amplitude	Unit	5	kg	10	kg
Amplitude	Unit	Amplitude	Unit	t:2h/v (linear)	a: V ² /2h	Amplitude	Unit	t:2h/v (linear)	a: V ² /2h	Amplitude	Unit	t:2h/v (linear)	a: V ² /2h	Amplitude	Unit	F: ma	Unit	F: ma	Unit
200 m/min	3.33 m/s	3.33 m/s	Unit	0.003 s	1111.1 m/s ²	0.006 s	555.6 m/s ²	0.009 s	370.4 m/s ²	0.1 m/s ²	0.1 m/s ²	0.1 m/s ²	0.1 m/s ²	0.1 m/s ²	0.1 m/s ²	1851.9 N	Unit	3703.7 N	Unit
2.5 m/min	0.04 m/s	0.04 m/s	Unit	0.240 s	0.2 m/s ²	0.480 s	0.1 m/s ²	0.720 s	0.1 m/s ²	0.1 m/s ²	0.1 m/s ²	0.1 m/s ²	0.1 m/s ²	0.1 m/s ²	0.1 m/s ²	0.3 N	Unit	0.6 N	Unit
25 m/min	0.42 m/s	0.42 m/s	Unit	0.024 s	17.4 m/s ²	0.048 s	8.7 m/s ²	0.072 s	5.8 m/s ²	0.072 s	5.8 m/s ²	0.072 s	5.8 m/s ²	0.072 s	5.8 m/s ²	28.9 N	Unit	57.9 N	Unit
125 m/min	2.08 m/s	2.08 m/s	Unit	0.005 s	434.0 m/s ²	0.010 s	217.0 m/s ²	0.014 s	144.7 m/s ²	0.014 s	144.7 m/s ²	0.014 s	144.7 m/s ²	0.014 s	144.7 m/s ²	723.4 N	Unit	1446.8 N	Unit
200 m/min	3.33 m/s	3.33 m/s	Unit	0.003 s	1111.1 m/s ²	0.006 s	555.6 m/s ²	0.009 s	370.4 m/s ²	0.009 s	370.4 m/s ²	0.009 s	370.4 m/s ²	0.009 s	370.4 m/s ²	1851.9 N	Unit	3703.7 N	Unit
250 m/min	4.17 m/s	4.17 m/s	Unit	0.002 s	1736.1 m/s ²	0.005 s	868.1 m/s ²	0.007 s	578.7 m/s ²	0.007 s	578.7 m/s ²	0.007 s	578.7 m/s ²	0.007 s	578.7 m/s ²	2893.5 N	Unit	5787.0 N	Unit

Table 2. The change of estimated impact force and acceleration for standard impact speeds and loads

2,5kg mass was dropped from 61cm and 25cm heights. Since the impact interval and HSC camera recording time is very small, the simultaneous or small different phased starts of drop and HSC starting is crucial. While HSC control was being made from a computer, drop is started by a switch which makes electromagnets energised or not. Two electromagnets were used to hold the mass carrier plate and mass of experiment mechanism at free fall height. Each one of the electromagnets have capacity to lift 65kg, 12Volt and 9,7W of operating characteristics. The interval of recording of HSC in this experiments is 8000fps. The image resolution is at this frame rate is 512x128 pixels. That's why the recording region is focused at the impact point. Below, figure 5 shows the sketch of impact test. Experiments were recorded and analysed via HSC software (Photron Fastcam Viewer PFV ver.3541). In this experiment, main purpose is to build a valid FEM constitution rather than to analyse full geometrical details of sample rubber during impact. Therefore, uniaxial squeezed height measurements in vertical axis were taken from HSC pictures and analysed using Ms Excel. Table 3 shows the basic experimental results and their analyses. In analyses, squeezed height of the sample versus time helped to constitute speed vs time, acceleration vs time, and erk vs time. 4th degree or greater degree polynomials were used for parabolic regression with R^2 (coefficient of determination) more than 0,998. This polynomial was called also as trendline. The equation of that trendline has helped us to find speed vs time and other by taking derivatives of trendline equation.

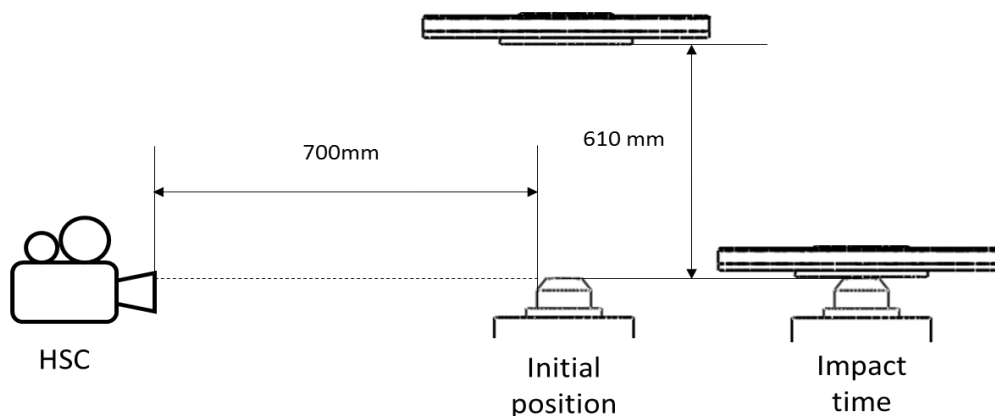


Figure 5. Initial height of the mass and HSC (High Speed Camera) position in experiments

Experiment Name			d15 61 cm 2.5 kg free fall					
Interval of Camera (fps)			8000					
t ₀ (Impact Start Frame #)			7651					
Length of 1 pixel (mm)			0,2912					
4th order polinomial trendline								
y = -1.701.472.672t ⁴ + 37.901.085t ³ + 64.736t ² - 3.699t + 22,26749 R ² = 0,99780								
Experimental Values								
			y		Δy/Δt	(dy/dt)	(d ² y/dt ²)	(d ³ y/dt ³)
			y	y1 (mm)				
Period	Frame#	Time (s)	(height)	(trendlin	v1 (m/s)	v (m/s)	a (m/s ²)	e (m/s ³)
			(mm)	e)				
t ₋₁	7650	-0,000108	23,8	22,7	-2,70	-3,71	105	231803
t ₀	7651	0,000000	23,0	22,3	-7,51	-3,70	129	227407
t ₁	7652	0,000108	22,4	21,9	-5,41	-3,68	154	223010
t ₂	7653	0,000215	21,8	21,5	-5,41	-3,67	177	218614
t ₃	7654	0,000323	21,3	21,1	-5,41	-3,65	201	214218
t ₄	7655	0,000431	21,0	20,7	-2,70	-3,62	224	209822
t ₅	7656	0,000538	20,4	20,3	-5,41	-3,60	246	205426
t ₆	7657	0,000646	20,1	19,9	-2,70	-3,57	268	201030
t ₇	7658	0,000754	19,5	19,5	-5,41	-3,54	289	196634
t ₈	7659	0,000861	18,9	19,2	-5,41	-3,51	310	192238
t ₉	7660	0,000969	18,6	18,8	-2,70	-3,47	331	187842
t ₁₀	7661	0,001077	18,1	18,4	-5,41	-3,44	351	183446
t ₁₁	7662	0,001184	17,8	18,0	-2,70	-3,40	370	179049

Table 3. Experimental Data and Calculations

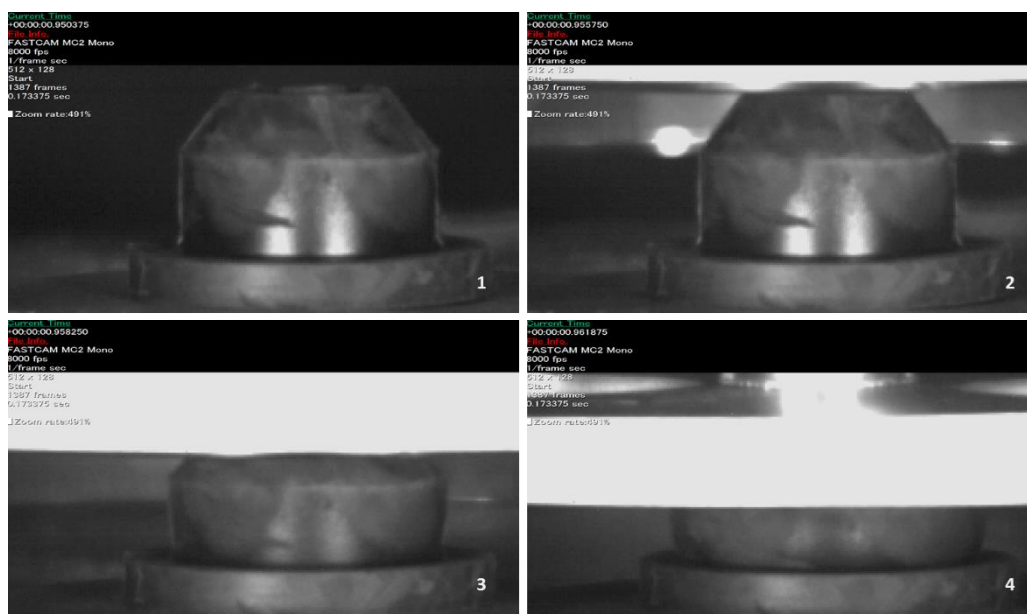


Figure 6. Steps of Impact – Captured with HSC

Further studies will be focused on to get more detailed results and data from experiments by digital image correlation (DIC) techniques.

4. NUMERICAL ANALYSIS

Finite element analysis was carried out initially using solid model of the rubber specimen. As the material deformation is very large and two surfaces are self-contacting, non-linearity of the problem is quite high. This involves very large number of iterations to converge to a solution in each increment. A reasonable 3D model needs more than 300.000 nodes. Since the initial 3D analysis solution times required more than 24 hours, symmetric form of the model was considered as axisymmetric. The number of nodes in 3D model is 20 times more than the axisymmetric model.

Explicit dynamic analysis was carried out using the boundary conditions and the 2D axisymmetric mesh as shown in Figure 7.

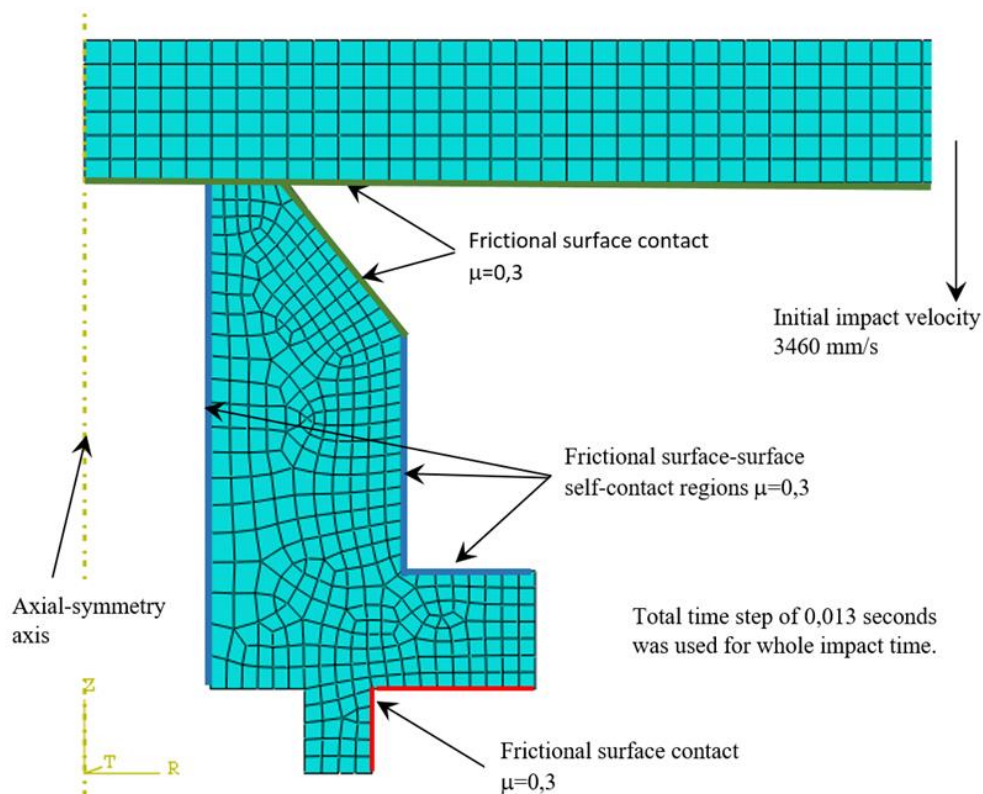


Figure 7. Boundary conditions applied to axisymmetric model

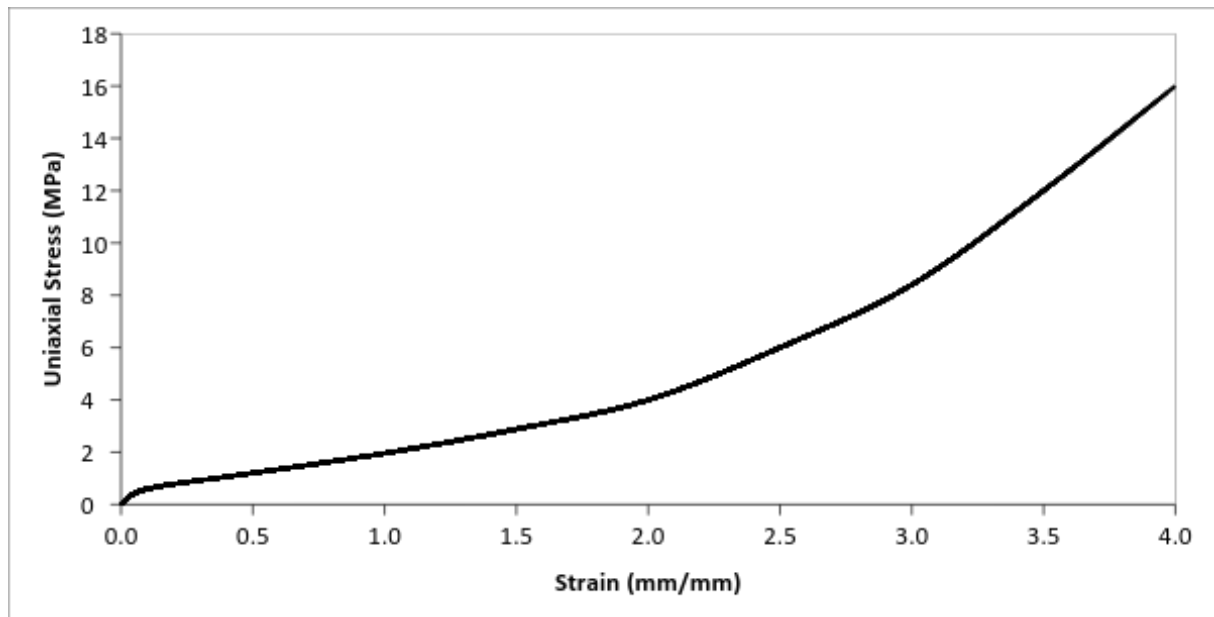


Figure 8. Uniaxial stress vs strain diagram of sample material

The elastomeric material's stress-strain diagram as shown in Figure 8 was used in Abaqus model.

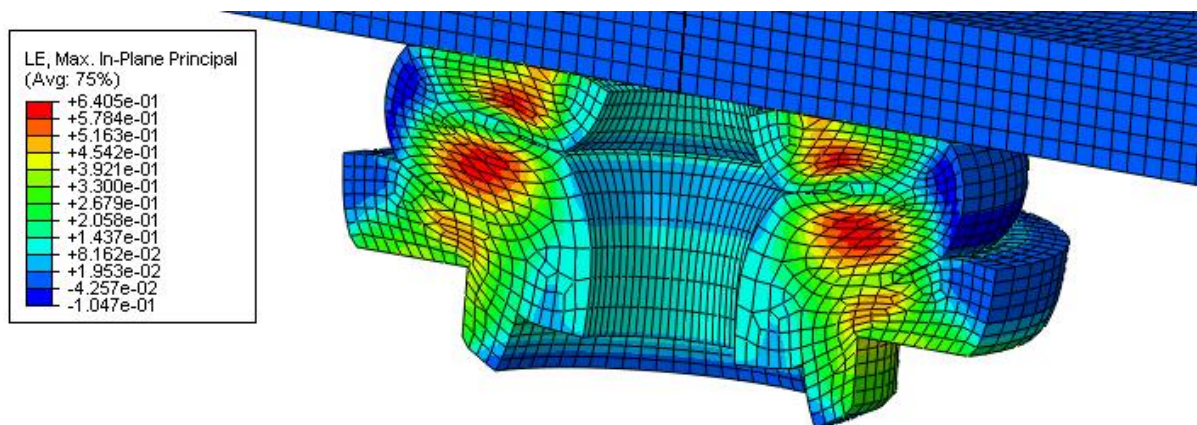


Figure 9. Logarithmic strain of the deformed specimen

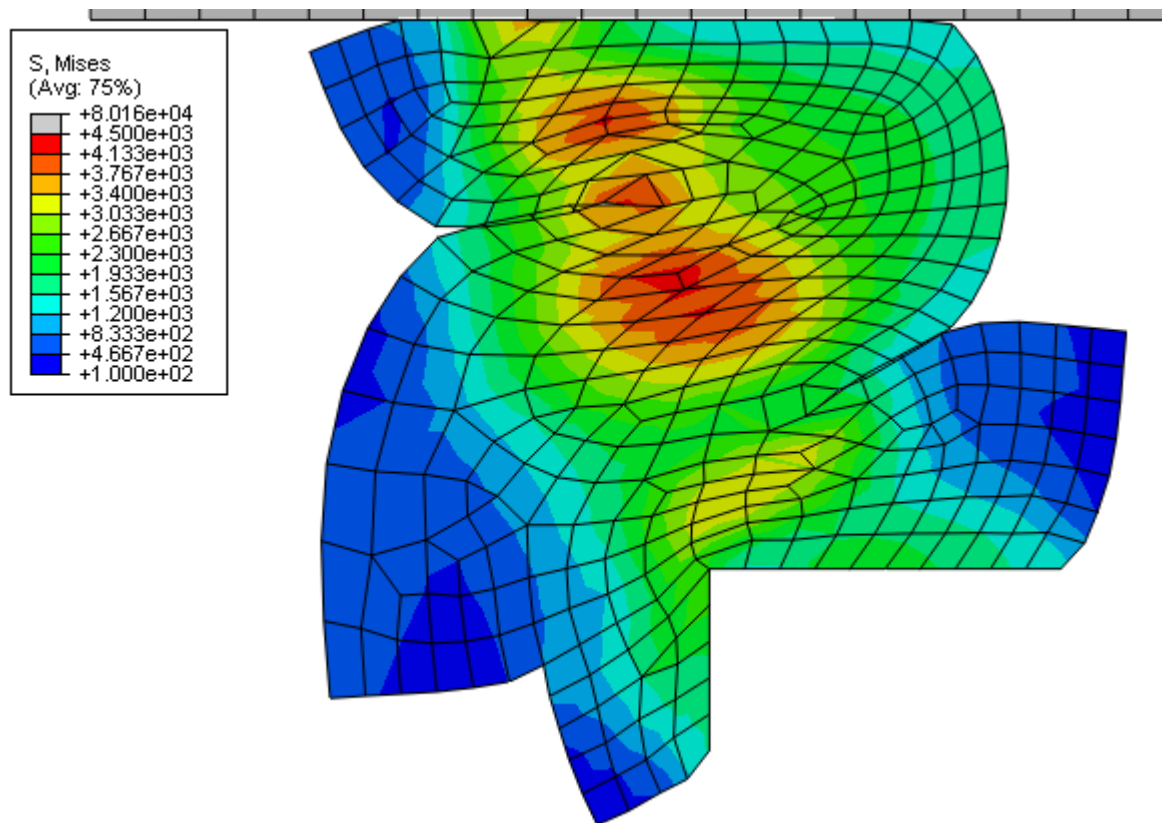


Figure 10. Von Mises equivalent stress distribution in the highest deformed state

The numerical results from the axisymmetric model shows Von Mises stress and logarithmic strain distributions in Figure 9 and 10. These illustrations are useful when designing absorber geometry and material. The accuracy of these contour drawings is highly depend on well-defined material properties. The deformation state during the impact for both experimental and FEM results are given in Figure 11. This result is received using the properties given in Figure 8.

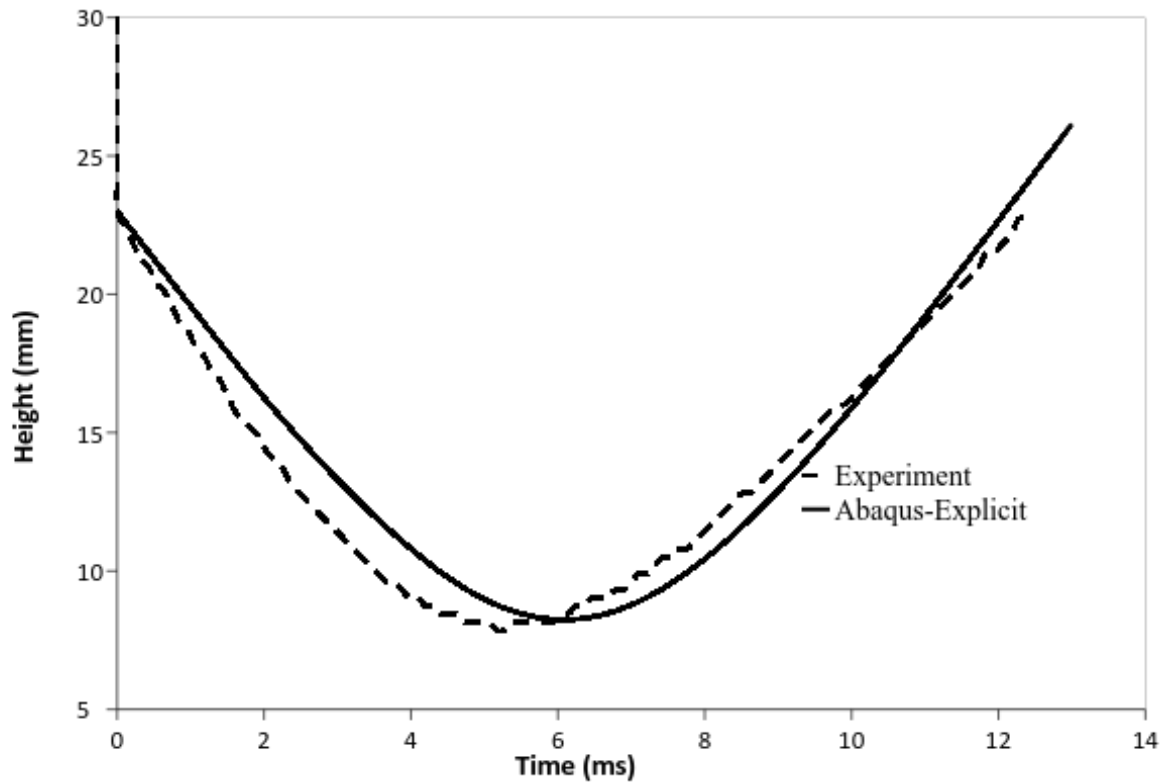


Figure 11. Experimental and numerical deformations rate by time when 2,5kg load dropped from 61cm

The accuracy of the defined material was tested in a different experiment. The results of the FEM model of the new experiment conform quite well as shown in Figure 12.

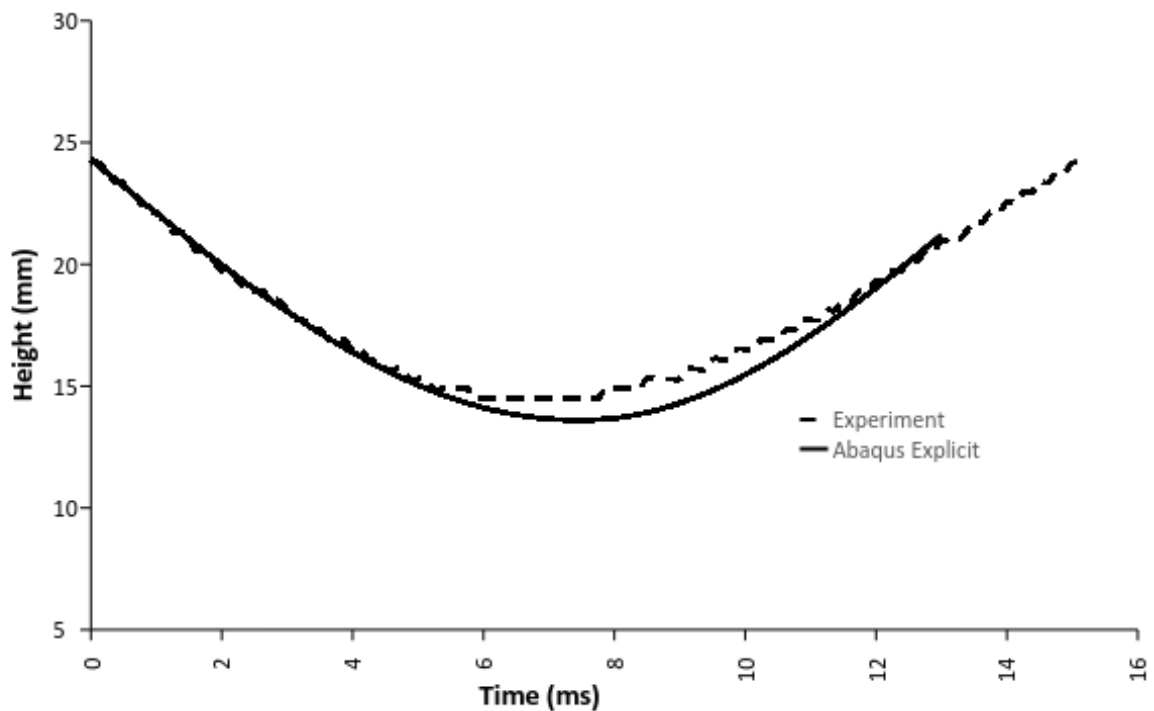


Figure 12. Experimental and numerical deformations rate by time when 2,5kg load dropped from 25cm

5. CONCLUSION

In this paper a novel experimental apparatus designed for measuring impact characteristics of any workpiece was introduced. A special elastomeric absorber is used to determine hyperelastic behaviour when a weight of 2,5 kg was dropped from a height of 61 cm in accordance with DIN3763 standards. Since the impact occurs in 0,06 seconds it is very difficult to measure the distance in high frequency sampling accurately. A high speed camera recording of 10000 fps is very convenient to measure distances from the images. The recorded measurements were used to calibrate the finite element model's material behaviour. Hyperelastic elastomeric behaviour was fitted in the Mooney-Rivlin model so that the deformation progress of the analysed model is in good agreement with the experimental results. In the next step of this study, the material model was tested with a different experiment. When the weight was dropped from a height of 25 cm, the recorded experimental measurements compared to the finite element model with already adjusted material properties. The results were in quite well agreement with the developed material properties. The same material model will be tested in different shapes of the material in the further studies. Real time working conditions would be taken into account in future simulations.

REFERENCES

- Albrecht, A.B. and Ravi-Chandar, K., (2014), 'High strain rate response of rubber membranes', *Journal of the Mechanics and Physics of Solids*, 64, pp.377-395.
- Dean, G. and Read, B., (2001), 'Modelling the behaviour of plastics for design under impact', *Polymer Testing*, 20(6), pp.677-683.
- Dean, G. and Wright, L., (2003), 'An evaluation of the use of finite element analysis for predicting the deformation of plastics under impact loading', *Polymer Testing*, 22(6), pp.625-631.
- Duan, Y., Saigal, A., Greif, R. and Zimmerman, M.A., (2002), 'Analysis of multiaxial impact behavior of polymers', *Polymer Engineering & Science*, 42(2), pp.395-402.
- ITT Enidine Inc., 2016, *About Industrial Shock Absorbers | Benefits of Shock Absorbers | ITT Enidine*, viewed 14 May 2016, <<http://www.enidine.com/Resources/Industrial-Shock-Absorbers/>>.
- Luo, R.K., Wu, W.X. and Mortel, W.J. (2000), 'Effect of loading environment on rubber bolster springs used in railway vehicle bogies', *Plastics, Rubber and Composites*, 29(2), pp.88-91.
- Luo, R.K., (2016), 'Impact simulation and experiment on rubber anti-vibration systems', *Polymer Testing*, 50, pp.335-342.
- Niemczura, J. and Ravi-Chandar, K., (2011), 'On the response of rubbers at high strain rates—II. Shock waves', *Journal of the Mechanics and Physics of Solids*, 59(2), pp.442-456.
- Verron, E., Chagnon, G. and Le Cam, J.B., (2010), 'Hyperelasticity with volumetric damage', *Constitutive Models for Rubber VI*. Rotterdam, The Netherlands: Balkema, pp.279-284.