International Journal of Earthquake Engineering– IJE
Volume 2: Issue 1 [ISSN 2475-2754]
Publication Date : 30 April, 2015

CHARACTERISATION OF A NOVEL FOAM FILLED FLUID VIBRATION ISOLATOR

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Abstract— **Foam-filled fluid (FFFluid) is an innovative material technology that can be used to design anti-vibration devices. This material technology is able to dissipate energy via a number of mechanisms due to the combination of elastic and buckling properties of foams, viscosity properties of fluids and the method of packing the material. The relationship between the energy isolation mechanisms can be altered by modifying the properties of the constituent components which provides significant opportunity for tailoring the response of the isolator to meet the different demands placed upon it.**

While previous studies have characterized the FFFluid shock absorbers, this paper covers the characterization of the mechanical properties of FFFluid vibration isolators. The work presented here starts by studying the parameters that have an effect on the performance of an FFFluid isolator theoretically. Then, the influence of a selected number of factors on the transmissibility of an FFFluid isolator is systematically studied following the Taguchi Parameters Design method. The investigated factors include size of particles, ratio of foam/fluid, viscosity of the fluid, size of package, displacement and frequency. The main conclusions of this research are (1) the biggest volume of FFFluid and highest viscosity of fluid is providing better results in isolating the vibration sources, and (2) filling 90% of a container with foams that have diameters 5 mm are providing the best force transmissibility characteristic compared to other examined ratios or used sizes.

I. Introduction

The presence vibrations can give rise to hazardous conditions in any type of dynamic system, ranging from large multi-bladed helicopters to small electronic component systems. Consequently vibration control has been a point of concern for engineers to improve system performance. There are several ways for controlling unwanted disturbances [1]. Polymeric foam materials are one of the materials which have been used to design vibration isolation system. It is characterized by its low weight and low cost and it is also able to be shaped into small sizes [2-4]. Polymeric foam is able to dissipate a large quantity of energy due to the combination of its elastic, plastic and buckling modes of the constituent cells that occur during the loading and unloading, it also has the ability to dissipate energy due to the viscosity of the fluid inside the structure of foam. Although utilization of fluid in polymeric foam is leading to improving their performance and minimizing their drawbacks, this mechanism either is not exploited in dry foam or partly exploited in fluid filled foam (FFFoam) [5].

Foam Filled Fluid (FFFluid) is another innovation that improves the exploitation of fluid in polymeric foam. It is made of a blend of polymeric foam capsules that are suspended in the fluid and contained in a closed package. A number of applications have been investigated using this technology such as vehicle bumper system [6], shock absorbers [7] and vibration isolator [8]. There are several advantages of FFFluid mixtures over dry foam for eliminating vibrations. The multi-axis loading of the foam prevents localised stress concentration keeping the loading of the foam in the elastic region and also enabling lower density foams to be utilised. These advantages help raise the ability of the FFFluid for absorbing the vibrations. Moreover the FFFluid composite material has smart properties. It could be designed as a smart structure by using FFFluid mixture without any external control system. A vehicle system bumper has been designed by using FFFluid [6]. This structure is able to have a stiff design impact between vehicle to vehicle, and stiffness in the case of an impact between a vehicle and pedestrian. When FFFluid is subjected to a compression load, the energy is absorbed due to the elastic and buckling properties of foams, viscosity properties of fluids and the method of packing the material. This combination can be altered by changing the properties of the constituent components. In turn, this provides significant opportunity for tailoring the response of the FFFluid to meet different demands placed upon it. Previous studies focused on characterising shock absorbing performances of the FFFluid technology [7, 9], while this paper investigates the contribution of a selected set of design parameters on the transmissibility of an FFFluid anti-vibration system using the Taguchi Parameter Design method.

The paper is organised as follows: section II presents a theoretical study on the parameters that have an effect on the total performance of the isolator, then the experimental procedures to examine the most critical parameters are described in section III, the experimental program consists of the following steps: determine the objectives and identification of the variables; then followed by performing and executing the designed experiment. In section V, the results are analysed statistically, and final conclusions are drawn in sections VI.

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II. Parameters of FFFluid Isolator

The performances of an FFFluid isolation system are influenced by several parameters such as the volume of FFFluid mixture and type of package. This section investigates of the parameters that have an effect on the performance of an FFFluid vibration isolator based on known theory. The process parameters can be grouped into four main categories: foam material variables; matrix fluid variables; packaging material variables and vibration event variables. The next sub-section presents these categories and variable parameters in more detail.

A. Foam material variables

Foam materials are made up of an interconnected network of solid plates or struts which form the faces and edges of cells. The purpose of the foam beads in FFFluid mixture is to absorb energy under a compression load by deforming elastically or buckling its walls and faces. The different factors of the foam material that affect the performance of FFFluid are:

Type of the foam cells: The polymeric foam capsules can be grouped into two classes: open-cell and close-cell foam. Both types are able to absorb energy if they are subjected to compression loads. However, when the gases in open-cell are squeezed out under compression load, they can not be able to return to their original shape when load is removed. Therefore, only close-cell foam is used in an FFFluid isolation system in this research.

The shape of the foam: The forms of polymeric foams can vary from long sheets to small beads. Any shape could be used to design an FFFluid device. However, the spherical shape is the only shape that can be packaged in a consistent manner, also loads applied to a sphere bead within a fluid is always perpendicular to its surface. This is an important point as it ensures uniform compression of the material. Therefore, only spherical shape foam will be used in this research.

The size of the foam: The size of foam ranges from beads of millimeters to blocks of ten centimeters. Using a small size of foam will lead to an increase in the volume of foam and provides more passages for fluid, which may lead to increase in the performance of the device. Foam with large size cells has also some advantages as its cells are able to carry a higher load. There are no clear rules about the size of foam to be used; therefore this factor will be investigated experimentally.

Relative Density of the Foam: it is the ratio of the density of the foam structure divided by the density of solid material the structure is made of. It is one of the important features to control the properties of polymeric foam; increasing the relative density leads to an increase in the elastic region of foam [2].

Mechanical Properties of Foam: The main mechanical property that has an effect on the absorbing energy and deformed shape is the Young's Modulus of the material that the foam is made of. Increasing the Young's modulus of foam will lead to an increase in the elastic stress [2].

Initial Pressure of the Cell: The pressure of gas inside the cell affects the behavior of the foam; a higher pressure requires more force to buckle the cell walls. Increasing the initial pressure inside close-cell foam will lead to an increase in the elastic stress [2].

Number of foam capsules: FFFluid devices are designed by filling package fully with foams, then adding the fluid in the container. However, filling the full package with foam may lead to using a small amount of fluid, especially for small size foam, which will lead to more contact between the foam cells and less ability to distribute the load equally around all the foam. Therefore using different amounts of foam in the package may lead to different performances. Although the previous investigations of FFFluid devices have used a different ratio of foam/fluid volume, the effect of this factor on the total performance of the devices has not been investigated experimentally. Therefore, this parameter will be considered in this study.

B. Matrix Fluid Variables

Fluids have two main purposes in FFFluid devices: to transfer the pressure equally around all capsules of foam; and to provide an additional contribution for eliminating unwanted vibration by moving the fluid between and around foams. The parameters of fluid that have an effect on the total performance of FFFluid devices are:

Viscosity: The viscosity is the resistance of a liquid to flow. Increasing viscosity of the liquid reduces its ability to flow. Therefore an increased viscosity is desirable for eliminating energy, while reducing the viscosity has the advantage of distributing the pressure around foams. Previous investigations of fluid viscosity in FFFluid shock absorbers were carried by [7, 10]. Energy absorbing performance increases with increasing the viscosity of the fluid, but this effect is not linear which may be due to the above trade off. For this reason, this research will investigate the effect of fluid viscosity on FFFluid isolator devices.

Chemical Properties: Some fluids could cause corrosion and have harmful effects on either the packaging material or elastomeric capsules. These possible chemical reactions can have an effect on the performance of the device after a short period of time. Therefore the chemical properties should be studied. The chemical effect of fluid around foam will be investigated and checked for corrosion. Drops of considered fluid will be placed on a sample and each of the samples of foam will be kept aside and observed after a week.

C. Packaging Material Variables

The function of the package is to retain the mixture in one container and to keep the pressure around the mixture. Parameters of package that effect on the performance of FFFluid are:

Design of Packaging: Different types of FFFluid packages have been used previously. The design of the package could be: a piston/cylinder arrangement, a rubber cylinder, elastic bags or others. The elastic packaging helps to increase the contribution of eliminating energy, while stiff packaging helps to increase the ability to carry higher static loads. However, to better understand the behavior of FFFluid, non-deformable package is used. Therefore the piston/cylinder package will be only considered in this research.

Volume of Packaging: The volume of a package is dependent on the length and radius of the cylinder. Rising in the length or radius of the cylinder will lead to increase the number of elastomeric elements; therefore the ability of isolation vibration will be increased. Thus, the isolated energy is proportional to the volume of a cylinder. For this reason, different volumes of FFFluid mixture will be examined in this research to measure their effect experimentally.

D. Vibration Event Variables

The value of stiffness and damping coefficients of FFFluid devices are mainly dependent on the input vibrations. The parameters of input vibration are the amplitude of displacement and frequency, and therefore these parameters will be studied in this section:

Amplitude of input displacements: the behavior of FFFluid is linear at low displacement and is nonlinear at high displacements [8]. The magnitudes of applied displacements affect the contributions of all the components of the FFFluid mixture. The amount of deformed foams is dependent on the amplitude of applied displacements. Also fluid's passageways are dependent on the value of applied forces. Therefore, applied displacements affect the total performance of the devices. The previous investigations of the effect of the magnitude of the force were studied under impact force. In this research, various vibrations with different amplitude will be applied to the FFFluid to examine their effect.

Strain Rate (Frequency): Not only will the magnitude of the displacement has an effect on the contribution of FFFluid contribution, but its frequency also has an influence on the contribution of each component of the FFFluid mixture. Increasing the speed of the applied displacement will lead to an increase in the strain rate, and the properties of foam are dependent on the strain rate [2, 11]. Therefore the effect of the strain ratio should be considered in the design of FFFluid devices.

III. Experimental program

Due to the large number of FFFluid parameters and the difficulty in examining all of these parameters only, the most critical parameters which may have an important effect on the performance of FFFluid mixture were examined. For this reason, the experimental program followed a number of steps: the first step was the determination of objectives; then the identification of the variables was examined and the planning of the experimental design. The final step was the realization of the designed experiment. The following subsections present these steps.

A. Determination of Objectives

The objective of the experimental program was to understand the relationships between process parameters and impact performance. More importantly, it was to quantify the contribution of individual process parameters (independent variables) upon impact performance (response variables).

B. Experimental of design

The possible variables for the foam are: shape, size, relative density, mechanical properties, initial pressure of the cell and number of foam capsules. Because of the importance of having the foam in a sphere shape, and polystyrene is the only foam that is found in a spherical shape, therefore the mechanical properties of foam will not be investigated experimentally. Also the relative density and initial pressure of cells were not examined due to unavailability at different levels in the market. Therefore the parameters of foam that were investigated experimentally were the size of foam, and the ratio of foam/fluid. The other selected parameters were viscosity of fluid, the volume of FFFluid mixture and the amplitude of applied displacement. All of the considered parameters were examined at different vibration frequencies.

Appropriate levels were determined by a series of trial experiments using the experimental setup. To simplify the experiment, the test rig simulated the vibration isolator of a medium size machine with a maximum load of 10kg. An example of this machine is a suspension system of an L7e vehicle. The levels of inputs were chosen based on previous papers and availability in the market. Table 1 shows the selected parameters and their levels.

Table 1. Parameters and their levels.

Parameter	Input			
Diameter of particles	5 mm	2 mm	20 mm	Nest
Foam/Fluid ratio	100%	95%	90%	85%
Viscosity of fluid	100(cSt)	1000(cSt)	12500(cSt)	
Volume of FFFluid	0.40L	0.65L	0.9L	1.15L
Displacement	5mm	10mm	20mm	30mm

C. Experiments

The sample composition and preparation are described in [6]. The test facilities within the Cardiff University Structural Performance (CUSP) Laboratory enable the use of an apparatus able to apply force to 100kN, and a frequency up to 2 Hz. The integrated data acquisition system comprises an instrumented type of load cell that digitally records the histories of the impact load–displacements. The experimental test was conducted using L16 orthogonal array- Taguchi method. The experiments were repeated for four different levels of frequencies: 0.75, 1, 1.5, 1.75 Hz.

V. Results and Discussion

At each experiment, the stiffness and damping coefficient were determined, from these values the transmissibility was determined by using the following relationship: relationship:

$$T_f = \frac{F_T}{F_0} = \sqrt{\left\{\frac{k^2+\omega^2 c^2}{[(k-m\omega^2)^2+\omega^2 c^2]}\right\}} \quad (1)$$

Where: T_f is the force transmissibility, F_T is the transmitted force, F_0 is the applied force, ω is the natural frequency, k is the stiffness coefficient, and c is the damping coefficient. Force transmissibility against frequency of force was recorded for each of the tests. The test data were evaluated based on what is required from a manufacturer's perspective of different systems.

A. Influence of Bead Size

Changes in elastomeric beads size upon the efficiency of isolator were investigated. Three samples of the bead sizes were examined, and the fourth sample was the nest sample which is a combination between three different sizes as shown in table 1. The transmissibility force for each of the test results is compared against change in the frequency as shown in Fig 1. From this figure, the transmissibility is improved by increasing the frequency of the system as described in equation (1), it can also be seen that the intermediate level (i.e.5 cm) is providing the lowest transmissibility. To explain this result, it is necessary to look at the energy isolation process. Energy isolation by an FFFluid composite material occurs by two mechanisms. One is the work done in compressing the elastomeric material, and the other is work done by the matrix fluid as it shears.

By using the biggest foams size (20 mm) in a container that has a radius 40 mm is leading to provide a bigger void than with other foams, therefore the amount of foam is decreased, which lead to reduce the amount of eliminated vibrations due to the reduction of elastomeric materials compressed. In case of using foam that has a diameter of 1mm in the same container, there is less space available for fluid. Therefore, it is difficult to distribute the pressure around all foams, and the amount of isolation vibration due to reduction of fluid shear. This is leading to reduce the performance of FFFluid devices.

The performance of the system is improved by using the nest sample, but the best sample to providing vibration isolation is foam that has 5 mm size.

Suitable size of foam depends on the size of the container. The best size of foam for this test rig is 5 mm. However, this size may not the best size for other containers.

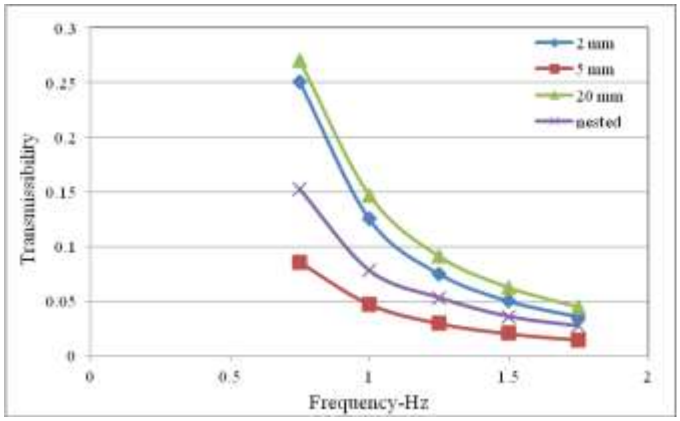

Fig. 1: Transmissibility against frequency for different size of foam in FFFluid pad sample.

B. Influence of Foam/Fluid ratio

The sample of FFFluid mixture was prepared by filling the whole container with foam capsules, then the fluid was poured to fill the voids between the foams, some samples of FFFluid pads were prepared by using different ratios of Foam/fluid. The Fig. 2 shows the effect on transmissibility for different value of foam/fluid ratios. From this result, filling the 90% of package with foam capsules, then pouring the fluid is providing the best force transmissibility. To interpret this result, filling the 100% of the package with foams lead to using a small amount of fluid, especially for small size foam, which may lead to more contacts between the foams, and less ability to distribute the load equally around all foams. Therefore, the amount of isolation vibration due to fluid shear will be reduced. While using 85% of the package volume with foam is reducing the amount of foam, therefore the isolating vibration due to compression foam is also reduced.

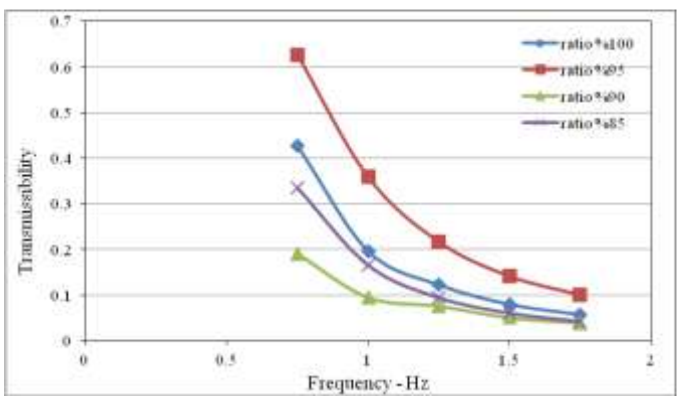

Fig. 2: Transmissibility against frequency for different ratio of foam in FFFluid pad sample.

C. Influence of Matrix Fluid Viscosity

Fig. 3 shows transmissibility against frequency for different viscosities of fluid in the FFFluid pad sample. These results indicate that the vibration isolating performance increases with increasing the viscosity of fluid which is the same effect as FFFluid shock absorber. Although the low viscosity of fluid has the advantage if distribution pressure around the foam, the main purpose of fluid is providing the contribution of isolating vibration. The viscosity of the matrix fluid is increased; the shear stress is far greater. This result the higher viscosity of a fluid is better to improve the performance of FFFluid vibration isolator.

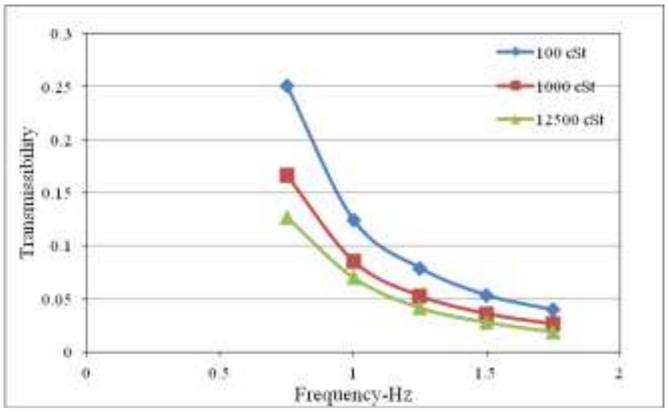

Fig. 3: Transmissibility against frequency for different viscosity of fluid in FFFluid pad sample.

D. Influence of volume of the device

These series of tests investigated change in FFFluid volume (by increasing the length of the cylinder) upon force transmissibility. The force transmissibility for each of the test results is compared against change in frequency for different values of FFFluid volumes is displayed in Fig. 4. From this figure, it could be observed that transmissibility decreased with an increasing volume of FFFluid mixture, also a transmissibility is decreased with increasing the frequency of the system.

To explain these observations, the process of the energy isolation process is required to investigate. The mechanism of energy isolation in this system occurs by compressing the elastomeric material, and shearing the matrix of fluid. By looking at these contributions individually: the strain-rate of the individual foam beads is reduced by increasing the volume of FFFluid. Experimental work on foams [12] has shown that bead of polystyrene foam is strain rate dependent and that stress increases at higher strain rates. Therefore, for a larger volume of FFFluid the work done in compressing the elastomeric material is reduced. This leads to increase the efficiency of isolating unwanted vibration.

If the strain-rate of the individual beads is less within a larger volume of FFFluid, then the shear rate of the matrix fluid would also change. For a Newtonian fluid, the shear rate is directly proportional to shear stress. Therefore the contribution to the work done by shearing of the matrix fluid would therefore be less as FFFluid volume is increased. This also leads to improve the efficiency of the system.

To conclude: Increasing the volume of FFFluid mixture is leading to increase the amount of foam and fluid, therefore the performance of FFFluid device is also increased due to increase the compression of elastomeric material and movement of shear fluid.

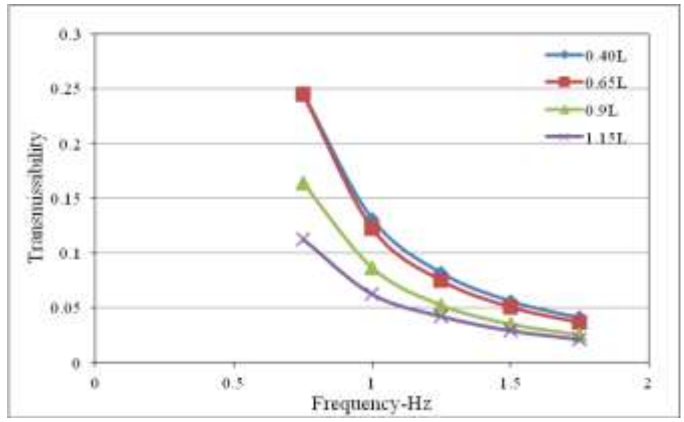

Fig. 4: Transmissibility against frequency for different size of foam in FFFluid pad sample.

E. Influence of applied displacements

These series of tests investigated change in displacements on force transmissibility. Although the displacement is the input for the devices and it is not controlled before designing the FFFluid. However, this parameter is investigated to observe and its effect on the total the performance, and also to explore the best range of the displacement on the performance of this device.

The force transmissibility for each of the test results is compared against change in frequency for different displacement are shown in Fig. 5. From this figure, the maximum displacement were 300 mm which is the linear region only, therefore it is not possible to examine the nonlinear region by using this test rig, it could be observed that there is no big change in the transmissibility as all input were in the linear region.

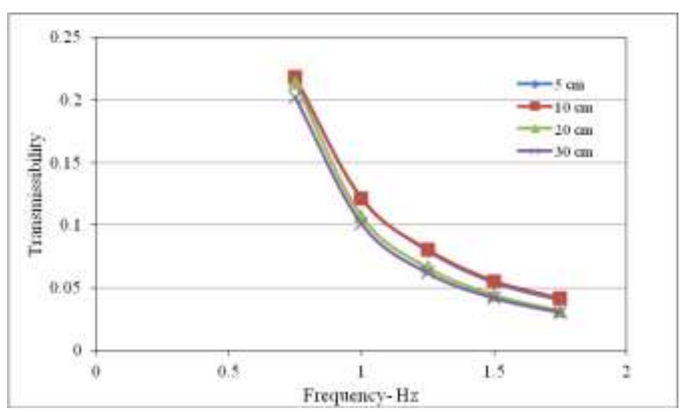

Fig. 5 Transmissibility against frequency for different applied displacement of FFFluid device.

F. The contribution of each factor

Analysis of variance ANOVA is used to measure the contribution for each parameter. The result of ANOVA is shown in Table 2. From this table, it can be seen that the contribution size of bead is 35.80%, which is the highest contribution to overall performance. The volume of the mixture and viscosity of the fluid also has considerable contribution at 25%, 22% respectively. The contributions of displacement and ratio of foam/fluid are the smallest considered variables, it is made 9% and 7% respectively.

Slight changes in percentage contributions of parameters are obtained at different frequencies, but they show a similar trend.

Table 2. Analysis of variance (ANOVA)

ANOVA Table - Average Force values					
Factors	DOF	Sum of Squares	Variance	Variance Ratio (F)	Percent contribution
Foam size	3	0.0193	0.00645	3.580E-01	35.80
Ratio foam/fluid	3	0.0049	0.00164	9.095E-02	9.09
Viscosity	3	0.0122	0.00407	2.260E-01	22.60
Mixture Volume	3	0.0137	0.0046	2.535E-01	25.35
Displacement	3	0.0039	0.00129	7.153E-02	7.15

VI. CONCLUSIONS

Previous investigations on FFFluid isolators concluded that the Foam Filled Fluid has appropriate characteristics for designing vibration isolators. FFFluid is a material technology that has the potential to provide a technically non-restrictive countermeasure that will enhance safety. However, there are considerable challenges that need to be overcome. Characterization of the innovative material technology proposed presents real difficulties because of the large variations that are possible in the physical and mechanical properties of the constituent components. The characterization of the mechanical properties of FFFluid vibration isolators was reported in this paper.

The work reported here presented with a theoretical study of the parameters that have an effect on the performance of an FFFluid isolator. Then an experimental programme was carried out looking at selected key factors over a number of levels. It was shown that: the biggest volume of FFFluid and highest viscosity of fluid provided better results for isolating the vibration sources, while filling 90% of a container with foams that have diameters 5 mm gave better force transmissibility compared to other examined ratios are used sizes. The contribution for each of critical parameters was also determined, and it was observed that size of bead had the highest contribution.

References

[1]. Rao, S.S., Mechanical Vibrations. Fifth edition ed. 2011: Pearson Education South Asia Pte Ltd.

[2]. Gibson, L.J. and Ashby, M.F., Cellular Solids: structure and properties. Second edition ed. 1997: Cambridge university press.

[3]. Harris., C.M. and Piersol. A., eds. Harris' shock and vibration handbook. Fifth Edition ed. 2002, McGRAW-HILL.

[4]. Cardone, D., Gesualdi, G., and Nigro, D., Effects of air temperature on the cyclic behavior of elastomeric seismic isolators. Bulletin of Earthquake Engineering, 2011. 9(4): p. 1227-1255.

[5]. Dawson, M., Modeling the Dynamic Response of Low-Density, Reticulated, Elastomeric Foam Impregnated with Newtonian and Non-Newtonian Fluids, in PhD THESIS, Mechanical Engineering Department. 2008, Massachusetts Institute of Technology.

[6]. Davies, H.C., Development of a novel material for improved crash energy management in collisions involving vulnerable road users. International Journal of Crashworthiness, 2011. 16(4): p. 343-350.

[7]. Courtney, W.A. and Oyadiji, S.O., Characteristics and potential applications of a novel shock absorbing elastomeric composite for enhanced crashworthiness. International Journal of Crashworthiness, 2000. 5(4): p. 469-490.

[8]. Elderrat, H., Davies, H.C., and Brousseau, E., Investigation of the Foam Filled Fluid Technology for Anti-Vibration Devices. Proc. of the International Conference on Advances in Civil, Structural and Mechanical Engineering-CSM 2014., 2014: p. 86-90.

[9]. Georgiades, G., et al., Characterization of the Core Properties of a Shock Absorbing Composite. Journal of Engineering Materials and Technology, 2006. 129(4): p. 497-504.

[10]. Courtney, W.A. and Oyadiji, S.O., Preliminary investigations into the mechanical properties of a novel shock absorbing elastomeric composite. Journal of Materials Processing Technology, 2001. 119(1-3): p. 379-386.

[11]. Meyers, M. and Chawla, K., Mechanical Behavior of Materials. 2 ed. 2009: Cambridge university press.

[12]. Liu, D.-S., et al., Influence of environmental factors on energy absorption degradation of polystyrene foam in protective helmets. Engineering Failure Analysis, 2003. 10(5): p. 581-591.