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Elastic-Plastic Behaviour of Ultrasonic Assisted Compression of Polyvinyl Chloride (PVC) Foam

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Abstract. The present study aims to investigate the elastic-plastic behaviour of ultrasonic assisted compression of PVC closed-cell foam. A series of static and ultrasonic compression test of PVC closed-cell foam were conducted at a constant cross head speed of 30 mm/min on dry surface condition. For quasi-static test, specimen was compressed between two rigid platens using universal testing machine. In order to evaluate the specimen behavior under ultrasonic condition, specimen was placed between a specifically design double-slotted block horn and rigid platen. The horn was designed and fabricated prior to the test as a medium to transmit the ultrasonic vibration from the ultrasonic transducer to the working specimen. It was tuned to a frequency of 19.89 kHz in longitudinal mode and provided an average oscillation amplitude at 6 μm on the uppermost surface. Following, the characteristics of stress-strain curves for quasi-static and ultrasonic compression tests were analyzed. It was found that the compressive stress was significantly reduced at the onset of superimposed ultrasonic vibration during plastic deformation.

1. Introduction

Multifunctional materials that are lightweight, strong, stiff and tough attracts many engineering disciplines including marine, aircrafts, industrial, wind energy, recreation, road and rail applications. Such material is called polyvinyl chloride (PVC) closed-cell foam which has received attention since 1970s. It provides superior strength to weight ratio which has widely used as core materials in sandwich structures for all composite applications which require damage tolerance and weight saving [1, 2]. Formulations has been refined over the years and the characteristics of PVC closed-cell foams fit the needs of other application as well.

Today, PVC closed-cell foam could be extended to the high frequency cyclic force such as in aircraft structure, high speed machine and gas turbine components. Therefore, this is a requirement to identify the response of this material to this condition. Several studies have been conducted to investigate the properties of PVC closed-cell foam following quasi-static and dynamic conditions in order to determine the material responses [2, 3]. The compressive behavior at low and high strain rate as well as the energy absorption had also been discovered [4, 5]. However, a specific study on the effect of ultrasonic vibration on foam is still limited.

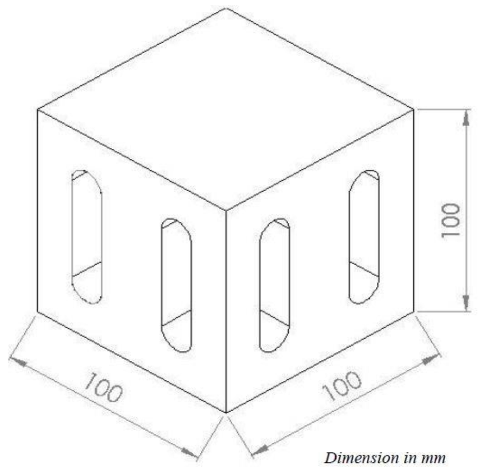
Ultrasonic application is subject to the feasibility of the ultrasonic technology for generation and transmission of acoustic energy at the required intensity and frequency. This interesting phenomena that are associated with intense and inaudible acoustics waves have many promising fields of ultrasonic application which involve scientific, engineering, chemical, industrial, biotechnology and medical [6]. Here, ultrasonic was used in high-intensity applications which refer to power ultrasonic to change the physical and chemical properties of the materials or systems to which it is applied. Common operating frequencies for high-power ultrasonic application is range between 20 and 100 kHz [7].

The versatility of ultrasonic has been exemplified by the wide range of applications that emerge for this technology. Many attempts have been made on the effects of ultrasonic vibration on the mechanical properties of solid metal [8, 9]. It was found that by superimposing an alternating stress on a workpiece, it highly affected the process rate and reduced the force needed for deformation of the workpiece [8]. The effectiveness of superimpose ultrasonic vibration during the deformation process was related to the friction condition, process rate, vibration mode, ultrasonic frequency and amplitude, material properties and type of deformation [9].

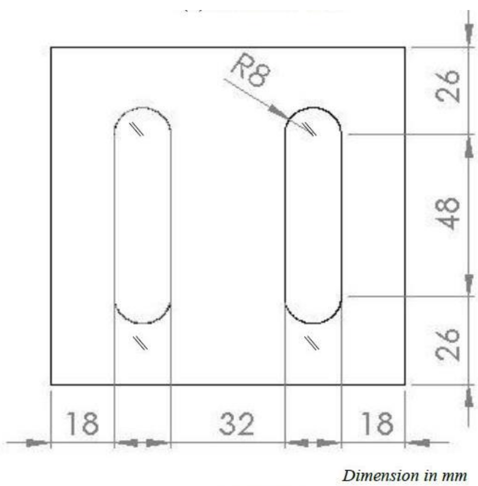
This study had triggered the developments of ultrasonic vibration on a material other than the normally metal. Hence, this study aims to investigate the elastic-plastic behaviour of ultrasonic assisted compression on PVC closed-cell foam. It is expected that through in-depth understanding of material response under high cyclic stress provides useful information for PVC closed-cell foam design, fabrication and application.

2. Finite Element Modelling of Ultrasonic Horn

Prior to the ultrasonic compression test, a specifically design of double-slotted block horn was adapted to enable ultrasonic excitation at a frequency of 20 kHz in longitudinal mode. The horn was made of aluminum with dimension 100x100x100 mm and density of 2712 kg/m3. It was fabricated with a double-slotted through both its width and thickness and simulated in a commercial Finite Element (FE) simulation code, ABAQUS 6.14. The slotting configurations were included in this design to maximize vibration amplitude uniformity at the working space. Figure 1 shows the detail of the final profile of this horn.



(a) Isometric view



(b) Side view

Figure 1. Designed profile horn.

A three dimensional model was developed to calculate the longitudinal natural frequency and mode shape of the horn. A static and dynamic responses of loaded structures is analyzed using a frequency analysis to define the mode shape and natural frequencies with free boundary condition. A vibrational analysis consists of two prescribed step which were frequency step using Lanczos to obtain natural frequencies within the specified frequency range and steady-state dynamics direct step. The frequency step predicts natural frequencies and mode shapes of the system and the steady-state dynamics direct step predicts the stress and displacement amplitude for the applied loading condition. Figure 2 depicts the mode shape of the longitudinal vibrational mode of a double-slotted block horn derived from the FE modelling.

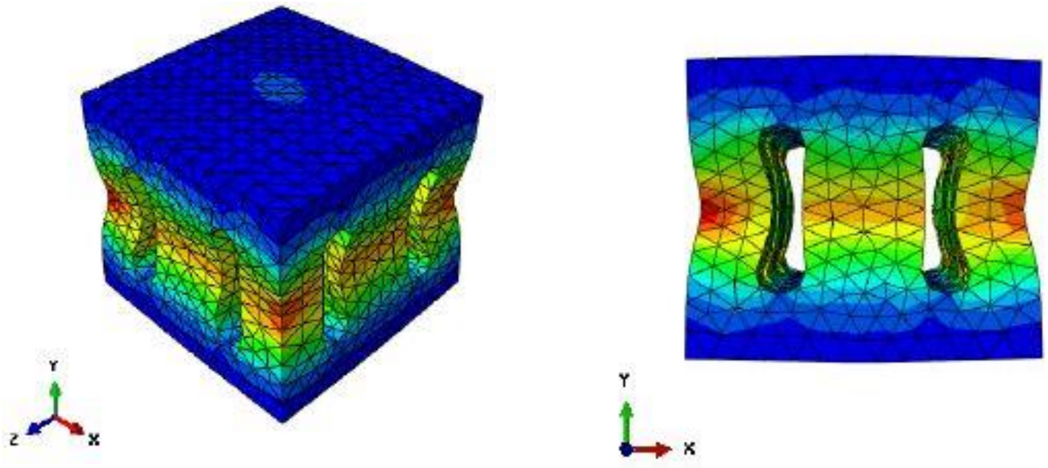


Figure 2. Longitudinal mode shape diagram.

Figure 3 depicts the measured frequency response of a unique nodal on the horn top surface in y-direction which is in longitudinal mode. The extensional length frequency obtained by the simulation was 19.89 kHz. Referring to Figure 3, a clear spectrum at maximum frequency was obtained, as a result from the designed double-slotted block horn at displacement of 0.7 mm.

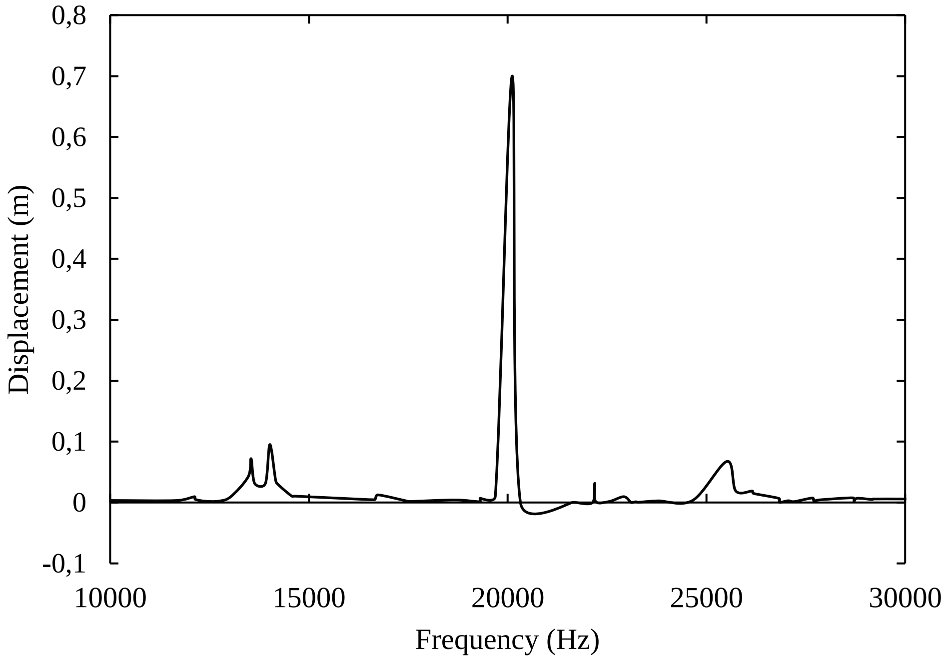


Figure 3. Frequency response in y-direction.

Figure 4 depicts the actual ultrasonic compression test set-up condition. The ultrasonic system consists of several fundamental elements which are electrical power source, ultrasonic generator and ultrasonic transducer. Initially, the ultrasonic generator converts the frequency and power characteristics of the electrical energy received from the power line as required to operate the ultrasonic transducer which attached to a double-slotted block horn. Then, the horn vibrated at 20 kHz frequency in longitudinal mode and transfer the vibrational energy to the working specimen.

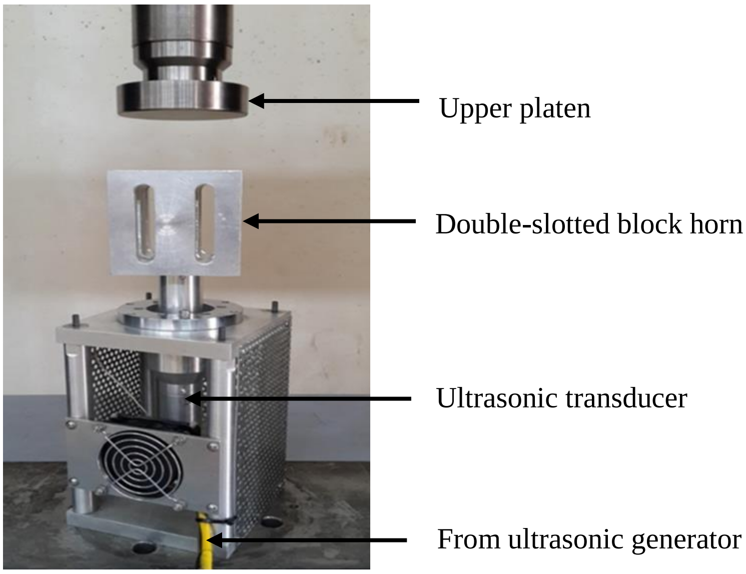


Figure 4. Ultrasonic compression test set-up.

3. Material and Testing

3.1. Specimen Preparation

Cylindrical specimen of PVC closed-cell foam as shown in Figure 5, were used in the static and ultrasonic compression test. Three types of PVC foam which differed by its density were used. Specimens were cut by using laser cutting machine with a laser power of 65 W and cutting speed of 10 mm/s. Details of the foams are given in Table 1.

Table 1. Characterization data for the PVC closed-cell foam samples.

Diameter (mm)	Height (mm)	Density, ρ^* (kg/m^3)	Relative density, ρ^*/ρ_s
20	20	40	0.02857
20	20	60	0.03929
20	20	80	0.05714

ρ_s = 1400 kg/m^3

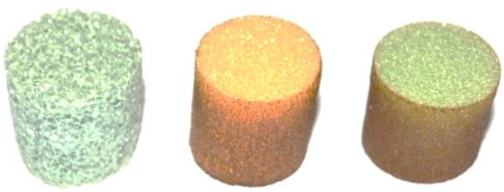


Figure 5. A cylindrical specimen of PVC closed foam.

3.2. Quasi-Static and Ultrasonic Compression Test

3.2.1. Quasi-static test procedure. A series of static compression test of PVC closed-cell foam was conducted at a constant cross head speed of 30 mm/min on dry surface condition. Normal procedure for the quasi-static compression test was conducted where the specimens was statically compressed between two rigid platens.

3.2.2. Ultrasonic test procedure. The test procedure was then repeated for the ultrasonic compression test, but the lower rigid platen was replaced with a double-slotted block horn. Two sets of ultrasonic compression test were conducted. For the first set, the ultrasonic vibration was applied during post-yield for three short intervals by switching on the ultrasonic generator for duration of 1 second. Successively, when the ultrasonic vibration was discontinued, static compression was continued between these intervals. For the second set, the ultrasonic excitation was applied continuously from the onset of plastic deformation to the completion of the test. Both quasi-static and ultrasonic compression test specimens were stopped until the specimens reduced for more than 50% of its original length. Load-displacement data were recorded through hardware and software of the universal testing machine.

4. Results and Discussion

A typical static compression stress-strain curve is depicted in Figure 6. Foams were initially deformed in elastic behaviour until it strained at approximate 0.04 mm/mm. A steady-state stress was continued after it reach plastic collapse stress and followed by a regime of densification where the stress rises steeply. The densification shown a rapid rise in stress starting from the end of the steady-state region. It was observed that the lowest foam density undergo a larger deformation compared to other foam. It is because the foam had low value of steady-state stress and therefore able to withstand a larger deformation as it comes up to densification. In addition, a comparison of compressive strength with several density of PVC foam showed that for increasing density, the plastic collapse strength increased up to 1.46 MPa. Mechanical properties were evaluated as a function of foam density using three type of compression test frame as shown in Table 2.

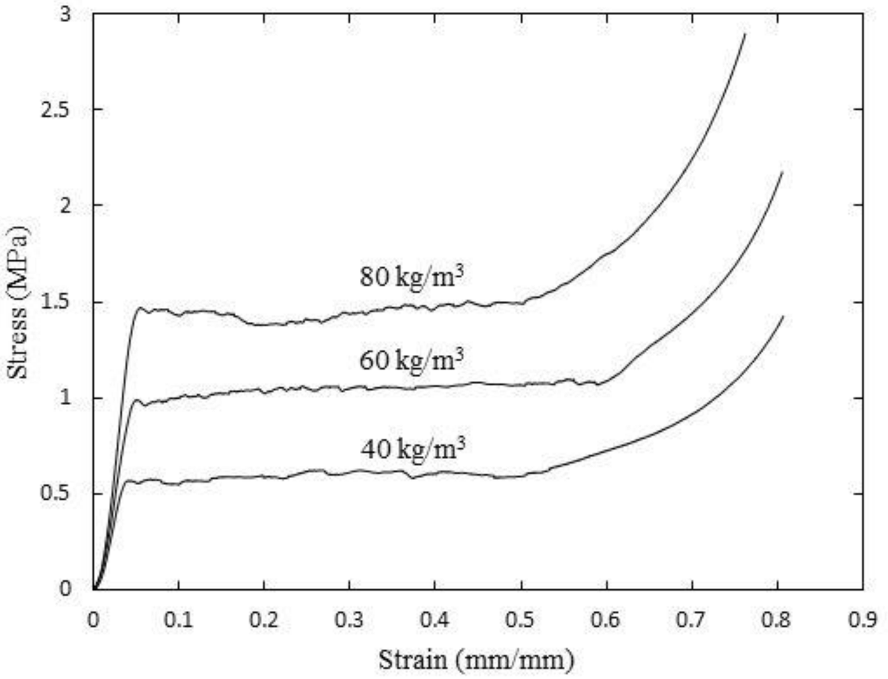


Figure 6. Stress-strain curve for static compression of 40, 60 and 80 kg/m3 of PVC closed-cell foams.

Table 2. Mechanical properties of PVC closed-cell foam.

Type of compression	Density (kg/m³)	Plastic collapse stress, σ_{pl} (MPa)	Compressive modulus, E_c (MPa)	Steady-state stress, σ_{ss} (MPa)	Stress reduction, σ_r (MPa)	Percentage of stress reduction (%)	Densification strain, ε_D (%)
Static	40	0.57	21.34	0.59	0.00	0.00	52.60
	60	0.99	28.68	1.05	0.00	0.00	59.09
	80	1.46	40.17	1.44	0.00	0.00	55.59
Intermittent ultrasonic	40	0.63	17.90	0.49	0.37	58.96	62.32
	60	1.02	20.11	0.71	0.63	61.95	69.82
	80	1.54	29.25	0.83	0.96	62.71	64.82
Continuous ultrasonic	40	0.61	15.39	0.06	0.35	57.77	79.82
	60	1.02	25.67	0.30	0.63	62.17	79.17
	80	1.54	44.28	0.44	1.05	68.55	79.97

The stress-strain curves for quasi-static and ultrasonic compression are plotted in Figure 7. Foams were initially deformed in elastic behaviour until it strained at a similar value from the previous test. Figure 7 (a) shows the intermittent ultrasonic compression where the stress drop drastically after yield when the ultrasonic vibration was applied and start to regain repetitively at a lower stress value than the yield stress. This process continues for three irregular intervals, corresponding to the three times application of ultrasonic vibration. Then, the stress rises rapidly until it reach more than 50 % of its height reduction. The stress variation in the plastic deformation regime can be explained by the repetitive ultrasonic vibration application. It was observed that the stress reduced when ultrasonic vibration applied.

Significant stress reduction has been recorded for the continuous ultrasonic compression as shown in Figure 7 (b) when the ultrasonic vibration applied after it reached plastic collapse stress. It can be observed that the stress reduced up to 50 % when the ultrasonic excitation applied. In addition, the densification regime was also eliminated since the stress continue to drop until the completion of the test. It suggested that the excitation of high frequency at lower platen has remarkably reduced the stress.

Details of the mechanical properties for intermittent and continuous ultrasonic compression test are summarize in Table 2. Besides the remarkable stress reduction given by the intermittent and continuous ultrasonic compression test, densification strain value for continuous ultrasonic compression test were the highest compared to other test. It suggested that the application of ultrasonic excitation at the onset of plastic deformation until completion of the test has restrict the stress from rising steeply for densification process to take place. This is occurred because the foams has the lowest value of steady-state stress and therefore able to withstand a larger deformation such as it eliminate the densification regime.

It was clearly observed that ultrasonic compression has remarkably lowered the stress distribution compared to static compression. It has also been reported by the previous researchers [10-12] who showed that the stress flow of compressive deformation reduced by superimposing ultrasonic vibration on the static load in compression test. This phenomena was defined as Blaha effect or known as acoustoplastic effect. It was described as a decrease in the flow stress during deformation at an increase strain rate during plastic deformation under a constant stress [13-15]. Another researchers [10-12] who claimed that the stress reduction was due to the change of elastic-plastic properties and material softening that occurred under the influence of ultrasonic vibration.

It is allegedly reported that the exact time when the ultrasonic excitation is superimposed to the static compression could also influence the amount of stress reduction. This is because if the ultrasonic vibration applied during the weakest point of the compressed foam, definitely further stress drop is obtained due to these combined effects. Besides, another researcher showed that the material flow stress in ultrasonic compression test was under the influence of friction [16]. It occurred when the oscillatory velocity of the lower platen exceeds the specimen velocity. Friction vector is a result from the relative motion between the lower platen and specimen which normally acts in perpendicular direction to the specimen motion. But the friction vector is reversed when the lower platen is vibrated. This is because the motion of the lower platen is parallel to the specimen motion, such that it assists the motion to the specimen in the working direction and therefore reduced the friction force then stress.

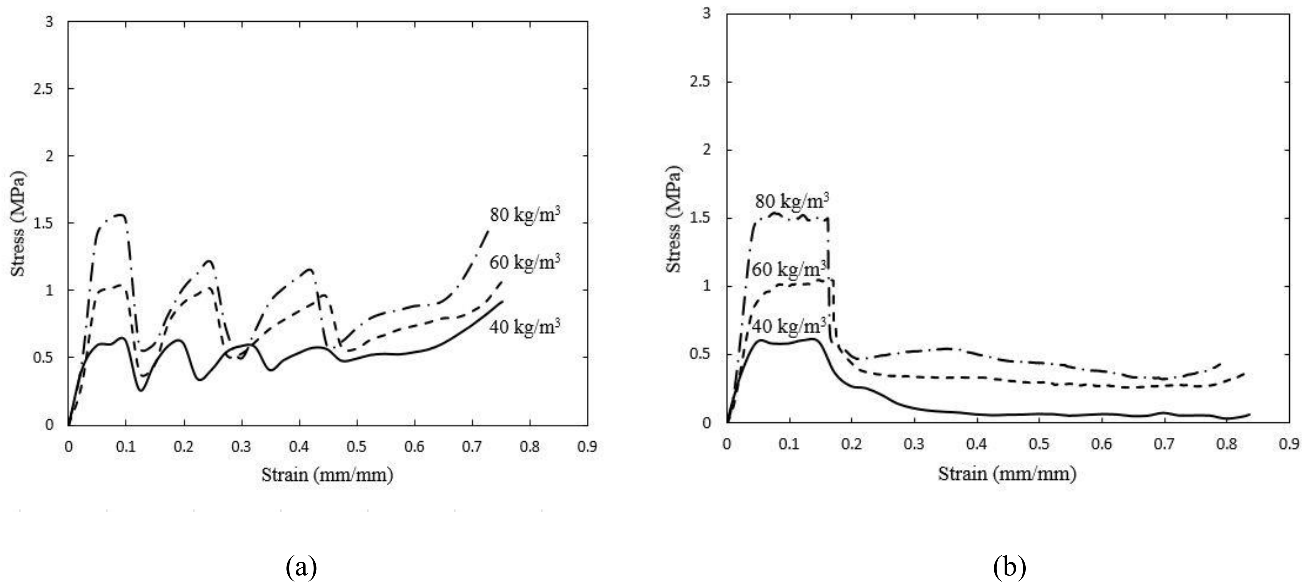


Figure 7. Comparison of the three different density of PVC closed-cell foam under (a) intermittent ultrasonic and (b) continuous ultrasonic compression test results.

The influence of superimposing ultrasonic vibration during compression test on the energy absorption capability was studied. Energy absorption subjected to foam density were calculated. This can be understood by observing the bar chart in Figure 8. To ensure the value of energy absorption are comparable within tests and specimens, the calculation was limited to 50 % of strain and below. The highest energy absorption was recorded by the highest density of foam. This is because if the density is too low, the densification zone is reached and a very high force is obtain before all the energy has been dissipated. On the contrary, if the density is too high, the force exceeds the critical value before enough energy has been absorbed, while the material compressive strain remain only partially utilized [17]. Another substantial observation from the figure is that the energy absorption of foam was reduced when ultrasonic vibration applied in the test. This means that the ability of the foams to absorb energy was lowered by the application of ultrasonic vibration in the compression test. The material softening effect described earlier was proven by this lowered energy absorption as it reduced the material toughness. It is therefore, with the presence of ultrasonic vibration during compression test, foams can withstand low resistance to deformation when stressed.

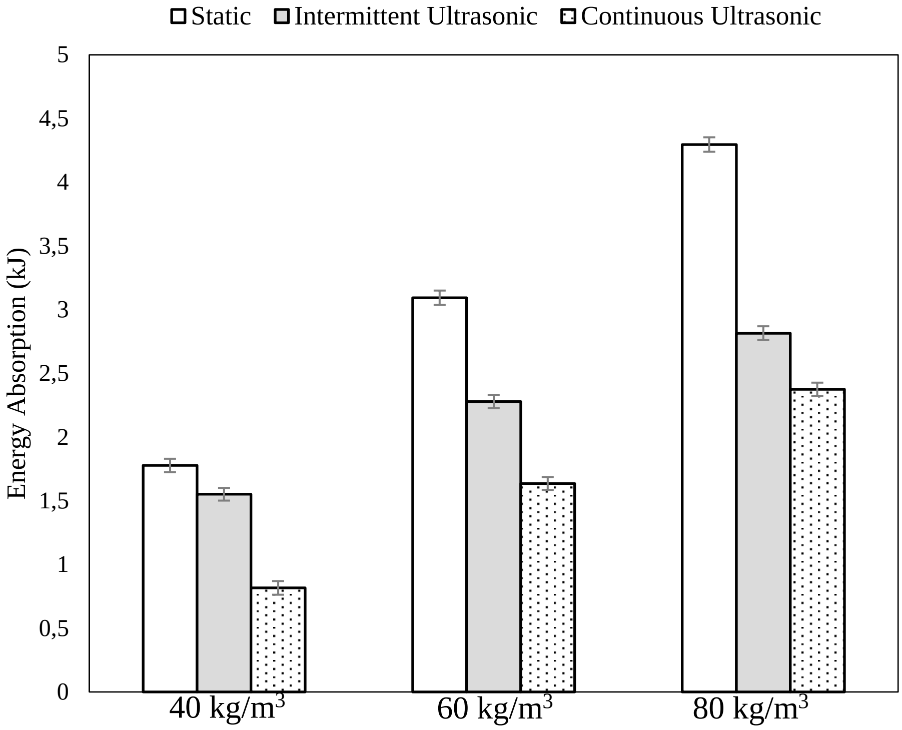


Figure 8. Energy absorption for quasi-static and ultrasonic compression of PVC closed-cell foam.

5. Conclusion
The application of ultrasonic vibration during the plastic deformation process of compression test on foam has remarkably reduced compressive stress and lowered the energy absorption. This effects was related to the material softening such as it exhibited a special temporary softening material properties during the application of ultrasonic vibration. The elastic-plastic behaviour of compressed foam under the ultrasonic compression test is similar to the normally compressed metal in the literatures. It demonstrated that superimposed ultrasonic excitation on the compression test worked effectively in other materials, particularly foam apart of metal. Further investigation on the underlying mechanisms of the stress reduction can be carried out and it is expected that through in-depth understanding of material response under high cyclic stress provides useful information for PVC closed-cell foam design, fabrication and application.

Acknowledgement
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