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# Mitigation of Blast Induced Acceleration using Open Cell Natural Rubber and Synthetic Foam

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**ABSTRACT**

In addition to high pressure generated by explosion, the induced high acceleration can also cause severe injuries to occupants and structural damage, especially in anti-vehicular land mine blast scenario. This problem has not been studied well and only few techniques to reduce the deadly effect of high acceleration are reported in literature. In the present work, the mitigation of blast induced acceleration using add-on layers of open cell natural rubber and synthetic foam on rigidly fixed composite plate has been studied experimentally under increasing blast wave strengths. The blast wave strength was varied by increasing quantity of plastic explosive from 0.150 kg to 0.550 kg. The induced vibration in the composite plate due to impingement of blast wave was measured in terms of acceleration using piezoelectric accelerometer. It was observed that the sharp rising acceleration signals were transformed into a slowly rising and low amplitude signals with the addition of foam. The mitigation of high frequencies and amplitude of acceleration signals was also verified with the fast Fourier transform study. The rubber foam shows better acceleration mitigation than synthetic foam. This study has suggested that the material like rubber and synthetic foam can be used for mitigating the acceleration resulting from the impact of blast wave.

**Keywords:** Acceleration mitigation; Natural rubber foam; Synthetic (Polyurethane) foam; Acceleration measurement

## 1. INTRODUCTION

The strength of blast wave generated due to detonation of high explosive depends on the amount and nature of explosive used. The blast wave generated in explosion may lead to a mild injury or fatality to the living being and damage to structures depending on its strength. In open air explosion, the injuries[1,2] are mainly due to the shear effects at the air-tissue interface (primary injury), striking of propelled fragments from the explosion (secondary injury), and the victim being propelled by the blast pressure or blast winds (tertiary injury). These injuries include nerve damage, soft tissue damage, internal bleeding, broken bones, torn ligaments, spinal damage, etc. due to low tolerance limits of human body[3]. However, in the case of anti-vehicular (AV) land mine explosions[4-6] where the target is generally situated in a protected vehicle, the injuries are mainly due to large acceleration[7-8] propagating through the solid media enclosure. The AV mines and improvised explosive devices (IEDs) explosions were responsible for 45.6 per cent combat deaths of the coalition and local security forces in Iraq and Afghanistan[2].

A detailed study[9] by analysing mine incident casualty data suggested that the basic vehicle modifications like V-shaped hull[10], increased ground clearance, widened axles, heavy vehicles and blast deflectors can significantly reduce injury and casualty rates. The combat vehicle designers are also focusing on other improvements like the use of monocoque hull, high strength material, composite floor, etc. to enhance the crew survivability against the explosion of land mines and IEDs. These improvements mainly reduce the effects of blast overpressure and debris formed from vehicle body. However, the occupants still faced injuries or fatality due to the large acceleration force exerted on them by the imparted shock[11]. Materials like polyurethane (PU) foams, metal foams, sand and low-density aluminum honeycomb, etc. were investigated by researchers[12-16] for protection against blast overpressure and energy absorbing applications.

Many techniques and materials have been proposed in the literature to mitigate the blast pressure and energy, but only two techniques are predominantly used at present for minimising the acceleration imparted to the vehicle compartments resulting from explosion of land mines. In the first, the occupants are separated from the vehicle floor using roof hanging / wall mounted seats. In second, specially designed energy absorbing seats, circular tubes, square tubes, frusta, struts, honeycombs, and sandwich plates are used to decrease the loads acting on the occupants[17,18]. Some other techniques such as the thin walled cylinder, upward convex hull and polyurea coating were also reported for mitigating the acceleration[19-21] but no experimental study has been reported on acceleration mitigation using foam. Only Cendón[5], *et al.* in his numerical simulation study has

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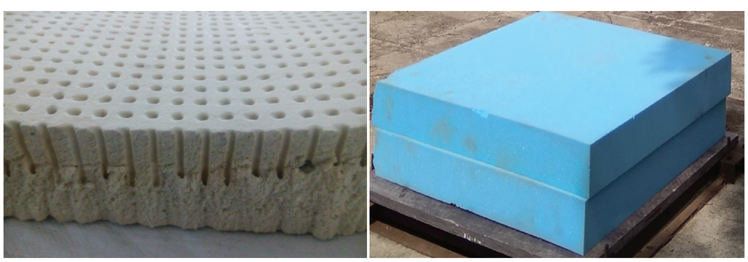
shown that appropriate thick foam seat can also be a potential candidate for the occupant's protection against the acceleration in armoured vehicle. Hence, in the present study, blast induced acceleration mitigation capabilities of natural rubber foam and synthetic foam are compared under different blast wave strengths.

## 2. MATERIALS, EXPERIMENTAL SETUP AND INSTRUMENTATION

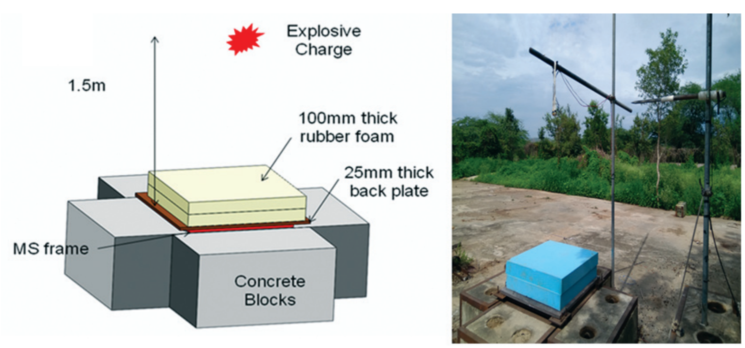
The open cell natural rubber foam of thickness 0.1 m manufactured by M/s Pyare Lal Group, Meerut, India was used for present acceleration mitigation study. One face of the foam has holes of about 0.006 m diameter in grid form extended up to 0.065 m with the center to center inter-separation distance of 0.023 m as shown in Fig. 1(a). The foam has density of 110 kg/m$^3$ in overall and 120 kg/m$^3$ for solid region. The low density (50 kg/m$^3$) synthetic (Polyurethane) foam of same thickness shown in Fig. 1(b) used for comparison was manufactured by M/s Sheela Foam Limited, Ghaziabad, India and has uniform construction. An E-glass fibre reinforced phenolic resin composite plate (DMRL Hyderabad, India) with a cross section area of 1 m × 1 m and thickness of 0.025 m was used as back plate for placing the foam samples. The composite plate having density of 2010 kg/m$^3$and tensile strength of 350 MPa, was mounted rigidly on a mild steel (MS) frame using nuts and bolts. The MS frame was welded with steel frames of four concrete blocks each of approximately 1000 kg to form a rigid structure (Figs. 2(a) and (b)). Plastic Explosive Kirkee (PEK) obtained from the High Explosive Factory, Khadki, Pune, India was used for generating the blast loading. It has a TNT equivalent (weight) of 1.17[22] and comprised of 85 per cent Trinitrophenylmethylnitramine (Tetryl). The explosive stand-off distance was kept as 1.5 m from the top surface of composite plate in all experiments. The spherical explosive charges of different weights used in these experiments were prepared manually at laboratory and detonation was achieved by using electric detonator.

A piezoelectric accelerometer was used for measuring the vibration (acceleration) signal produced in the composite plate. It was deployed though its threads on an adaptor mounted rigidly backside of plate at its center using nut bolts. The sensitivity of sensor was 0.5 mV/g and the measuring range of 10,000 g's where 'g' is the acceleration due to gravity. A piezoelectric pressure sensor having sensitivity of 3.6 mV/kPa was also deployed in flush with top surface of plate to record the blast pressure loading. The output signals from the sensors were brought to the instrumentation shelter with the help of special low-noise coaxial cables and the data was recorded on Tektronix® make oscilloscope (Bandwidth 1GHz) at a sampling rate of 10 MS/s The experiments were conducted in three test configurations, namely without foam, single layer of foam and double layer of foam. The effect of different blast loading in these test configurations were examined by varying the amount of explosive from 0.150 kg to 0.550 kg. The composite plate was intact after the tests and small tearing at the edges was observed in few foam samples.



(a) (b)

**Figure 1. Experimental specimens: (a) Natural rubber foam and (b) Synthetic foam.**




(a) (b)

**Figure 2. Experimental setup: (a) Schematic and (b) Photograph.**

## 3. RESULTS AND DISCUSSIONS

### 3.1 Consistency of the Acceleration Data

Figure 3 shows the acceleration data acquired in without foam test configuration in three tests performed with 0.150 kg explosive. Peak accelerations of 898 g's, 892 g's, and 987 g's was recorded in these tests. The percentage variation of peak accelerations from average value was within ± 7 %. This variation might have resulted from the environmental conditions and experimental errors. The large fluctuations in acceleration time histories after the peak acceleration are resulted from the elastic nature of the composite plate.

### 3.2 Effect of Foam on Acceleration Mitigation

The measured acceleration histories in three test configurations with rubber foam and synthetic foam for explosive weight of 0.150 kg are as shown in Figs. 4(a) and 4(b), respectively. Since the time of arrival of acceleration signal at the accelerometer differ for three test configurations due to increased thickness of the test samples, the oscilloscope was triggered at different times in different tests. Therefore, synchronization of arrival times of acceleration signals was performed using a MATLAB® program to compare the amplitudes and time histories of the acceleration.

A sharp rise of acceleration in the composite plate was altered into a gradual rise when synthetic or rubber foam layers were added over it. This happened due to the spread of unidirectional blast energy into multi-directional due to interaction with foam and elastic deformation of foam. In case of 0.150 kg explosive, the peak acceleration of 987 g's with bare plate was reduced to about 390 g's and 240 g's for single and double layer of rubber foam respectively. However, the same peak acceleration is reduced to about 550 g's and 460 g's for single and double layer of synthetic

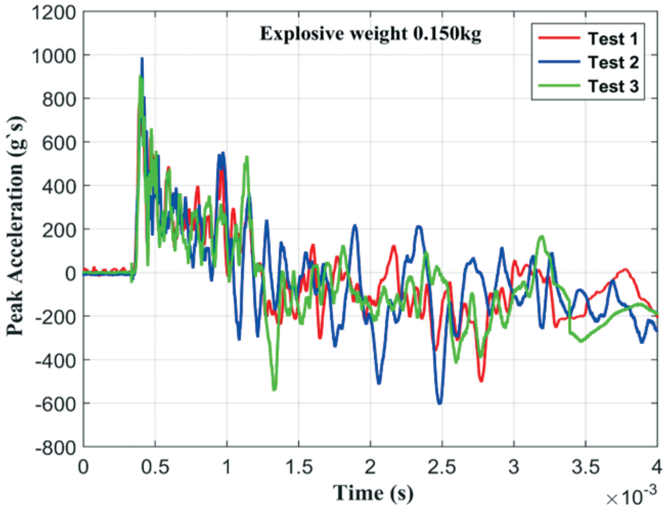



**Figure 3. Acceleration histories on composite plate with 0.150 kg explosive.**

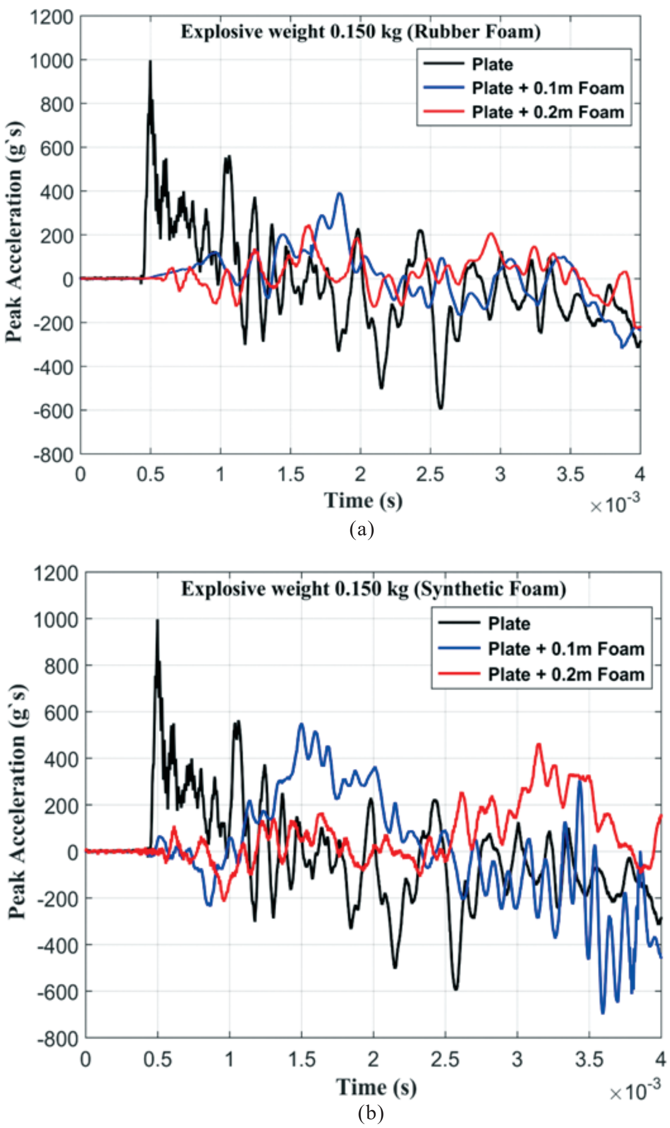



**Figure 4. (a) Acceleration histories through rubber foam for 0.150 kg explosive and (b) Acceleration histories through synthetic foam for 0.150 kg explosive.**

foam, respectively. Similar trend in mitigation of peak acceleration values was observed in other tests with higher explosive weights also. It was observed that in all the cases, the addition of foam layer reduces the peak acceleration which further decreases with increase in foam thickness. This may be due to the mitigation of blast wave strength in foam which further decreases with increase in foam thickness as pointed by Kitagawa[19], *et al*.

Figure 5 shows the effect of blast wave strength (explosive weight) on peak accelerations with rubber and synthetic foam for different test configurations. The strength of blast wave originated from the explosion increases with increase in the amount of explosive as the energy release during detonation is proportional to explosive weight. Therefore, plate acceleration values increase with increase in explosive weight, however, the increase in peak acceleration values was slow with add-on foam layers. It is clear from the figure that the acceleration mitigation increased with increase in foam thickness and the rubber foam is more effective in mitigating the acceleration as compared to the low density synthetic foam. The observed higher acceleration mitigation in natural rubber foam is due to the high energy absorption in foams with higher density as suggested for pressure mitigation by Makris[23], *et. al*. Figure 6 shows the variation of acceleration and pressure signal with time. It is clear from the figure that acceleration and loading pressure follow the same trend. The appearance of peak acceleration and peak pressure at almost same time indicates that acceleration depends upon the blast wave pressure peak than impulse.

### 3.3 Spectral Analyses of Acceleration Data

A MATLAB® program was used for calculating the discrete frequencies existing in the acceleration data for all test configurations. This program calculates the dominant frequencies up to half the sampling rate of the acquired acceleration signal. The frequency components present in rubber foam test with 0.150 kg explosive are as shown in Figs. 7(a) and 7(b) to emphasize the mitigation taking place in

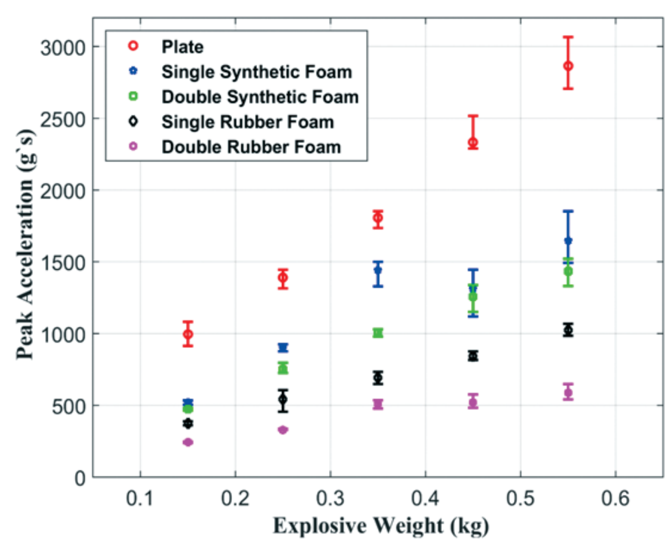



**Figure 5. Effect of blast strength on acceleration with rubber and synthetic foam.**

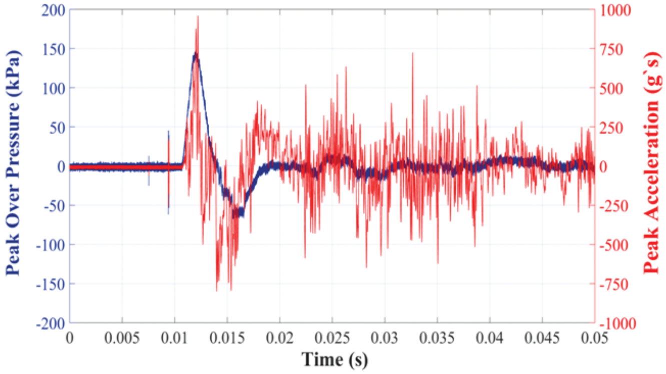



**Figure 6. Variation of loading pressure and acceleration with time.**

both amplitudes and frequencies. Here, the amplitude shows the square of the magnitude of each frequency existing in the time domain signal. Figure 7(a) shows the mitigation of low-frequency components upto 200 Hz and Fig. 7(b) shows the mitigation of high-frequency components upto 85 kHz. The large amplitude fluctuations existing in the baseline acceleration signal of plate was transfer to small amplitude fluctuations with addition of single layer of foam. These are further reduced when another foam layer added over the composite plate. The amplitude of high-frequency fluctuations was also decreased with the addition of single layer of foam. However, it almost vanished when two layers of foam samples were placed over the composite plate. Similar trend of FFT plots was observed with higher explosive weights. The amplitude of lower frequency components increases with increase in explosive amount from 0.350 kg onwards with addition of single foam layer. This implies better mitigation at higher pressure loading i.e more energy absorption due to start of compression region of foam. These results also confirm that the sharp rising baseline acceleration has been modified into slow rising compression wave of lower frequency by the application of foam.

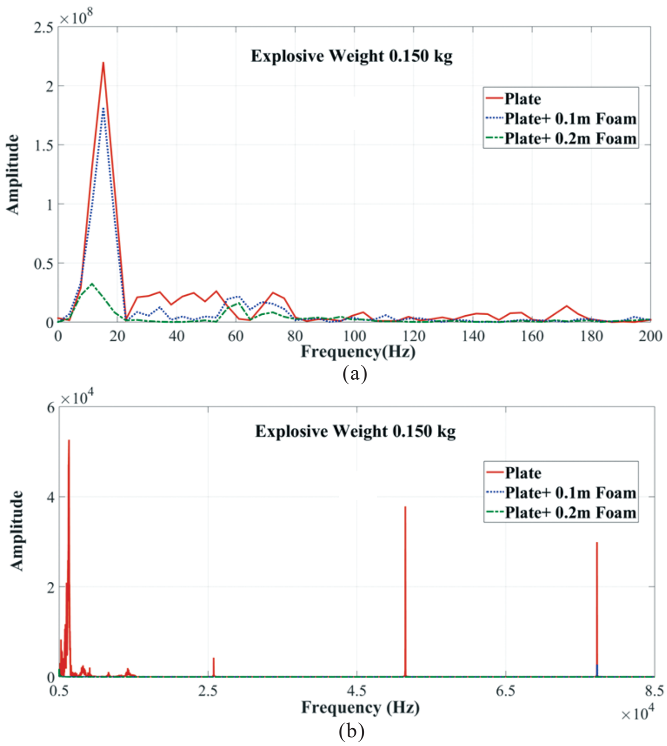



**Figure 7. Power spectrum of acceleration data for 0.150 kg explosive test (a) Frequency up to 200 Hz and (b) Frequency up to 85 kHz for three test configurations with rubber foam.**

## 4. CONCLUSIONS

Blast induced acceleration mitigation in a composite plate due to addition of open cell natural rubber foam and synthetic foam of different thickness has been studied experimentally for different blast wave strengths. Maximum acceleration mitigation of about 50 per cent was observed in double layer of synthetic foam and that for rubber foam was up to 80 per cent. The FFT analysis of acceleration signal obtained for different test configurations with foam also showed the conversion of high frequency components in base plate acceleration into low frequency and low amplitude components. The results show that rubber foam is better than synthetic foam for acceleration mitigation and the thickness of foam plays a major role on mitigation besides the physical characteristics of foams. Therefore, the foam of appropriate thickness may be considered as a potential candidate for mitigation of blast induced acceleration applications.

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In the current study, he contributed in planning and conduct of these experimental tests, processed the raw data from tests for evaluation and analysis, and reviewed the literature and prepared the draft manuscript.

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In the current study, he contributed by writing various MATLAB® programs for experimental data processing, analysis and plotting. He also contributed in data interpretation and elaborated the manuscript to the final form.

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In the current study, he contributed in this study in planning of experiments, overall guidance during the work and reviewing the manuscript.