Abstract: In this paper we present the effect of acoustic emission (AE) and shock waves impact on a rigid polyurethane (PU) foam having density of 320 kg/m$^3$. Diaphragm less shock tube is used to produce shock waves of about 1.3 Mach number. When this shock wave enters the open atmosphere produces large AE due to sonic boom at the open end of the shock tube and continues to travel in the atmosphere. PU foam materials were placed at different distance from the open end of the shock tube to study the attenuation of AE. The PCB piezoelectric acoustic pressure sensor is used to measure the AE with and without PU foam. The results shows the attenuation of the AE measured at different position varied between 72 to 65% in the air medium.

Shock wave impact on PU foam was studied using material shock tube. PU foam was mounted inside the end flange of the driven section of the shock tube and exposed to different shock strength (Mach number 2 to 3.1). The PCB piezoelectric pressure transducers are used to record both reflected and back-wall transmitted shock pressure at the end of the shock tube. Result shows that the pressure amplification at the back-wall of the PU foam is about 2 to 2.6 times the reflected shock pressure at the front-wall of PU foam. The details of the experimental setup and the results obtained will be presented in this paper.

Keywords: shock tube, acoustic emission, attenuation, shock pressure amplification, polyurethane foam

1. Introduction

Dynamic loading of shock and blast waves on materials have attracted a lot of scientific attention in recent years. Presently, many devices like light gas gun, ballistic shock tube, explosive launchers and conventional shock tubes are used to study hypervelocity impact, dynamic compressibility, strength characteristics and spallation phenomena on the materials in the laboratory. Such devices are capable of producing strong shock waves and acoustic emission (AE). Interaction of short duration strong shocks with material leading to the formation of a diffuse distribution of micro cracks or voids in the interior of the material body. Reduction of the energy content in AE during shock and blast waves plays an important role in the protection of civilian and military structures. To overcome these problems light damping materials are used as barriers.

Many NDT methods have been used to characterize on going processes such as the generation, propagation of shock waves and their attenuation into elastic waves. NDT method is a valuable tool to determine the attenuation characteristic of target material by measuring AE before, during and after hypervelocity impact [1]. The porous foam materials with different properties and geometries were used for the shock attenuation studies [2-3]. During shock impact, the internal energy imparted to the porous material is much greater than that imparted to the solid of the same material. Usage of lightly compacted material such as sand and aqueous porous foam results in the attenuation of the peak over pressure in blast waves which has been reported in the literature [4]. Studies were also performed to attenuate AE produced during detonation using porous foams and wire mesh as damping materials [5]. Attenuation of weak shock waves propagation in atmosphere was investigated using urethane and fiberglass material [6]. Polyurethane foam materials are widely used as shock absorbent material because of its high porosity. Experiment to find the influence of attenuation of AE in transparent thin films [7], crossply and quasi-isotropic panels made up of carbon fibre
reinforced polymer are reported in the literature [8]. Investigation of seven different types of foams exposed to shock waves which was observed that the transmitted pressure is amplified at the back-wall due to the transfer of gas momentum to the foam mass [9]. Shock impact on a surface covered with a layer of flexible foam [10] and porous fabric materials [11] have shown interesting phenomenon of pressure amplification.

In this paper, diaphragm less shock tube (DST) is used to study the attenuation of AE in rigid PU foam material at the exit of the shock tube. Attenuation of AE is performed in open atmosphere at 1.3 Mach. Material shock tube (MST1) is used to study amplification of transmitted pressure at the back-wall of the PU foam at different shock strength. Experiments were conducted at four different shock Mach number by mounting PU foam at the end of the shock tube.

2. Material and Experimental Details

Rigid PU foam (FR-4520) of density 320 kg/m$^3$ was procured from General Plastics Mfg. Company. Effect of shock induced acoustic emission and shock wave impact experiments were performed on this PU foam. Diaphragm less shock tube is used to study shock induced acoustic emission and material shock tube (MST1) is used to study the effect of shock wave impact on PU foam.

2.1. Acoustic emission experiments using diaphragm less shock tube

DST consisting of a driver section (one meter) and a driven section (4 m length) with 80 mm inner diameter is used to produce shock waves. The driver section filled with compressed air of about 8 bar pressure and an electrically operated solenoid valve is opened to produce single pulse shock wave of about 1.3 Mach number. When this shock wave enters the open atmosphere produces large AE due to sonic boom and further travels in the atmosphere. In the present experiments, PU foam material was used to study the attenuation of AE at different distance by placing them at 30° angle from the open end of the shock tube as shown in Fig. 1(a). The experiments were performed on FR-4520 rigid polyurethane foam of 38 mm thick to investigate the attenuation of AE. The PCB piezoelectric acoustic pressure sensors (model: 103B02) are mounted to measure the AE with and without the PU foam at four different locations 1.15 m, 1.73 m, 2.31 m and 2.88 m as shown in Fig. 1(a). The typical AE signals acquired with and without PU foam using the Tektronix digital storage oscilloscope are shown in Fig. 1(b).

Experiments were performed by keeping two sensors at an angle of 30° from the exit of the open end of the DST. Four locations were marked at 1.15 m, 1.73 m, 2.31 m and 2.88 m from the open end of the shock tube and provisions are made to mount the acoustic pressure sensor at both sides of the shock tube at 30° angle. The emitted acoustic signals travel in the open atmosphere and are detected by an acoustic transducer mounted without PU foam at a distance of 1.15 m and another transducer mounted at back side of the PU foam to measure the attenuation of AE signal at the same distance from the source. Similarly experiments were repeated by changing the position of acoustic transducers to 1.73 m, 2.31 m and 2.88 m. During each experiment, acoustic emission data acquired from both the transducers were stored in the Tektronix digital oscilloscope.
2.2. Shock wave impact experiments using material shock tube

MST1 consists of two sections: the driver section and the driven section. The length of the driver and driven sections are 2 m and 5 m long with 80 mm inner and 115 mm outer diameter. The driver section is separated from the driven section (shock tube) by an aluminium diaphragm. The thickness of the Al diaphragm dictates its bursting pressure which will influence the shock Mach number; the higher the bursting pressure the stronger the shock. The shock tube employed here is used to test the PU foam material at different shock strength. The schematic diagram of MST1 along with the typical pressure signal acquire are shown in Fig. 2. The arrangements were made to mount the PU foam material at the end of the shock tube. The PU foam experiences the reflected shock pressure ($P_5$), estimated temperature ($T_5$) at the front-wall and the transmitted shock pressure ($P_t$) at the back-wall as shown in Fig. 2(a).

The experimental procedure starts by placing the aluminum diaphragm in between the driver and the driven section and the PU foam mounted at the end flange of the shock tube. The driven section (shock tube) is filled with air at 1.0 bar pressure and the driver section is filled with high-pressure helium gas until the diaphragm bursts and generates the shock wave. Different thickness Al diaphragm is used to produce different Mach number ranging from 2 to 3.1. Shock impact on foam material occurs at different velocities ranging from 600 m/s to 1100 m/s at different reflected shock pressure. Pressure sensor $P_5$ and $P_t$ at the end of the shock tube is used to record the front-wall reflected shock pressure and back-wall transmitted shock pressures respectively are shown in Fig. 2(b). The PU foam experiences both $P_5$ and $P_t$ pressure during shock tube experiments and are measured using dynamic pressure sensors (Model 113B22, PCB - Piezotronics Ltd., USA). A similar procedure is followed to perform experiment at different Mach number. The shock speed ($V_s$), $P_5$ and $P_t$ data were acquired and stored in a Tektronix digital storage oscilloscope (TDS2014B). Time taken ($\Delta t$) for the shock to travel the distance between the two pressure sensors ($\Delta L = 0.5$ m) is calculated from the acquired data. These experimental data are used to calculate the shock velocity ($V_s = \Delta L/\Delta t$) and the shock Mach number ($M_s = V_s/a_1$), where $a_1$ is the speed of sound in the test.

**Figure 1(a)** Schematic diagram of a diaphragm less shock tube showing the position of the acoustic pressure transducer from the open end of the shock tube, **1(b)** Typical AE signals recorded with and without PU foam using Tektronix digital storage oscilloscope.
gas present in the driven section of the shock tube. The reflected shock temperature (T₅) for a given shock Mach number is estimated using the 1D normal shock equations [12].

\[
\frac{T_5}{T_1} = \frac{2(\gamma - 1)M_s^2 + (3 - \gamma)(3\gamma - 1)M_s^2 - 2(\gamma - 1)}{(\gamma + 1)^2 M_s^2}
\]  

[1]

The estimated temperature (T₅) of the test gas (air) behind the reflected shock is a function of shock Mach number, specific heat ratio of gas γ and the ambient temperature T₁ of the test gas. Table 1 shows the experimental pressure data (P₅ and P₇) and estimated reflected shock temperature (T₅).

### Table 1: Experimental and estimated values of shock conditions.

<table>
<thead>
<tr>
<th>Mach Number</th>
<th>Estimated Temperature T₅ (K)</th>
<th>Reflected Shock Pressure P₅ (bar)</th>
<th>Transmitted First Peak Pressure P₇ (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>690</td>
<td>10.48</td>
<td>50</td>
</tr>
<tr>
<td>2.6</td>
<td>1175</td>
<td>32</td>
<td>89</td>
</tr>
<tr>
<td>2.9</td>
<td>1400</td>
<td>45.51</td>
<td>109</td>
</tr>
<tr>
<td>3.1</td>
<td>1580</td>
<td>58.62</td>
<td>130</td>
</tr>
</tbody>
</table>

3. Results and Discussions

3.1. Acoustic emission experiments

Measurements of acoustic emission (AE) are considered as unique techniques comparing with that of other non-destructive techniques. Many of the NDT are static measurements but the AE have major advantage to record the dynamic data. A large or considerable amount of acoustic energy released during micro-cracking, friction, shock waves induced acoustic emission, etc. can be recorded by acoustic sensors mounted on the surface of the material.
Spontaneous release of localized strain energy from the stressed material during shock impact is recorded as AE within few meters to millimeters length. We recorded the first arrival of the elastic waves from the exit of the DST using acoustic sensors located along 30° angle at a distance of 1.15m, 1.73 m, 2.31m and 2.88 m as shown in Fig. 1. The recorded AE data with and without PU foam are analyzed to understand the percentage of acoustic attenuation.

The arrival of the original acoustic emission signals detected without PU foam at a distance of 1.15m and 2.88 m are shown in the Fig. 3(a). The acoustic pressure signal recorded show the first peak value of 2.53 psi and 0.88 psi for the corresponding distances of 1.15 m and 2.88 m respectively and subsequent decays of the AE signal is also recorded until 1.5 ms time scale. In presence of PU foam, attenuated AE signal from the same location shows a broad peak where the intensity of AE signal decreased to 0.73 psi at 1.15m to 0.26 psi at 2.88m as shown in Fig. 3(a). In all the experiments oscillation of AE signal is characterized by compressive and tensile stress experienced by the material due to the impact of acoustic waves. Figure 3(b) shows the non-linear characteristic of the first arrival of the peak AE signal acquired at four different locations without PU foam. We can clearly observe that drastic attenuation of AE detected at the back-wall of the 38 mm thick, 320 kg/m$^3$ density PU foam (FR-4520) as shown in Fig. 3(b). The percentage of attenuation of AE signal from minimum distance to maximum distance varies from 72% to 65% respectively.

**Figure 3(a)** Data acquired from the open end of the DST; AE detected by PCB 103B02 acoustic sensor at a distance of 1.15 m and 2.88 m with and without PU foam material. **3(b)** Intensity plot of the first arrival peak of AE signal with and without PU foam at different location and also shows the intensity of attenuation.

### 3.2. Shock wave impact experiments

Shock tube experiments were performed with and without PU foam at the end flange of the shock tube at different shock Mach numbers. The recorded pressure signals at the end flange of the shock tube without PU foam are shown in Fig. 4(a). The corresponding peak pressure increases as a function of Mach number and as the time progresses its amplitude decays as shown in Fig. 4(a). The experiments were performed by rigidly fixing the PU foam to the end flange with a pressure sensor. At this condition (i.e. the foam is placed against a rigid solid surface) a significant pressure amplification is produced at the back-wall of the PU foam.

However, if gap exists between the PU foam and the sensor the PU foam attenuates the reflected shock pressure. The present experiments were done only to study the shock pressure
amplification. Figure 4(b) shows the transmitted pressure-profiles recorded at the back-wall of PU foam at different Mach numbers. First peak pressure at the back-wall of the PU foam shows amplification of about 2-2.6 times the front-wall pressure. The profiles of the pressure signals shows damped oscillations and decays within 2 ms as shown in the Fig. 4(b). The plot of shock Mach number versus transmitted shock pressure with and without PU foam is shown in Fig. 5(a). A non-linear variation of pressure signals are found as a function of shock Mach number. Figure 5(b) shows the plot of \( P_5/\)front-wall pressure of PU foam with respect to transmitted peak pressure which represents the pressure amplification due to the shock-PU foam interaction.

Figure 4(a) Shock tube end pressure profiles showing pressure signal oscillation without PU foam at different Mach number. First peak pressure signal value is indicated using the arrow mark, 4(b) Transmitted pressure-profiles at the back-wall of PU foam showing damped pressure oscillation during shock-PU foam interaction. First peak pressure signal shows amplification of pressure signal at different Mach number as indicated using the arrow mark.
Figure 5(a) Plot of shock Mach number versus transmitted peak pressure signals with and without PU foam material, 5(b) Plot of side-wall pressure data (reflected shock pressure) versus transmitted peak pressure signal.

4. Conclusions

DST is used to produce AE signal which are measured at different location like 1.15m, 1.73m, 2.31m and 2.88m from the open end of the shock tube. In presence of rigid PU foam the intensity of the AE signal drastically reduced due to the attenuation property of PU foam. To investigate the amplification property of the PU foam shock tube experiments were performed using MST1. Shock waves of different Mach number 2, 2.6, 2.9 and 3.1 were produced and made to interact with the PU foam. Study shows that the transmitted pressure at the back-wall of the PU foam amplifies comparing with that of front-wall pressure. It is concluded that the pressure amplification varies with Mach number, reflected shock pressure and properties of the PU foam. In future we are planning to perform both AE and transmitted pressure amplification experiments with foam materials of various densities.

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6. References