New Metrologies to Assess the Dynamic Response of Soft Protective Materials used in Helmets and Pads

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Abstract. Blunt trauma and brain injury can occur during impacts at energies and velocities below those observed in ballistic and blast events. During low to medium velocity impacts, the shell helps to prevent bone fractures and the padding helps limit the maximum linear or rotational acceleration of the head. Current test methods focus on the helmet and padding as a system (pad + shell) to quantify protective levels the equipment provides for the user. System level tests involve complicated loading paths, that make it difficult to determine the performance of the padding material within the helmet system to reduce the effects of impact. This lack of information complicates the process for improving helmet materials. National Institute of Standards and Technology (NIST) has recently developed a set of metrologies to quantify the impact mitigating properties of soft, non-linear materials under a broad range of impact energies and loading scenarios. These measurements can provide a more complete picture of *material* performance in order to guide incorporation of new materials into the helmet or padding system. This presentation will describe these metrologies and demonstrate their usefulness on several common energy absorbing materials.

1. INTRODUCTION

Soft non-linear materials are used to mitigate energy transfer between objects during high rate events. These impact mitigating materials (IMM) are used in a wide range of applications such as isolating rotating equipment, protecting buildings during earthquakes, and protecting humans from blunt impact. While IMMs have been successful at protecting electronic equipment, automobiles, and buildings for decades, the threats for these applications are specific in maximum energy, velocity, and impact angle. Protecting the brain from a concussion or blunt force trauma is a less well-defined challenge. Impact energies and velocities cover a broad range depending on the sport, player position, and player skill. The angle, energy, and frequency of impact depend on whether the head is impacting another body part, a stationary object, or the ground. In military environments, these impacts are often secondary to a larger blast, entry/exit from vehicles, or movement in confined space. There is a rise in mild traumatic brain injury (mTBI) rates [1-2] in sports such as football, hockey, and among military personnel. This suggests that new materials and designs are required to protect humans from blunt impact and that new metrologies are required to understand these effects.

Medical research has improved our understanding of the linear and rotational limits to prevent brain injury [2,3]. These limits may be experienced in military and sports activities. Recently, the sports sector has led the way in developing improved test methods to address concussion risk. Newer test methods, such as the Virginia Tech STAR rating system [4], have helped manufacturers produce safer helmets [5] for football by linking linear and rotational accelerations to an injury risk criteria. The National Operating Committee on Standards for Athletic Equipment (NOCSAE) [6] has developed a linear impactor test that incorporates more realistic head response during impacts. The National Football League (NFL) has also responded to rising injury rates by developing a roadmap for increasing the protection provided by professional player helmets [7]. These methods evaluate the helmet system and its interaction with the head during an impact at different energy levels and specified impact angles. Standard test methods for military applications often lag behind those of the commercial sector, opting for simpler methodologies (e.g., rigid neck, fewer sensors, etc.).

Despite the improvements in equipment, players continue to suffer from brain injuries and concussions. A breakthrough in materials is needed [8], but integrating material innovations is difficult without better measurements. These materials are subjected to high strains ($\varepsilon > 30$ %), high strain rates ($\dot{\varepsilon} > 50$ s^{-1}), and complex multi-axial (compression-shear) loading. Recently, different energy absorbing phenomena have been identified (e.g. jamming fluids, phase transitions, etc.) and architectures (e.g., metamaterials, auxetic behavior). These mechanisms have promise to absorb energy or redirect force during impact, but there are few metrologies to measure the dynamic response of soft, structured, non-linear materials in the strain, temperatures, and strain rate range identified for these impacts. As such, less experimental information is available to validate new constitutive models for dynamic responses of these new materials. NIST initiated a program to develop metrologies tailored for dynamic response measurements of IMM materials and composites at impact conditions relevant for contact sports. In this presentation, we characterize the viscoelastic properties of different elastomeric foams and their microstructures to understand the ability of this instrumentation to quantify structure-property behavior.

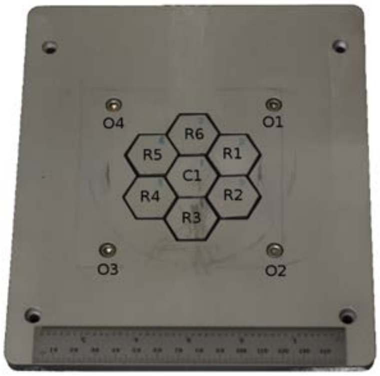
2. EXPERIMENTAL

Two different test geometries were developed to quantify the dynamic response of IMMs. The first impact geometry was a normal compression impact. A 3.3 kg drop mass with an aluminum hemispherical impactor (diameter = 70 mm, radius = 127 mm) was used to impact the IMMs. The impact energy is changed by changing the height of the drop mass up to a maximum height of 2.5 m, corresponding to an impact energy of 75 J that results in an impact velocity $\approx$ 7 m/s. The drop mass is equipped with an on-board data acquisition system (DAQ) with 8 gigabytes of memory to store readings from the mounted sensors. The DAQ system can record data up to 20 kHz. Three different sensors are mounted on the drop mass: a triaxial accelerometer ($a_{max} = 2000\,g$) near the DAQ, a triaxial accelerometer ($a_{max} = 2000\,g$) behind the hemispherical impactor, and a load cell (F_{max} = 20 kN) between the hemispherical impactor and drop mass body. The hemispherical tip of the impactor reduces stress at the edge and matches the curvature used in the NOCSAE linear impact test. High speed video (10 kHz) is used to measure the velocity of the drop mass before and after impact with the IMM. Figure 1 shows the drop mass, reaction force table, and the height-energy table.

a)

b)

Drop Height (m)	Energy (J)
0.25	7.5
0.5	15
1	30
1.5	45
2	60
2.5	75



c)

Figure 1. Instrumentation developed to measure the dynamic response of soft materials. a) Instrumented drop mass (3 kg mass) with onboard force, acceleration, and data acquisition system. b) The drop system can investigate a wide range of impact velocities and energies. c) the segmented load plate where O[i] = outer location, R[i] = ring location, and C1 = center location.

Foam materials exhibit a non-linear stress-strain response. At very low strains, the response is linear, but this initial linear behavior quickly transitions into a “plateau” region characterized by a smaller change in stress with increasing strain. The plateau region is critical in that it allows foam materials to undergo large strains while transmitting little stress. In this region, elastic bending and buckling of the walls in the foam absorb energy. In the case of a closed cell foam, the gas trapped within the cells is compressed and can store energy that may be returned to the impactor. Open cell foams may expel air from the interior that potentially increases the damping properties and limits elastic return of energy to the impactor. At higher strains, foam materials exhibit a densification region where the transmitted stress increases exponentially with strain. In this region, the cell walls have collapsed and only the wall material continues to carry stress. For a linear impact, increasing the density of the foam will shift the stress-strain curve toward higher stress and the densification strain to lower strain values. We utilize the NIST-developed impact equipment and method to characterize the dynamic response of these five different foam examples. The foams tested here are described in Table 1.

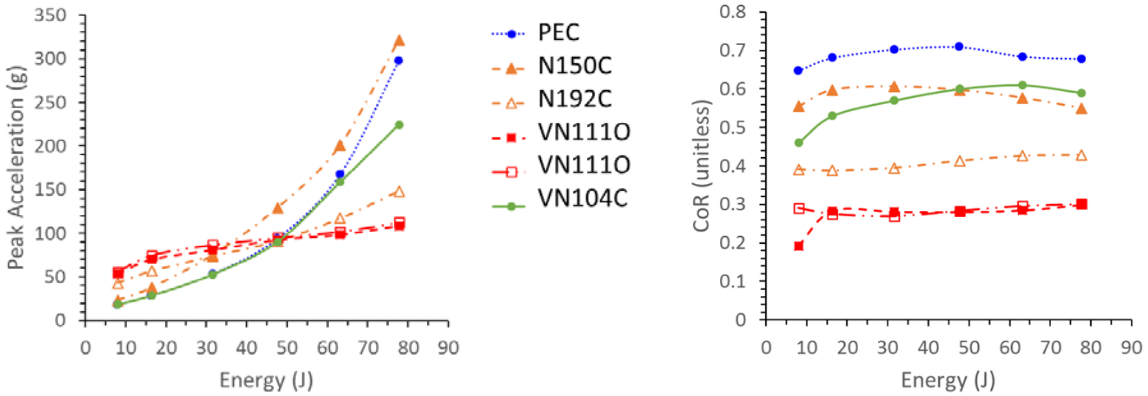
Table 1: Characteristics of foams. The dimensions of the foam samples were 75 mm diameter x 100 mm tall cylinders. In the case where the foam did not meet this specification, multiple layers were stacked together and bonded with a single piece of double-sided tape. Each point represents the mean of at least three mass and volume measurements. The standard deviation of the mean is approximately 10 % of the mean represented by each point.

Sample Name	Polymer Type	Foam Type	Density (kg/m^3)
N150C	Neoprene/EPDM/SBR	Closed cell	150
N192C	Neoprene/EPDM/SBR	Closed cell	192
PEC	Crosslinked Polyethylene	Closed cell	33
VN1110	Polyvinyl-nitrile	Open cell	111
VN104C	Polyvinyl-nitrile	Closed cell	108

The second impact geometry is a compression-shear impact fixture (not-shown). This fixture allows one to pre-compress the sample prior to applying a shear load. This provides information on the ability of the material to limit shear load transfer as would be expected during a side or off-angle impact. A shear plate is impacted to generate the shear force and this plate is s equipped with a triaxial accelerometer (a_{max} = 2000 g) and load cell (F_{max} = 20 kN). High speed video is used to measure the velocities of the drop mass and motion of the impact plate. The specific details and results from this fixture will not be addressed here, but will be elaborated in the presentation. Step tests were conducted at drop heights of 0.5 m, 0.75 m, and 1.0 m with pre-compressions of 0.5 kN and 1.0 kN.

3. RESULTS AND DISCUSSION

In helmet or padding applications, the material is expected to absorb and dissipate impact energy across a broad range of strains and strain rates. The material is expected to limit the momentum transfer between impacting bodies. There are several measurements that NIST has selected to quantify material performance. For the impactor, these include maximum force, maximum acceleration, impact duration, and coefficient of restitution (CoR). The ability of the material to limit force transmission is quantified by the load plate via the following quantities: total maximum force on all segments (outer, ring, or center), maximum pressure on each segment, pressure ratio (max. pressure/min. pressure). Figure 2 shows measurements of peak impactor acceleration (Figure 2a) and CoR (Figure 2b) from a series of impacts at heights up to 2.5 m. The peak transmitted force has similar trends to the peak acceleration shown in the graph. While the N150C, VN104C, and PEC foams perform better (lower peak acceleration) than the VN1110 open cell at low energy, there is a crossover at 30 J to 40 J. At this point, N150C, VN104C, and PEC foams begin to densify, while the VN1110 and N150C foams do not exhibit a clear densification region under impact. At the high energies, these two foams reduce the maximum acceleration from impacts > 50 J by approximately 50 %. This a function of the microstructure of the foam and the energy absorption of the polymer. The CoR (Fig. 2b) is one area where the VN1110 foam outperforms all the other materials. The CoR is approximately 0.3, while the everything else is above 0.4. This highlights the damping capabilities of the open cell VN1110 foam. This presentation will focus on the use of this methodology to provide a comprehensive performance of impact mitigating materials and, their performance will be discussed in terms of the polymer damping properties measured using dynamic mechanical analysis and structural characterization of the foam pores.



a) **b)**

Figure 2. a) Peak acceleration as a function of impact energy; **b)** Coefficient of Restitution (CoR) as a function of impact energy. Each point represents the mean of at least three tests. The standard deviation of the mean is approximately 10 % of the mean represented by each point.

4. CONCLUSIONS

NIST has developed a suite of characterization tools to measure the impact performance or dynamic response of soft materials under compressive or multi-axial loading. Impacts can be conducted across an energy range from 7.5 J to 75 J. Forces and accelerations on the impactor and forces transmitted through the impact mitigating material can be measured at frequencies up to 20 kHz. We demonstrate the ability of this system on polymeric foams with different densities and polymer backbone materials. While these metrologies were developed with contact sports in mind, they have relevance to the development of future impact mitigating materials for military and civilian law enforcement applications.

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