Title: *Using finite Element Methods to Predict the Response of Polymeric Foams to both Shock-Tube and Free-Field Loadings for* 25th International Symposium on Ballistics

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Current personnel protection against blast often consists of multi-layered material systems utilizing a combination of rigid materials, such as ceramic plates, and soft materials such as compressible foams. A good understanding of the response of polymeric foams to blast loadings is essential to ensure better guidance in the development of protection equipment. There are multiple approaches currently in use for characterizing the response of foam to blast loading and these include shock-tube and free-field trials. The loading generated from a shock-tube is quite different from the one in free-field trials. However, shock-tube experiments are more practical and efficient than free-field trials. This paper presents numerical and experimental results, which show the responses of polymeric foams to these two different loadings. Using finite element method, the two types of loadings were modeled and reasonable agreement between the experimental and numerical results was obtained.

INTRODUCTION

UN forces and military personnel are increasingly being deployed in scenarios where they are at risk from a variety of threats coming from improvised and traditional explosive devices. A number of studies are underway in Canada looking at injuries induced by blast in order to design lightweight personnel protective equipment. Due to their low densities and energy absorption capacity, foams show potential in such applications. Different experimental methods are used to characterize foams in the high strain-rate regime and among them are the shock-tube tests and the free-field trials. The loading generated from shock-tube tests have durations much longer than the ones in the free-field trials which leads to different behavior in the foams.

In general, foams are characterized by three different compression phases: the elastic region, the plateau and the densification region [1, 2]. Figure 1 shows the three regions during a compression test. At low strain, the foam deforms elastically. The plateau is characterized by a collapse region that has a relatively constant stress versus strain. At very high strain, foam cells collapse and contact each other, which lead to densification of the material. The mechanisms responsible for the amplification or attenuation of blast wave overpressure within the foam are still to be confirmed.

To model accurately the amplification or the attenuation of blast wave in foams, foams need to be characterize at high strain rate regime. Several numerical approaches exist for the simulation of interaction of blast loading with foams. They range from simple loading models based on the application of pressure-time history to relatively complex solutions using Arbitrary Lagrangian Eulerian (ALE) formulation [3]. While the simple models have the ability to quickly estimate the reaction of the foam, they often do not capture many of the material behaviors, which can be by using more complex approach. Using an explicit finite element code, an ALE method was used to conduct the simulation and the numerical results are compared to the experiments.

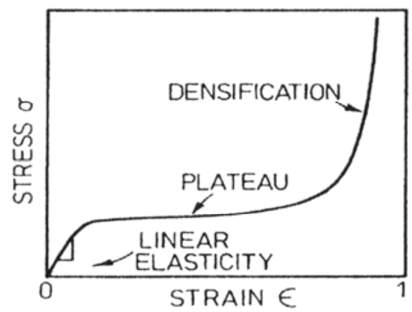

Figure 1: Schematic view of stress-strain foam behavior

TEST SETUP

Experiments using two different types of foams were conducted to examine the behavior these foams under two types of loadings: shock-tube and free-field. The aim was to characterise the three foam regimes under both types of loading.

Two foams of different thicknesses and densities were tested against loadings generated by a shock-tube test and free-field trial. In the free-field trial, a 170-g C4 charge detonated 1 meter above the foam in a blast chamber was used. Foam samples are placed on the trial platform over a pressure gauge that monitors the transmitted overpressure. The test setups and the experimental results are described in detail in reference [4]. The test matrices are listed in Tables I and II.

TABLE I. TEST CASES FOR THE SHOCK-TUBE LOADINGS

Material and density	Thickness	Positive phase duration	Reflected overpressure
PU 96, kg/m^3	12.5 mm	10 ms	1.8 MPa
HDPE 80, kg/m^3	40 mm	10 ms	1.8 MPa

TABLE II. TEST CASES FOR THE FREE-FILED TRIALS IN A CHAMBER

Material and density	Thickness	Positive phase duration	Reflected overpressure
PU 96, kg/m^3	12.5 mm	0.6 ms	1.6 MPa
HDPE 80, kg/m^3	20 mm	0.6 ms	1.6 MPa

NUMERICAL MODEL

In a classical Lagrangian formulation, the computational mesh defines the geometry of the problem. At each time step, variables of interest are computed on every node and element and the mesh is updated to account for material deformation. The rapid expansion of an explosive results in a shockwave that leads to a highly stressed state in the surrounding area. Therefore, significant deformation of the continuous medium is inevitable and blast analysis is more difficult to do using a Lagrangian formulation. An alternative to the classical formulation is a combination of both Lagrangian and Eulerian formulations. In the latter approach, the computational mesh is fixed and materials are flowing through it. There are two phases in each cycle of the Arbitrary-Lagrangian-Eulerian formulation. The Lagrangian approach is first used followed by an advection phase where flows are taken into account and mesh regularity is controlled by remapping nodes to their initial positions.

The current study has been done using an ALE formulation. The blast loading was modeled as a material flowing through a fixed finite element mesh. On the other hand, the foam was modeled using the Lagrangian approach. The two models were then coupled using a penalty-based method, with the interaction force between the fluid/solid interface determined by the nodes distance of separation and the contacting material properties [3].

The LS-DYNA finite element code [3] was used to simulate the behavior of the foams and to reproduce the experimental tests [4]. To simulate the foam response, *MAT_63, a crushable foam material model in LS-DYNA code, was used. This isotropic foam model crushes one-dimensionally with a Poisson's ratio that is close to zero. This model is used where cyclic behavior is unimportant. In the MAT_63 constitutive model, the stress-strain curve is given and the Young's modulus is assumed constant.

Several methods for creating blast overpressure applied to solids in LS-DYNA were investigated. Among them, there is the ambient elements method. This method was chosen due to its flexibility to generate the desired overpressure and pulse duration using specific temperature-time histories. By the ideal gas law, an increase of temperature produces a pressure increase. This local increase of pressure then moves toward the foam at supersonic speed. The shock waves created in the model are the same as the ones measured in the shock tube and blast chamber trials.

The numerical model shown in Figure 2 contains approximately, 46900 nodes and 37100 elements. The thickness of the target was comprised of four layers of elements for a total thickness of 1.4 cm. The thickness of the foam was then constrained by the thickness of the air confinement. The air mesh was 3 m by 0.4 m, while the foam has a width approximately equal to 0.13 m.

To minimize the computational time, a 2D finite element model was used. Finally, to allow a fine mesh in the test area containing the foam, the air mesh was biased through the centre region. The coarse areas of the mesh correspond to a mesh spacing of 40 mm while the fine mesh is spaced at 5 mm. These variations in the air elements allowed better fluid structure coupling while maintaining a reasonable computation time.

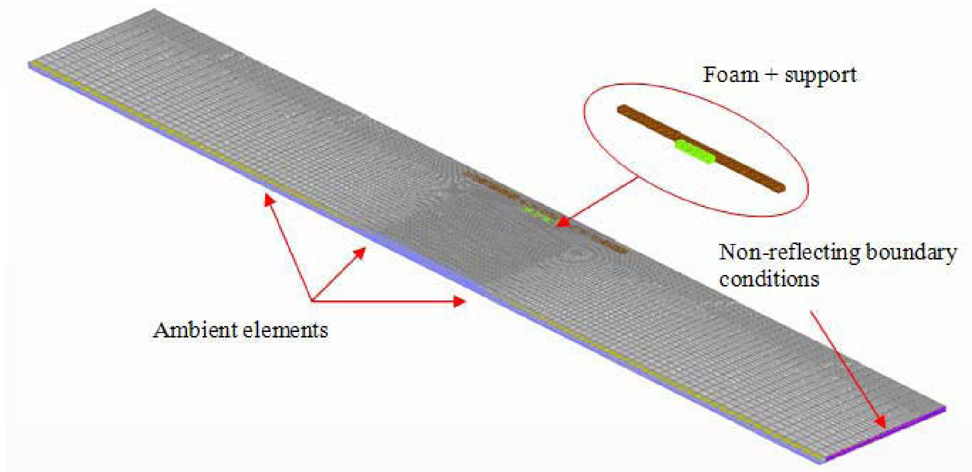

Figure 2: The FE model of the free field and shock tube tests

RESULTS AND ANALYSIS

Valuable data from numerical output can include stress and strain in the foam and the transmitted overpressure from the foam to the support. Upon impact with the foam, the blast generated a compressive wave that travels through the foam which results in an amplification or attenuation of the blast depending on the foam type and thickness. Figures 3 and 4 show, respectively, a comparison between the numerical and the experimental transmitted overpressure of the 12.5-mm thick PU 96 and 20-mm thick HDPE 80 foams. In the PU 96 case, the numerical simulation overestimates the transmitted overpressure while the opposite was observed for the HDPE 80. In general, reasonable agreement was achieved for both foams. In the case of the PU 96 foam, the experimental and numerical data show that the blast wave was capable of compressing the foam up to densification (80% to 90% air removed). This densification results in an amplification of the overpressure transmitted by the foam. 20 mm thick of HDPE 80 foam was sufficient to decrease the transmitted overpressure. The loading level of the foam resulted in the response being in the plateau of the stress/strain curve. This resulted in an attenuation of peak pressure.

Figures 5 and 6 show, respectively, the transmitted overpressure versus time of the 12.5-mm thick PU 96 and 40-mm thick HDPE 80 foams under shock wave loading. The energy from the shock wave was sufficient to compress 12.5-mm PU 96 up to densification leading in an amplification of shock. However, in the numerical simulation, the elastic phase was non-existent. Although the amplification phase was predicted numerically for the 40-mm thick HDPE foam, Figure 6 shows clearly that the numerical simulations did not correlate well with the experiment. The numerical plateau region was smaller than the experimental one. From the two loading regimes, the approach used to model the behavior of the foam was appropriate for the free-field loadings, which is characterized by shorter duration than the one from shock-tube loadings. To understand this difference, other simulations were performed and they have demonstrated that the inflow and outflow boundaries in the FEM influence the solution, most significantly for lower peak overpressures and longer durations. In the current study, these effects have the least impact on the results for blast wave regime. To use the current model for longer duration loading, the inflow and outflow boundaries must be positioned much farther from the foam location. This modification will lead to an increase in the calculation time.

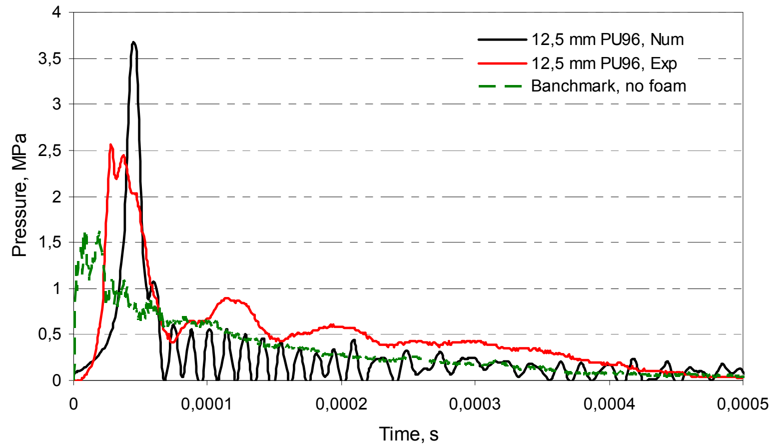

Figure 3: PU 96 response to free-field loadings

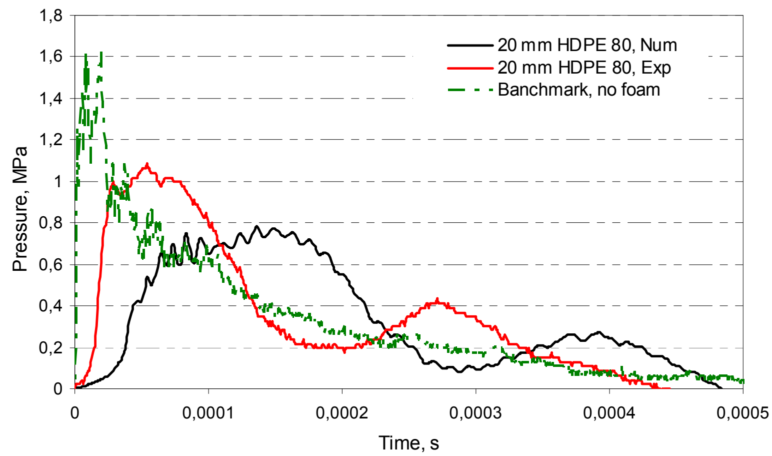

Figure 4: HDPE 80 response to free-field loadings

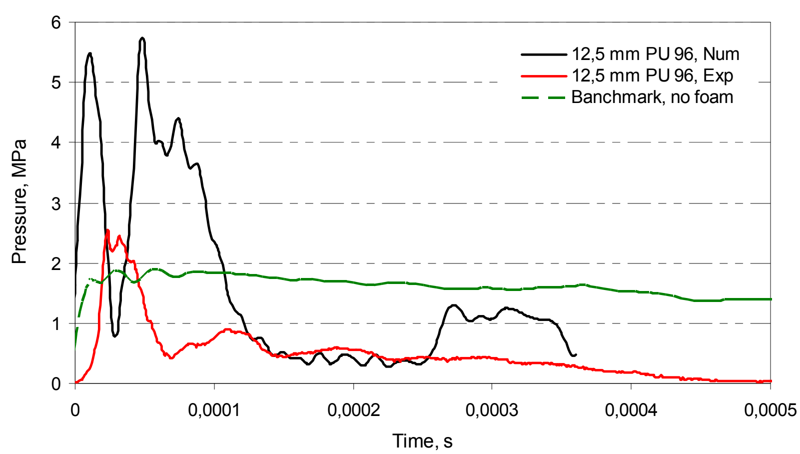

Figure 5: PU 96 response to shock-tube loadings

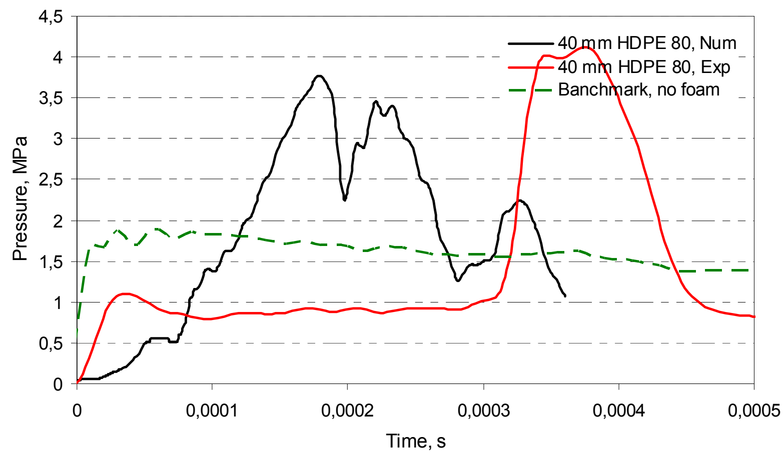

Figure 6: HDPE 80 response to shock-tube loadings

CONCLUSION

An LS-DYNA model of polymeric foams exposed to free-field and shock-tube loading was characterized for use in vulnerability analysis of current and future personnel protection equipment. Using ALE formulation, a penalty-based method was used to compute the interaction forces between the foam and the blast. The loading was applied to the foam using a temperature-time history specified at the inflow boundary.

The approach used to model blast was appropriate for short duration such as the one generated from free-field trials. The resulting numerical data, especially from the longer duration, must be treated carefully as it may contain non-physical behavior. Finally, in the case of free-field loadings, the two regimes of amplification and attenuation of transmitted overpressure can be identified using numerical simulations for a large variety of foams.

REFERENCES

1. Skews, B.W., A. Levy and D. Levi-Hevroni, 2000. *Handbook of Shockwaves*, edited by G. Ben-Dor, O. Igra, T. Elperin, Academic Press.
2. Lee, J.J., D.L. Frost and J.H.S. Lee, 1995. *Proceedings of the 19th International Symposium on Shock Waves*, Marseille, edited by R. Brun, L.Z. Dumetrescu, p.181
3. Hallquist, J., 2003. *LS-DYNA Users Manual – Version 970*. Livermore Software Technology Corporation, Livermore, CA.
4. Ouellet, S., D.L. Frost, A. Bouamoul, 2006. "*Using a shock tube to predict the response of polymeric foam to a blast loading*". 8th International conference on mechanical behavior of materials under dynamic loading, Dijon, France.