ARL-RP-0525 ● JUNE 2015

US Army Research Laboratory

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by Timothy Zhang and Sikhanda Satapathy

A reprint from Proceedings of ASME 2014 International Mechanical Engineering Congress and Exposition; 2014 Nov 14–20; Montreal, Canada. New York (NY): American Society of Mechanical Engineers; 2014. Paper No. IMECE2014-37143.

NOTICES

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REPORT DOCUMENTATION PAGE						*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE *(DD-MM-YYYY)* June 2015		**2. REPORT TYPE** Reprint				**3. DATES COVERED (From - To)** January–April 2014
4. TITLE AND SUBTITLE Effect of Helmet Pads on the Load Transfer to Head under Blast Loadings						**5a. CONTRACT NUMBER**
						5b. GRANT NUMBER
						5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Timothy Zhang and Sikhanda Satapathy						**5d. PROJECT NUMBER**
						5e. TASK NUMBER
						5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Research Laboratory ATTN: RDRL-WMP-B Aberdeen Proving Ground, MD 21005-5069						**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-RP-0525
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)						**10. SPONSOR/MONITOR'S ACRONYM(S)**
						11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.						
13. SUPPLEMENTARY NOTES A reprint from Proceedings of ASME 2014 International Mechanical Engineering Congress and Exposition; 2014 Nov 14–20; Montreal, Canada. New York (NY): American Society of Mechanical Engineers; 2014. Paper No. IMECE2014-37143.						
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15. SUBJECT TERMS helmet pads, blast, load transfer, underwash, finite element model						
16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**		**19a. NAME OF RESPONSIBLE PERSON** Timothy Zhang
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	UU	16		**19b. TELEPHONE NUMBER (Include area code)** 410-306-2984

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Proceedings of ASME 2014 International Mechanical Engineering Congress & Exposition
IMECE2014
Nov 14-20, 2014, Montreal, Canada

IMECE2014-37143

EFFECT OF HELMET PADS ON THE LOAD TRANSFER TO HEAD UNDER BLAST LOADINGS

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ABSTRACT

Recent wars have highlighted the need to better protect dismounted soldiers against emerging blast and ballistic threats. Current helmets are designed to meet ballistic performance criterion. Therefore, ballistic performance of helmets has received a lot of attention in the literature. However, blast load transfer/mitigation has not been well understood for the helmet/foam pads. The pads between the helmet and head can not only absorb energy, but also produce more comfort to the head. The gap between the helmet and head due to the pads helps prevent or delay the contact between helmet shell and the head. However, the gap between the helmet shell and the head can produce underwash effect, where the pressure can be magnified under blast loading. In this paper, we report a numerical study to investigate the effects of foam pads on the load transmitted to the head under blast loading. The ALE module in the commercial code, LS-DYNA was used to model the interactions between fluid (air) and the structure (helmet/head assembly). The ConWep function was used to apply blast loading to the air surrounding the helmet/head. Since we mainly focus on the load transfer to the head, four major components of the head were modeled: skin, bone, cerebrospinal fluid (CSF) and brain. The foam pads in fielded helmets are made of a soft and a hard layer. We used a single layer with the averaged property to model both of those layers for computational simplicity. Sliding contact was defined between the foam pads and the helmet. A parametric study was carried out to understand the effects of material parameters and thickness of the foam pads.

1. INTRODUCTION

The performance of helmets is better characterized against ballistic loads as compared to blast loads [1][2]. In both cases, the load transmitted to the brain through the helmet/pad system and its effect on structural and functional changes in the brain are of interest, and have been a subject of recent investigations [3]. Experimental investigations on human cadavers as well as animal models [4] have produced useful information on stress wave propagation and consequent injury to the brain tissues. However, since experiments can obtain measurements only at limited locations and for limited duration, numerical analysis provides a complementary avenue to assess structural response of the brain at greater spatial and temporal resolution. The numerical tools require careful evaluation of the constitutive response of constituent tissues, and appropriate experimental results for calibration and validation of model parameters. Constitutive model development for brain tissue and relevant experimental work, even though incomplete currently, has been the subject of intense research. In our previous study [10], a 3D model was developed to study the helmet/head response to blast loadings.

Interactions between air blast and helmet/head require use of Arbitrary Lagrangian Eulerian (ALE) methods to model the fluid/ structure interaction [5] so that underwash effect in the gap between the helmet and head can be captured. In our previous study [10], we developed a method to apply a ConWep blast function to the boundary of air zone, which surrounded the helmet/head system to simulate the blast loading. It was shown that a perfect spherical blast loading was generated, propagated in the air and then interacted with the head system. This was much more efficient compared to modeling the explosive and detonation.

In the current study, we extend our efforts from [10] in this area to fundamentally understand the load transfer mechanism. A 1-D plane-strain model is first used to investigate the effect of foam pads on the wave reflection and transmission at different material interfaces. Then a simplified 3D model is exercised to capture the stress transmission to the head. Identical material parameters are used in both models. Parametric study is carried out to study the effect of foam pad thickness and foam pads properties.

2. NUMERICAL MODEL

The main goal of this study is to investigate the effect of helmet/pad on the load transfer and subsequent pressure propagations inside the head. This is a very challenging problem due to the complex geometry, sensitivity of the material models, and limitations inherent in the numerical methods.

2.1. Geometry

The Enhanced Combat Helmet (ECH) geometry and head geometry were simplified in our study, as shown in Figure 1. The helmet, foam and head top part are spherical in shape, and the head bottom part is cylindrical (only half model is shown in the figure). Seven pads are attached to helmet shell, as shown in Figure 1 (a). When soldiers wear the helmet, the pads deform due to the helmet weight and strapping process, and conform to the head shape. In our model, the pad is assumed to make full contact with the head and the helmet. No initial deformation or stress is applied to the foam pads. Four major components of the head are modeled: skin, bone, cerebrospinal fluid (CSF) and brain (they are shown in green, yellow, brown and red, respectively, in Figure 1 (b)).

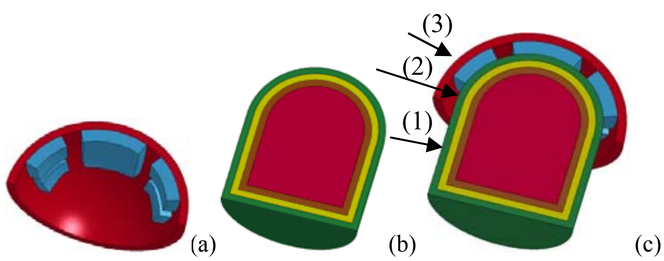


Figure 1 Simplified geometry of (a) the helmet and foam pads, and (b) head (skin, bone, CSF and brain), (c) assembly

One of the advantages of using such a simplified geometry is that it can be meshed into hexahedral elements for better accuracy and efficient computation. Inaccuracies leading to spurious deformation, such as checkerboard pattern, are likely to occur if tetrahedral meshes are used for the head.

The geometry shown in Figure 1 is simplified from a more complex geometry in our previous work [10], as shown in Figure **2**. In the original complex geometry, the ECH geometry was obtained from the PEO-Soldier's office, and the head geometry was obtained from MRI scan of a human head. The simplified geometry is kept as close as possible to the original geometry, as shown in Figure **3**. The simplified model is expected to provide reasonably accurate quantification of the foam pad effects on blast load transfer.

Figure 2 The original geometry before simplifications

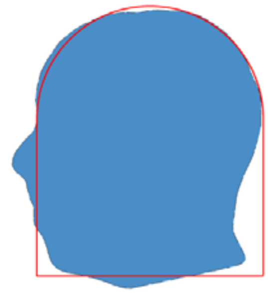


Figure 3 Head geometry comparisons before and after simplifications

2.2. Material Model

The foam pads comprise of two layers of foam: a hard and a soft layer, with a fabric covering both. A single layer is used to model both these layers using MAT_CRUSHABLE_FOAM in LS-DYNA. The stress-strain curve from [2] is used for the foam pads properties, as shown in Figure **4**.

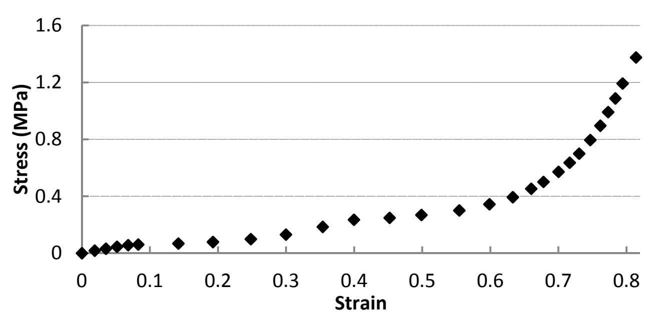


Figure 4 The stress strain curve for foam pads

The helmet shell is made of Ultra-High-Molecular-weight polyethylene fibers. It is made of 0/90º plies of unidirectional laminate sheets. *MAT_162 material model in LS-DYNA is used to model the helmet shell. To be more efficient, 0/90 cross-ply is modeled into one orthotropic layer rather than two individual layers (a 0º layer and a 90º layer). The detail of this model is given in [11].

The head component material models are listed here, more details can be found in [10]. The skin and skull are modeled as elastic materials, and the material properties are,

Skin: ρ = 1130 kg/m^3, E = 16.7MPa, ν = 0.499

Skull: ρ = 1710 kg/m^3, E = 5.37GPa, ν = 0.19

Brain is modeled as a viscoelastic material. The properties are,

ρ = 1040 kg/m^3, K = 2.19 GPa,

G_0= 41 kPa, G_∞= 7.8 kPa, β = 700 $/s$

where K, G_0, G_∞ and β are bulk modulus, short-term shear, long-term shear modulus and decay constant, respectively.

Gruneisen equation of state is used to model the volumetric response of CSF. The constants are,

ρ = 1000 kg/m^3, C =1484 m/s,

S_1=1.979, γ_0 = 0.11

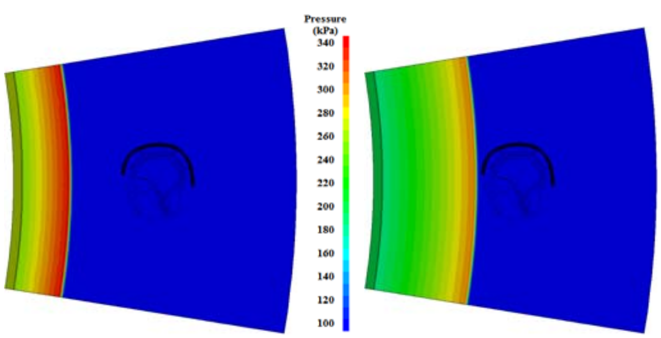
where C is the bulk sound speed, S_1 is the slope of particle-speed and shock-speed curve, γ_0 is the Gruneisen coefficient.

The cavitation pressure can vary from -0.1 MPa for distilled water saturated with air to -20 MPa for distilled water degassed at 0.02% saturation under acoustic wave [12]. For most experiments, the cavitation pressure for water is reported to be between -1 MPa and 0.1 MPa due to existence of cavitation nuclei [13]. The cavitation pressure level for CSF was found to have a significant effect on the transmitted stress in the CSF and brain. In this work, -0.1 MPa is chosen as the cavitation pressure for CSF.

Material failure is not modeled in the present study.

2.3. Air Blast Model

The blast loading to the head/ helmet can be simulated without modeling the explosive. Only a smaller air region surrounding the head is simulated with blast loading function (ConWep) applied to the air boundary (left side in Figure **5**). The pressure wave then propagates in the air and interacts with the helmet/head systems. Use of this technique along with spherical shell meshes allows pressure waves to propagate in perfect spherical symmetry, which could not be obtained in rectangular meshes [10]. The sample blast pressures in the air at two different times are given Figure **5**.



(a) (b)

Figure 5 Pressure in the air at (a) 300us and (b) 600us

The air zone size was selected so that the reflected waves from the boundary would not come back to the helmet/head during the time period of our interest. Since the air far away from the head is not important, coarser mesh was used away from the head. The number of hexahedral elements for the air was about 2.8 million.

The incident pressure corresponds to TNT explosive of 3.2 kg detonated at the head height 3 m away from the brain center. The peak reflected pressure at the skin is about 676kPa. The chosen charge size and distance are not expected to cause lung damage to a human [8].

2.4. Finite Element Model

The helmet, foam pads, head components including CSF are modeled as Lagrangian parts. It has shown in our previous work [10] that it is more appropriate to model CSF as Lagrangian part instead of an ALE part.

The foam pads have fabric coverings which are attached to the helmet through hook disks. Since the foam coverings and hook disks are not modeled, two different boundary conditions were used to bracket the effect: the foam pads and helmet shell shared nodes at the interface; a sliding contact with friction was defined between the helmet and foam.

The air surrounding the structure was modeled using ALE solver in LS-DYNA. Second-order advection method was chosen for the ALE calculations. The Fluid Structure Interaction (FSI) is modeled using the keyword *CONSTRAINED_LAGRANGIAN_IN_SOLID.

The fiber orientations in the helmet are complex, and are not readily available. We assumed the meridian and latitude directions of the sphere as the fiber orientations.

The Hex mesh size is ~2mm. The total number of Lagrangian elements is about 1 million. A contact is defined between the foam pads and the skin with a friction coefficient of 0.2.

Free boundary conditions are applied to the head. For longer response duration, appropriate boundary conditions need to be applied to represent the neck.

Only one half of the geometry is modeled to take advantage of sagittal symmetry of the head. The blast loading is applied from the frontal direction of the head.

3. RESULTS

The interaction between the air blast and the head is very complex. The blast loadings can be applied to the head in three different ways as shown in Figure 1: (1) the blast loading is applied to the skin directly, (2) the blast loading is applied to the foam pads, which then propagates to the skin/bone, and (3) the blast loading is applied to the helmet, which then propagates to foam pads/skin. The stress in the head is a combination of these scenarios. Before 3D calculations were conducted, the three different scenarios were studied in details through a 1D model. The 1D model can help us understand how the wave is propagated and reflected at different material interfaces.

3.1. 1D case

The 1D strain ($\varepsilon_x \neq 0, \varepsilon_y = \varepsilon_z = 0$) case is shown in Figure **6**. The thickness of each component is the same as the 3D case: the helmet thickness is 12 mm, the foam pads thickness is 18 mm, skin, bone and CSF are 10mm thick each, and the brain is 140mm thick. Contact is defined between helmet/foam and head. For the 1D problem, the air surrounding the helmet/head is not modeled. A pressure loading P (ConWep function) is directly applied to the left boundary of the structure, which gives the same loading to the structure but is much more efficient for computation.

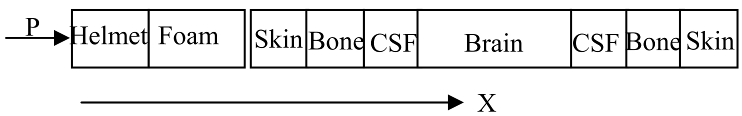


Figure 6 Schematic of 1D problem (not to scale)

3.1.1. Blast loading directly applied to the head

In this case the helmet and foam are not modeled.

The X-Stress (stress is negative in compression) propagation in the material is shown in Figure 7. The dotted lines are the material interfaces. Arrow signs show the wave propagation directions. A stress wave propagates towards the bone after the blast loading is applied. The stress wave is reflected when it enters the bone. The stress at the interface is about 30% higher due to higher acoustic impedance of the bone. Similarly, the stress at the bone/CSF interface is lower. The wave keeps reflecting and transmitting at the interfaces. The time history of stress in different materials is shown in Figure 8. The symbols, L, M and R denote the left, middle and right boundaries of the material, respectively. The stress at 'Skin L' is used to represent the incident loading.

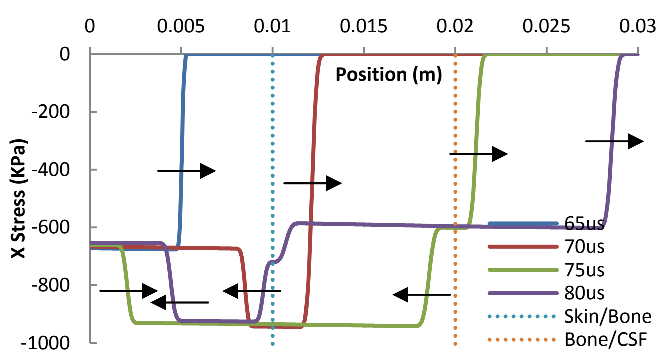


Figure 7: The wave propagation and reflection in different materials

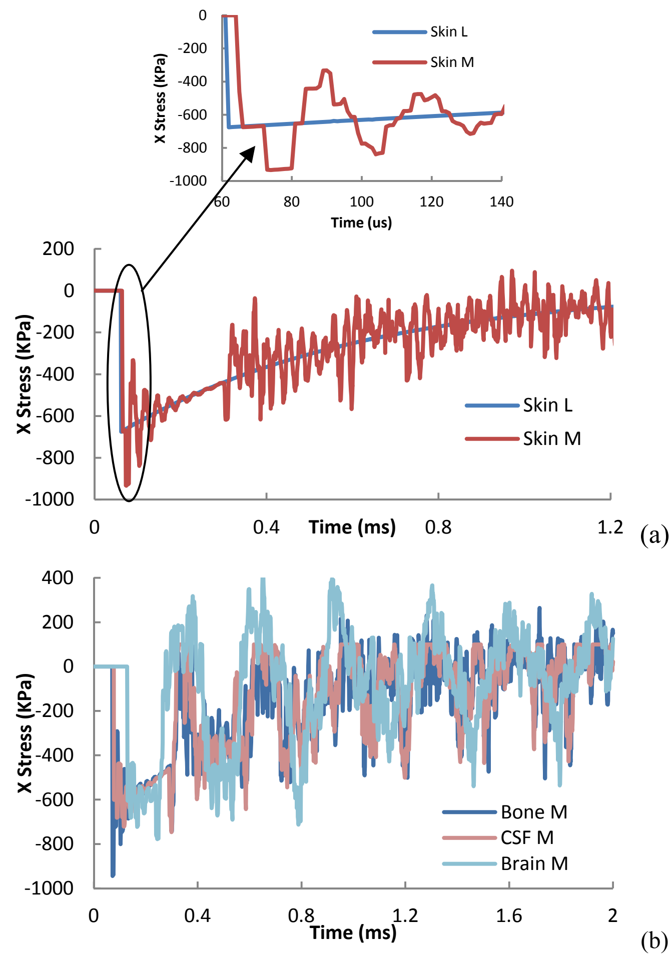


Figure 8: The time history of stress in the (a) skin, (b) bone, CSF and brain

The pressure in the brain is shown in Figure **9**. The pressures from the left and the right boundaries of the brain are similar in peak amplitude. The pressures at the left and right boundaries with CSF are capped at -100kPa, the assumed cavitation pressure of the CSF.

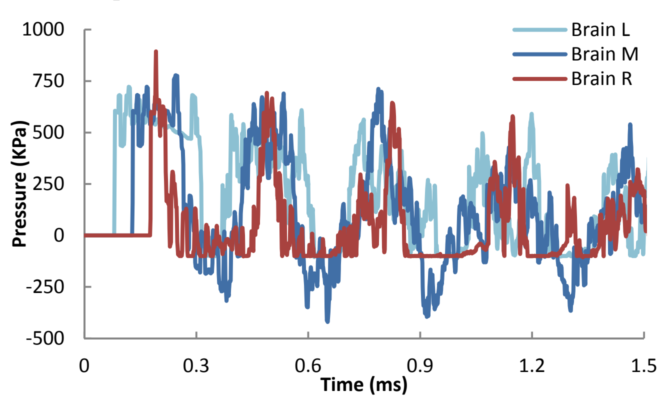


Figure 9 The time histories of pressure (positive in compression) in the brain

The result for the case without the skin in the model is shown in Figure 10. The results show that when the skin is included, the wave is amplified in the bone at the higher impedance. The peak stress in the brain is slightly higher in this case (when the skin is modeled,) and there are higher frequency oscillations present.

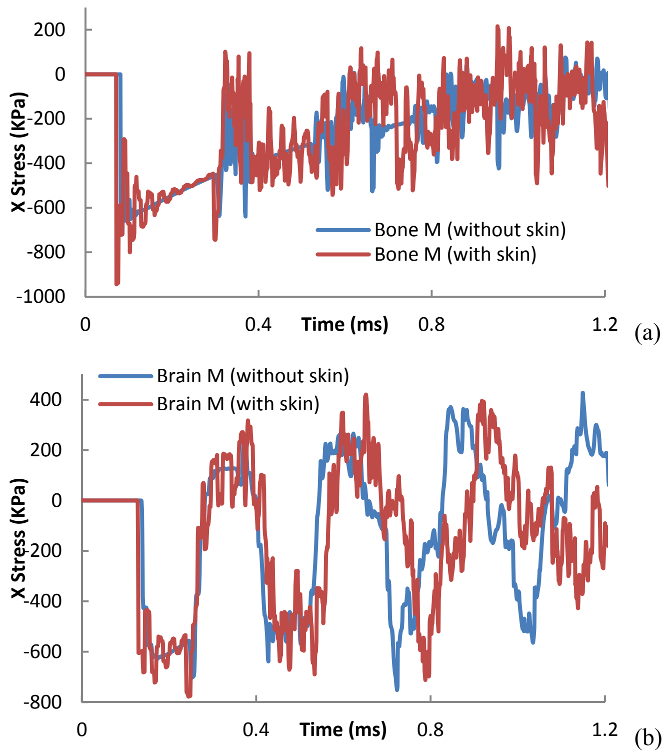


Figure 10 The time history of stress in (a) the skin, (b) brain with and without modeling the skin

3.1.2. The Blast loading is applied to the foam

The propagation of stress is shown in Figure 11 for the case when the pressure is applied to the foam. As the wave propagates, the pad thickness decreases and the density increases. The stress is reflected when it arrives at the skin and is about 2.5 times after reflection. In contrast, the stress in a metal increases by a factor of two when it reflects from a rigid surface. The non-linear compressibility of the foam is believed to contribute to this higher reflection coefficient.

The stress time histories in the foam pads for different levels of pressure loadings are given in Figure 12. As the stress propagates in the foam, its peak decreases slowly. The reflected stress at the foam/skin interface is found to be about 2 to 4 times the incident stress, depending on the incident stress amplitude.

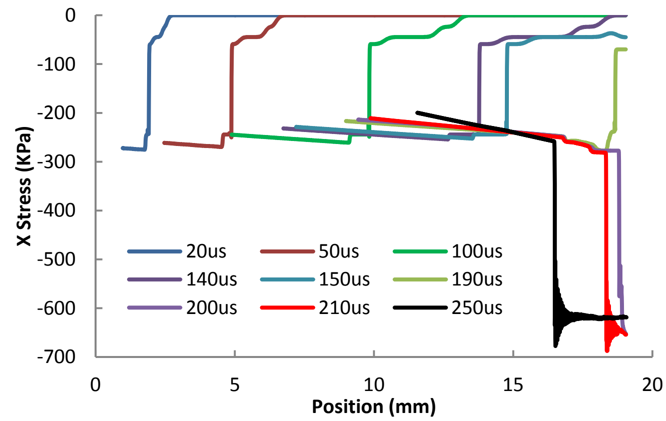


Figure 11: The wave propagations in the foam for various times (stress peak is 280K)

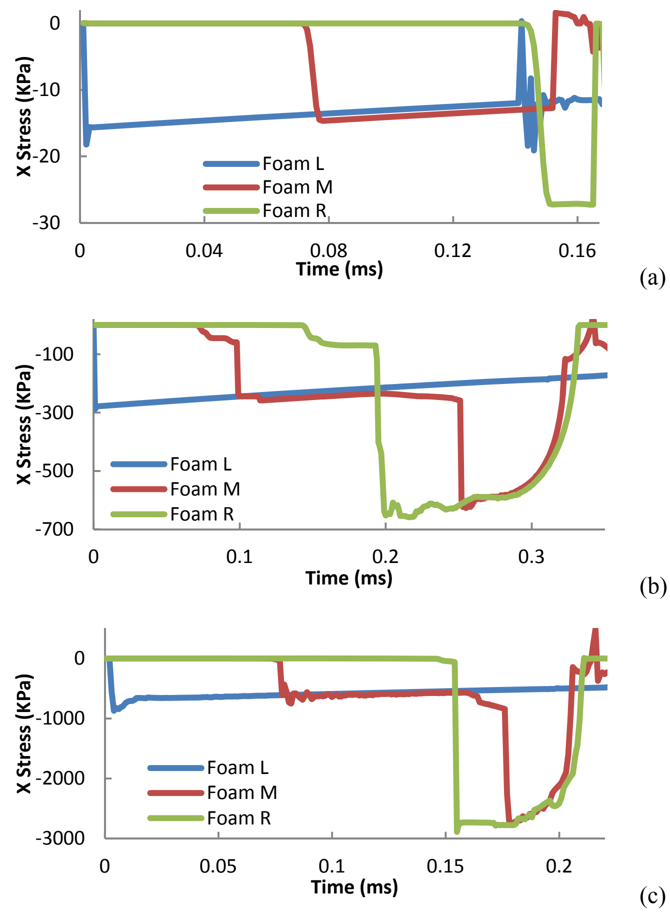


Figure 12: The time history of stress in the foam pads for (a) low pressure, (b) medium, and (c) large pressure

3.1.3. The blast loading is applied to the helmet

Figure 13 shows the time history of the stress in the foams for the case when the blast pressure is applied to the helmet. The stress at Helmet-L is the stress entering the helmet when the blast wave arrives. When the stress wave arrives at the foam, only a small portion is transmitted into the foam due to its much smaller acoustic impedance. The stress amplitude increases as it reflects at the skin-interface. The foam pads delay the arrival time of wave front and increase the rise rime. After the peak, the stress in the foam starts dropping to 0 when the foam is separated from the skin and the stress is zero at the free surface.

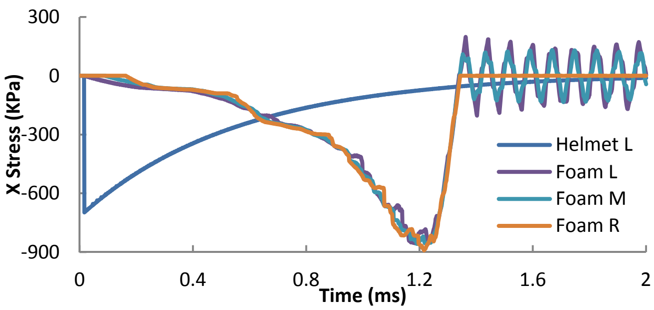


Figure 13: The time history of stress in the helmet and foam

The wave propagations in the helmet and foam pads are given in Figure **14**. The stress in the foam increases as the wave is reflected at the helmet/foam interface. The pad thickness drops from 19 mm to about 4.7 mm at 1195 us.

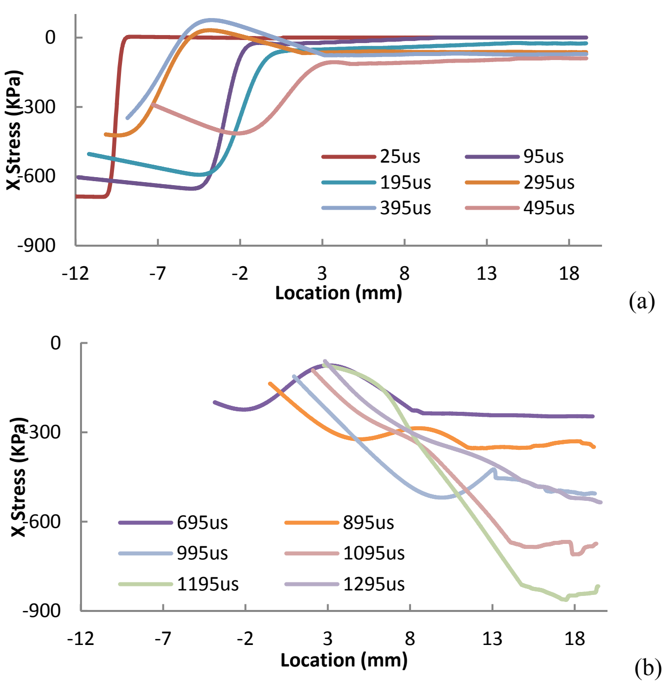


Figure 14 The wave propagations in the helmet and foam pads

Figure **15** shows the stress time history in the skin, bone, CSF and brain. The stresses are very similar in the skin, bone and CSF. However, as the stress propagates in the brain, its peak amplitude drops. But the pressure did not drop when the blast loading was applied to the skin directly, as shown in Figure **9**. The difference is due to the foam pads, which changes the shock wave to a slow-rising wave, which is assisted by unloading wave reflecting from the right skin boundary.

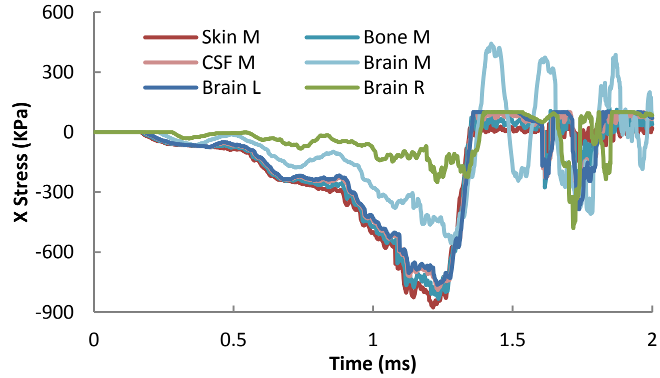


Figure 15 The time history of stress in the skin, bone, CSF and brain

The foam pads delay the arrival time of wave peak and also reduce the wave peak. We did a parametric study to investigate the effect of foam pad thickness and foam properties as reported below.

3.1.3.1. Effect of foam pad thickness

The stress in the foam pads center is given in Figure 16 for various thicknesses. The result for no foam pads (thickness is 0) is also given for comparison. As the pad thickness increases, it further delays the arrival time of peak wave. The wave peak drops and the pulse width increases when the pad thickness increases.

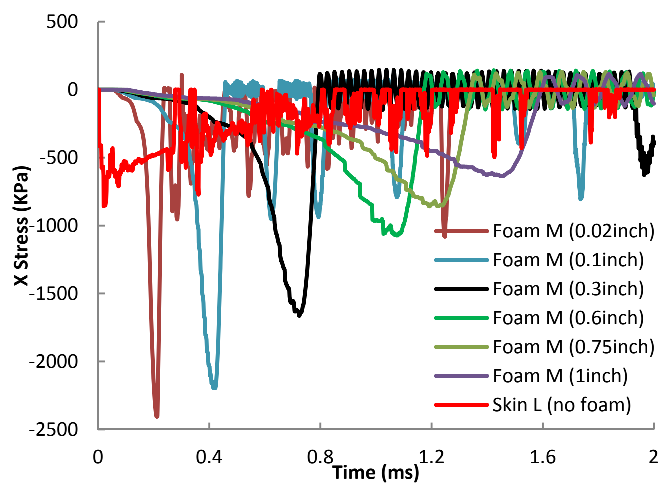


Figure 16: The time history of stress in the foam pads for various thicknesses

The stress in the skin is very similar to the foam. Interestingly, the stress peak in skin was found to be almost the same for cases of no foam pad and 0.75in thick pads for the given blast loading. Thinner foam pads showed higher stress peak in the skin, but longer time to peak.

3.1.3.2. Effect of foam pad property

The foam property effect was investigated by arbitrarily scaling the stress axis by a factor of 1.5 and 2 in its stress-strain curve. Figure **17** shows the stress-time histories in the foam pads. As the foam strength increases, both the stress peak and stress peak arrival time decrease. However the stress peak appears to level off as the foam strength increases.

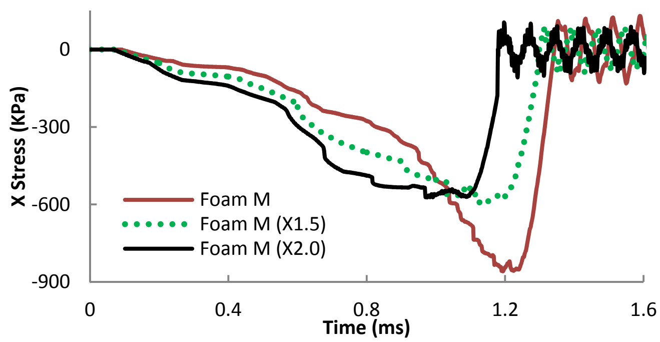


Figure 17 The time histories of the stress in the foam pads for various properties

We have analyzed three different scenarios of blast loading applied to the head. The 1D results provide us with how the wave propagates, reflects and transmits through different material interfaces. The foam pads changes the shape and peak amplitude of the blast loadings depending on the foam pad thickness and properties.

3.2. 3D case

The 1D study presented above was useful in exploring the foam pad effects. However, the 1D model cannot help understand the 3D effects such as underwash effects. Therefore, we constructed a simplified 3D geometry, as shown in Figure 18 for additional calculations. We explored the interactions between the foam pads and helmet, effect of foam pads thickness, and effect of foam properties using this model.

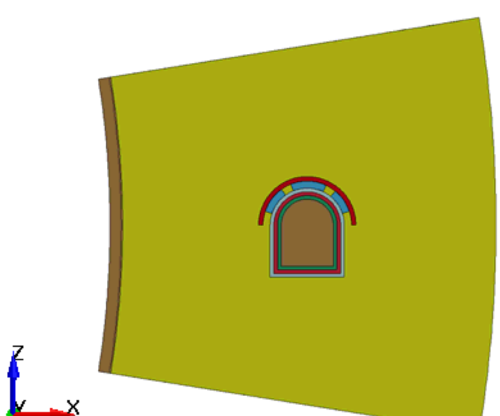


Figure 18 3D Model

3.2.1. Effect of interactions between the foam and helmet

As mentioned earlier, the interactions between the helmet shell and foam remain unclear since we ignored the hook disks and fabric coverings of the foam pads. We tried two extreme cases: (a) shared nodes at the interface, and (b) a sliding contact with a friction coefficient of 0.5. Figure **19** shows the deformation comparisons at two different times, 1 and 1.5ms. When the two materials share nodes, the foam does not deform with respect to the helmet at the interface. The foam deforms, however, at the skin interface. When the two materials do not share nodes, the foam can deform and slide on both interfaces.

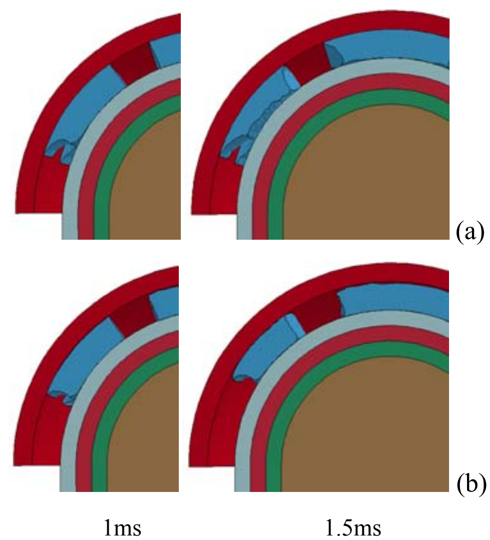


Figure 19 The deformation comparisons for (a) shared nodes, and (b) sliding contact between foam pads and helmet

The points designated in Figure **20** represent following locations, where stresses were evaluated. Brain-1: coup-location, brain-3: countercoup location, brain 5: brain stem region. The locations were chosen based on the original brain geometry. The time histories in the brain are compared in Figure **21**.

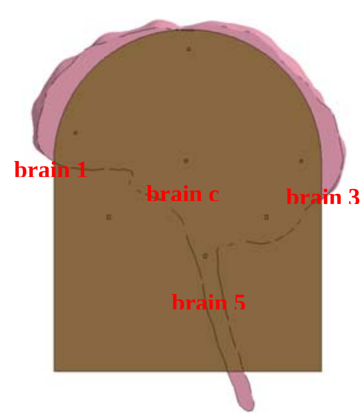


Figure 20 Typical locations in the brain

Since the helmet-pad interface condition did not significantly change the pressure distributions, we chose sliding contact between the foam pads and the helmet in remaining of the analysis.

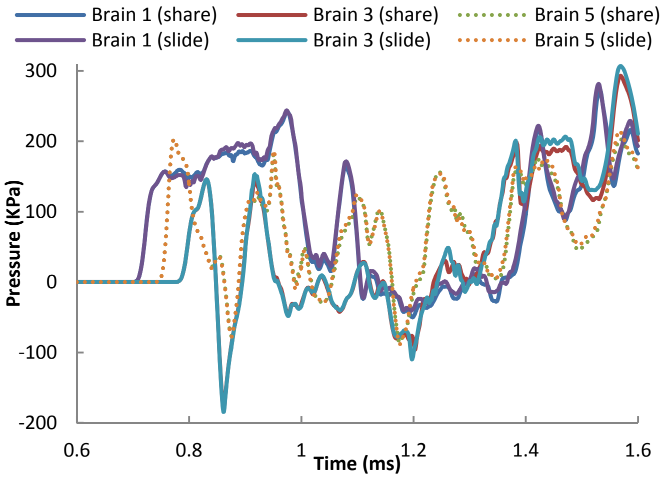


Figure 21 Pressures in the brain

3.2.2.Effect of helmet and foam

Three cases were studied: bare head, helmet without foam pads, and helmet with foam pads. The pressure time histories in the gaps are shown in Figure **23**. The locations are shown in Figure **22**. For bare head case, the stress wave always arrives earlier. In location, ‘gap 1’, the pressure is reflected into much higher value. The pressure loading is also found to be higher at location, ‘gap 4’. In presence of helmet, the pressure propagates in the gap around the foam pads. The reflected pressure amplitude depends on whether foam pads are present or not.

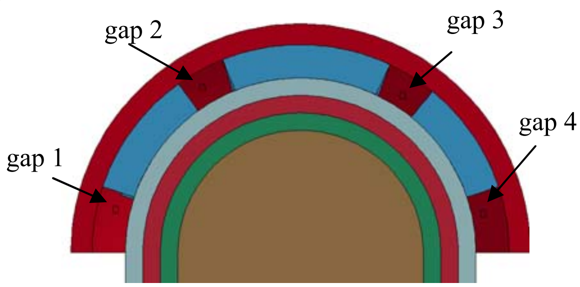
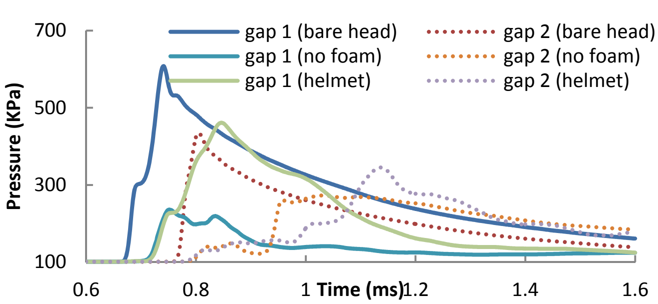


Figure 22 Four locations in the gap



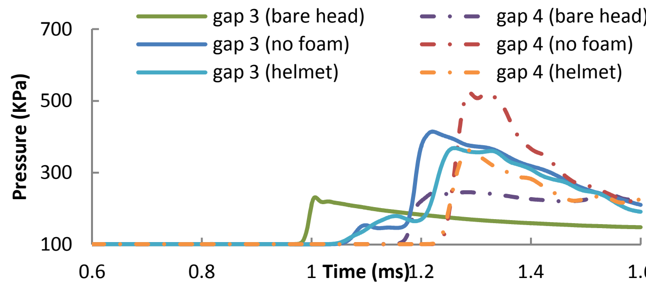


Figure 23 The pressure in the gaps for the three cases

The pressure time histories in the brain are given in Figure **24**. It can be seen that the pressure is the highest for bare head case, i.e., the helmet/foam pads seem to mitigate the blast loading. The countercoup (brain 3) location has a large tensile pressure. The pressure is higher at location 1, but is lower at location 3 when foam pads are used.

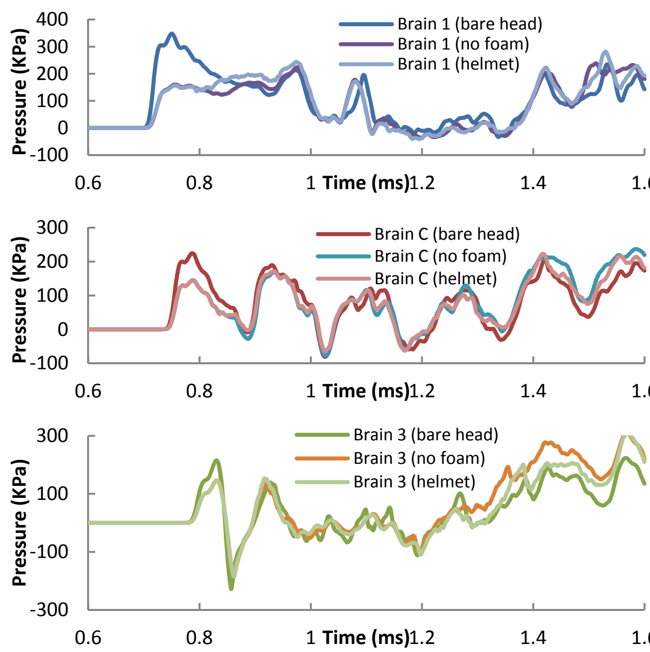
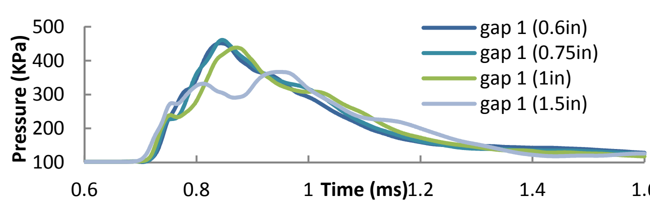


Figure 24 The pressure time histories in the brain

3.2.3.Effect of foam pad thickness

The pressure time histories in the gap are given in Figure **25** for different foam pad thicknesses. When the foam pad thickness increases, the pressure in the gap drops.



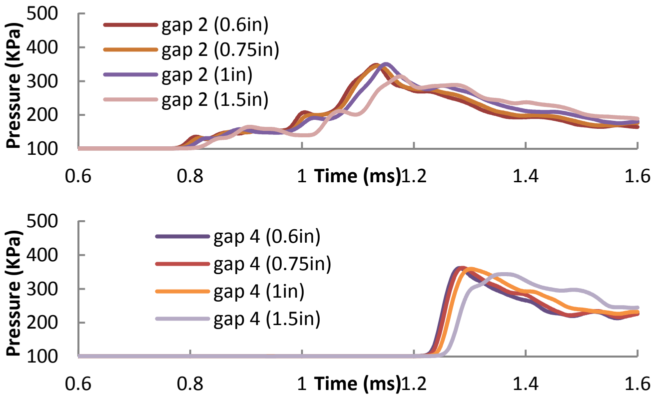


Figure 25 The pressure in the gaps for different pads thicknesses

The pressure time histories in the brains are given in Figure **26**. At location 'brain 1', the pressure is higher for smaller pad thickness due to higher pressure in the gap. Overall, the pressure peak does not change much as the foam thickness changes. Even when the foam pads are not used, the pressure peaks in the brain are also similar, as shown in Figure **24**.

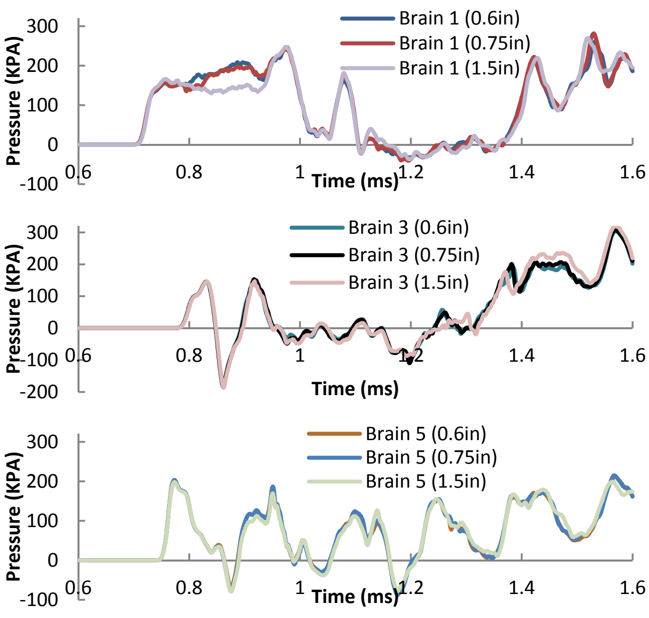


Figure 26 The pressure time histories in the brain for different pads thicknesses

Under blast loading from the front, the pressure loading is applied to the skin primarily through scenario (1) and (2) as shown in Figure 1. The loading transfer through the helmet and foam pads, i.e., scenario (3), where the foam pads can mitigate the blast loading, happens at later time especially after the pressure peak has arrived. Therefore the effect of the foam pads thickness is small for frontal blast loading case.

3.2.4.Effect of foam pad properties

The pressure time histories in the brain are shown in Figure 27 for a case where the foam stress-strain curve is arbitrarily scaled by a factor of three in the stress-axis. The effect on the pressure peak is found to be small, which is understandable because of earlier finding on foam pad effects in frontal loading case.

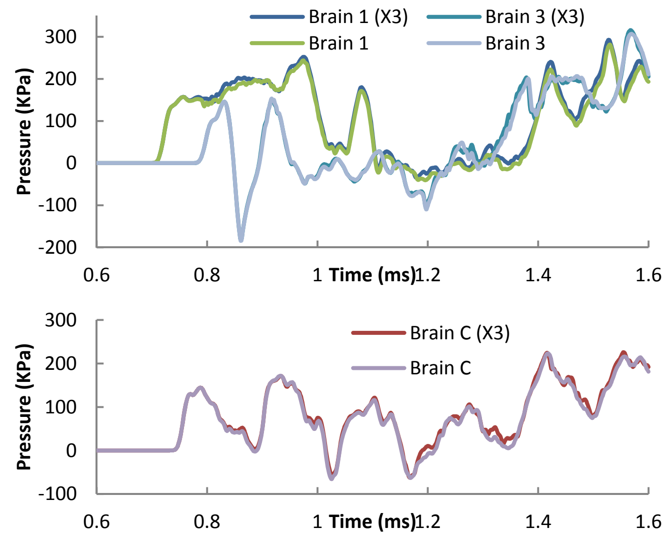


Figure 27 The pressure time histories in the brain for different pads properties

4. SUMMARY AND OBSERVATIONS

A numerical model to study the interactions between the blast loading and the helmet/head was developed. Several simplifications were made to the head geometry and the helmet system to understand the wave reflection and transmission in both 1D and 3D. However, important insights were obtained from these simulations.

The blast loading can load the head through three different scenarios: through the skin, through the foam pads and through the helmet/foam pads. 1D calculations show that the blast loading can be mitigated by the foam pads. The foam pads delay the arrival time of the pressure peak, which changes the shock wave to a slowly rising compressive wave.

The wave reflection from foam material to the skin depends on the peak pressure. The reflection factor can be 4 times for blast pressure peak of 700kPa.

As the pad thickness increases, it further broadens the stress pulse and drops the peak. Higher strength foam appears to shorten the arrival time of the wave peak, but also reduces the peak.

3D calculations were carried out with a simplified head/helmet geometry, modeled with a combination of spheres and cylinder. The overall dimensions were kept as close as possible. The results show that the helmet with or without foam pads can reduce the pressure in the brain. The primary load transfer to the head is through the skin, i.e., the frontal blast loading scenario. The load transfer through helmet/foam pads takes place later since the foam material delays the arrival time of wave peak. Therefore, it is not surprising that the effects of foam pads' thickness and foam properties are small.

Simplified geometry takes away finer topological features, which is essential for stress wave propagations. We will use more complex geometry better representative of head topology for future work.

ACKNOWLEGEMENT

This work was supported by TKC Global contract W911QX-14-C-0016 and Bowhead Science and Technology contract W911QX-09-C-0057.

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