

The Effects of Polyurea Coatings on the Underwater Explosive Response of Composite Plates

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1 Introduction

Composite materials are increasingly being employed in a wide range of industries and applications due to their numerous advantages over traditional construction materials, namely high strength-to-weight ratios, improved corrosion resistance, and overall reduced maintenance costs. Historically, the civilian marine industry has utilized composite materials in the construction of leisure and commercial watercraft. There has been a recent and increasing desire by multiple worldwide navies to implement these materials in military applications such as advanced ship hull designs, ship decks, unmanned underwater vehicles, and submarine components. However, structures which are employed in military environments are inherently at risk for being subjected to blast-type loading events. In the specific case of underwater explosions, these may occur either at large or very small standoff distances depending on the relative location of the explosive source and the structure of interest. The loading resulting from an UNDEX event is both complex and highly transient, signified by high peak pressures, rapid rise times, and spherical wavefronts. Due to the complex nature of both the mechanisms associated with these loadings, and a reduced knowledge base of the response of these advanced materials when subjected to high loading rates (10^{-1} to 10^3), including the evolution of damage, and the load carrying capacity in these materials, there is an inherent conservativeness in design. An extensive review of the use of composite materials in naval ships and submarines has been presented by Mouritz et al. [1].

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When composite materials are subjected to severe loading conditions, they may experience damage in the form of several distinct mechanisms occurring in the in-plane and through thickness directions. The in-plane mechanisms consist of fiber breakage and matrix cracking, while the through thickness damage is dominated by delamination of the plies. These damage mechanisms and their evolution in these materials have been studied through various experimental methods. The response of composites subject to UNDEX type loading is typically conducted in the laboratory-scale environments [2–10]. These studies have investigated different parameters associated with the structural response including charge standoff, impulse levels, material properties, and panel curvature. The effects of impact loading on damage mechanisms and energy absorption were studied in [11].

The finite-element modeling of damage in composites has been performed primarily on models simulating strain rates up to those representing drop test experiments with some work performed at the high strain rate regimes expected in shock loading. Analytical damage models, including implementation into computational codes for composites have been widely developed and are continually being refined and updated [12–17]. In general, these models assign an internal damage variable to each of the types of damage of interest (i.e., matrix cracking, fiber rupture) which, in simple form, are ratios of the stress state to a failure criterion. Early validation work focused on the low strain rate regime, rates below which blast/shock loading conditions would generate [18–21]. More recently, computational work has been performed on materials subject to higher loading rate events including UNDEX and high-speed impacts [22, 23] although the material inputs are derived from mechanical testing under quasi-static conditions. The through thickness strain rates for blast and ballistic impact events are significantly higher and the approach of using material inputs from quasi-static test data should be improved.

The use of elastomeric materials to increase the resistance of structures subjected to high rate loading such as blast and shock has become a recent topic of interest. One such material of interest is polyurea, a synthetic, high strength/high elongation coating that is typically spray cast onto existing structures. The armed forces have begun to investigate the suitability of these materials for use on military and naval vehicles such as Humvees, troop carriers, and ship hulls, Hodge [24]. Research efforts have recently studied the effectiveness of polyurea when applied to various substrates. Studies involving composite and sandwich construction applications [25–28] showed that the effect of the coating on the transient response and damage levels of these materials is dependent upon both coating thickness as well as location. Rate-sensitive constitutive models of these elastomeric materials have been developed to allow for numerical modeling of the coating effects under various high rate loading environments [29–33].

2 Composite Material

The composite material used in this study is Cyply[®] 1002, a cured epoxy composite with a nonwoven, parallel fiber construction with continuous E-Glass filaments. The specific laminate is a cross-ply construction with alternating plies of 0° and 90°, each ply having a thickness of 0.254 mm (0.01 in.). The cured material has a specific gravity of 1.85 and a resin content of 36 ± 3%. Mechanical properties of the material are provided in Table 1.

The composite laminate serves as the baseline substrate to which polyurea coatings are applied. The polyurea used is Dragonshield-BC which is a 2-part spray cast material that can be applied to a wide range of surfaces and materials. Mechanical characterization in both tension and compression for strain rates from 0.01 to 2000 s⁻¹ has been conducted. Characterization up to 100 s⁻¹ was performed using standard material testing machine whereas a split Hopkinson pressure bar was used to characterize the response of the material at 2000 s⁻¹. The response of the material at 2000 s⁻¹ was only characterized in compression and is assumed to be similar in tension. At the lower strain rates, unique tests were conducted for both tension and compression. The full material characterization is shown in Fig. 1. From this figure, it is seen that the material exhibits strong strain rate dependence and becomes stiffer with increasing loading rate. Furthermore, the material displays a stiffening effect in compression above 300%, whereas in tension the response exhibits a stress plateau-like behavior. In this study, both the thickness and location of the coating is varied to determine relative effects.

3 Experimental Methods

The experiments that are the basis for the work described in the following sections are designed to subject composite panels to shock loading conditions representative of far and near field underwater explosions. A conical shock tube facility is utilized to impart blast loading conditions representative of far field UNDEX events and a water-filled blast tank is employed for the conduct of near field experiments. During all experiments, the DIC methodology is used to capture the transient response of the back face of the panels. These measurements form the basis for correlation between the experiments and corresponding finite-element simulations.

Table 1 Cyply 1002 cross-ply—mechanical properties

	N/m ² (lb/in ²)
Tensile modulus (0°)	23.4e9 (3.4e6)
Tensile modulus (90°)	23.4e9 (3.4e6)
Tensile strength (0°)	482e6 (70e3)
Tensile strength (90°)	482e6 (70e3)
Compressive strength (0°)	689e6 (100e3)
Compressive strength (90°)	689e6 (100e3)

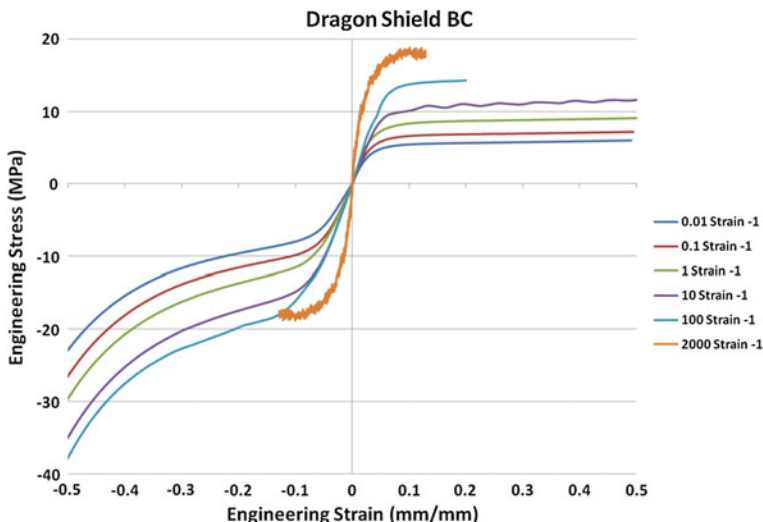


Fig. 1 Dragon shield BC polyurea stress-strain behavior

3.1 Conical Shock Tube—Far Field UNDEX Loading

The conical shock tube (CST) facility located at the Naval Undersea Warfare Center Division Newport (NUWCDIVNPT), has been utilized to generate shock loading conditions representative of explosions occurring at large standoff distances. The shock tube is a horizontally mounted, water-filled tube with a conical internal shape as seen in Fig. 2. The tube geometry represents a solid angle segment of the free field spherical pressure front resulting from the detonation of an underwater explosive charge. In an open water environment (free field), the pressure wave expands from the charge location as a spherically propagating wave. In the shock

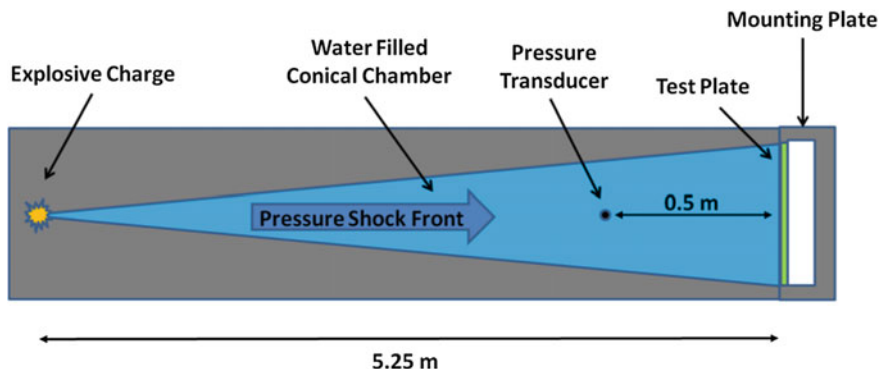


Fig. 2 Conical shock tube schematic (not to scale)

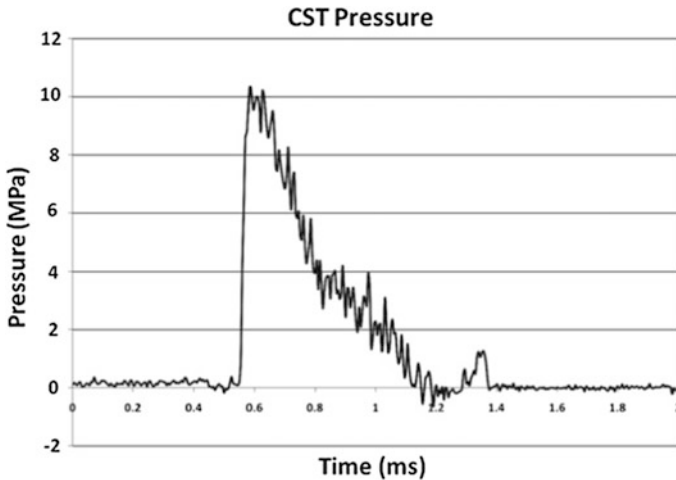


Fig. 3 Typical pressure profile generated in the conical shock tube

tube, the rigid wall acts to confine the expansion of the pressure wave in a manner that simulates a conical sector of the pressure field. The internal cone angle of the shock tube used in the current work is 2.6° . The pressure shock wave is initiated by the detonation of an explosive charge at the breech end of the tube (left side of Fig. 2) which then proceeds down the length of the tube. Peak shock pressures from 10.3 to 20.6 MPa (3000 lb/in^2) can be obtained depending on the amount of explosive charge used. A typical pressure profile, as obtained from the pressure transducers, is shown in Fig. 3. This figure illustrates the rapid pressure increase associated with the shock front followed by the exponential decay of the wave. A detailed description of the tube and underlying theoretical considerations are presented in [26, 34, 35]. A mounting fixture has been designed so the test specimens are air backed with fully clamped edges. The specimens have an overall diameter of 26.54 cm (10.5 in.) with a 22.86 cm (9.0 in.) unsupported middle section.

3.2 Water-Filled Blast Facility—Near Field UNDEX Loading

The near field UNDEX experiments in this study were conducted in a water-filled tank, Fig. 4. The tank has internal dimensions of $1.21 \text{ m} \times 1.21 \text{ m} \times 1.21 \text{ m}$ with 6.35 mm thick steel walls and is supported on a reinforced wooden stand. The tank contains $\sim 1500 \text{ L}$ of water when filled. Four window ports allow for the lighting and high-speed photography of the UNDEX event and plate motion. Mounted to the inner surface of one wall is a $304.8 \text{ mm} \times 304.8 \text{ mm}$, rectangular tunnel with a

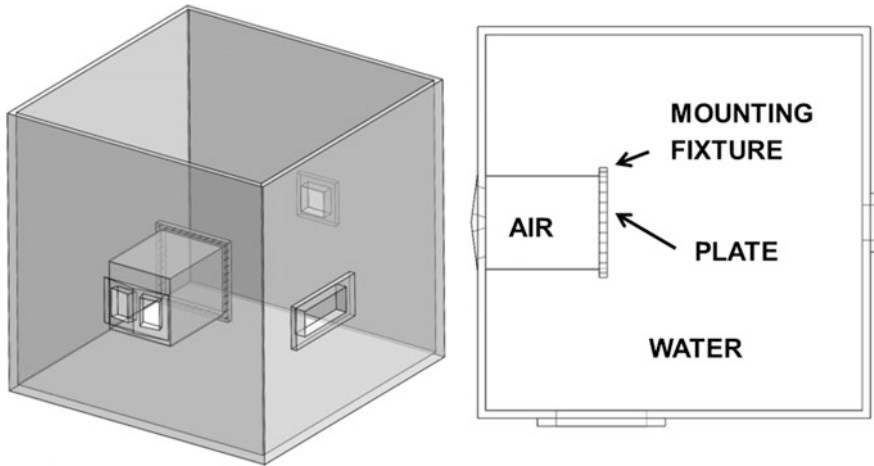


Fig. 4 UNDEX test tank

wall thickness of 12.7 mm, which serves as the base for the mounting of the composite plates. The tunnel extends 394 mm into the tank from the wall and a 38.1 mm wide flange is welded to the end of the tunnel. The flange has a series of through holes around the perimeter which allow for bolting of the test plates to the flange. The test plates are sandwiched between the flange and a second steel frame and are secured to the flange with a series of 1.59 mm diameter through bolts spaced at 38.1 mm. The use of the tunnel and mounting flange provide a watertight seal around the test plate and allows for the plates to be air backed.

The explosive used in the near field blast experiments is an RP-503 charge which is comprised of 454 mg RDX and 167 mg PETN contained within an outer plastic sleeve.

3.3 Transient Plate Response Measurements

In all experiments, the digital image correlation method is utilized for the capture of the transient response of the back face of all panels. Digital image correlation is a nonintrusive, optical technique for capturing the full field, transient response of the panels through the use of high-speed photography and specialized software. A detailed discussion of the DIC process and setup for each of the respective test facilities are presented in [26, 36]. The post-processing is performed with the VIC-3D software package (Correlated Solutions) which matches common pixel subsets of a random speckle pattern between the sequential deformed images. The matching of pixel subsets is used to calculate the three-dimensional location of distinct points on the face of the panel throughout time. Two high-speed digital cameras, Photron SA1, are utilized in each setup with frame rates of 20,000 fps.

4 Finite-Element Modeling

The numerical modeling of the two loading conditions requires different approaches to be employed. In the case of the far field loading experiments (CST) the tube geometry is explicitly captured and the incident shock wave is approximated as planar. In the modeling of the near field experiments, due to the close proximity of the charge to the plates, it is critical to capture the detonation of the charge as well as the bubble growth and spherical pressure wave expansion. The following is a brief overview of each approach. In all cases, the modeling of the experiments has been performed utilizing the LS-Dyna software code.

In all simulations, the material model utilized for the composite plate is *Mat_Composite_Failure_Option_Model*. This is an orthotropic material definition capable of modeling the progressive failure of the material due to any of several failure criteria including tension/compression in the longitudinal and transverse directions, compression in the through thickness direction, and through thickness shear. The material model for the polyurea coating is *Mat_Simplified_Rubber* which is a viscoelastic material definition that captures both the strain and strain rate effects through the use of a family of load curves. The model reproduces the uniaxial tension and compression behavior as obtained through material testing at discrete strain rates (see material section for properties). The model determines the appropriate strain rate curve from the family of curves through an internal calculation.

4.1 Far Field UNDEX Modeling

The complete finite-element model of the CST test setup is shown in Fig. 5. The model consists of the composite plate, polyurea coating, mounting fixture

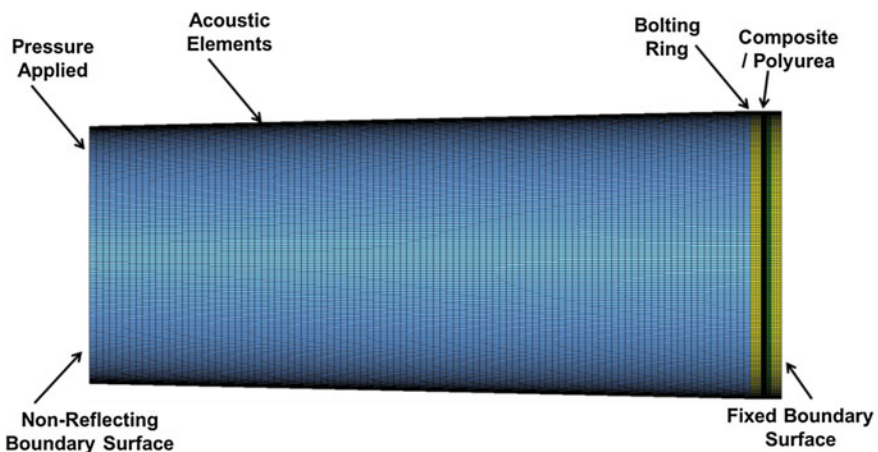


Fig. 5 Finite-element model of CST

(including the bolts) and the internal fluid of the shock tube up to the location of the pressure transducer used to record the UNDEX pressure profile. The fluid within the tube is considered in the simulation so as to capture the fluid structure interaction (FSI) at the interface of the fluid and test plate. The fluid is modeled with solid elements utilizing an acoustic element formulation which more accurately propagate the shock wave than the use of a structural element formulation combined with an equation of state (EOS) material definition. The pressure load is applied as a plane wave at the location of the test pressure transducer (left face of the fluid domain) and is taken to be the pressure profile that was measured during the test. The fluid–structure interaction is handled by utilizing a mesh that is equivalenced at the boundary between the fluid domain and composite plate. The mounting plate and fastening bolts are explicitly included in the model to obtain the correct interaction with the test plates. The polyurea coatings are assumed to be perfectly bonded to the composite plate and are thus meshed directly to the composite. The composite plate in the simulations is modeled using layers of solid brick elements with each layer representing a 0° and 90° combined ply. The polyurea is also represented in the model by solid elements.

4.2 Near Field UNDEX Modeling

The near field UNDEX models utilize the coupled Lagrange–Eulerian formulation of the code, which allows for the accurate representation of the detonation of the explosive charge as well as the fluid structure interaction between the fluid and the composite plate. The finite-element model of the UNDEX test setup is shown in Fig. 6. The model consists of the test plate, tank water, air, and the RP-503 charge. The model represents a sub-domain of the full experimental test tank for computational efficiency. The use of a sub-domain for the modeling of the corresponding

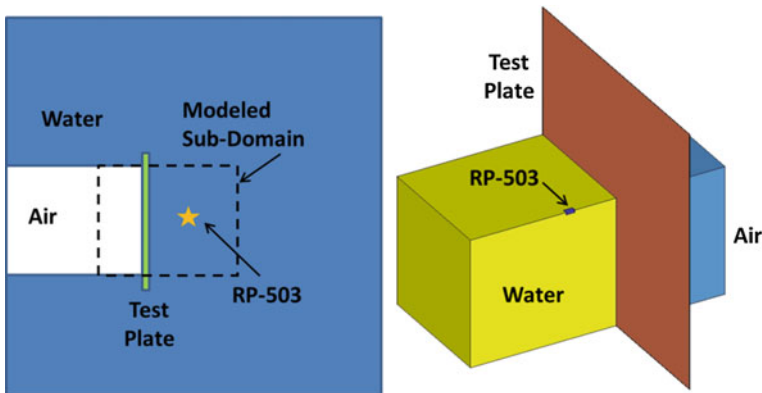


Fig. 6 Finite-element model of UNDEX experiment (3 Quadrants of Fluid Domain Hidden)

experiments is deemed appropriate as the loading of the plate and subsequent response occurs sufficiently fast that reflections from the tank walls do not affect the overall transient response of the plate. In the model, the outer surface of the fluid sub-domain is prescribed a non-reflecting boundary condition (*BOUNDARY_NON_REFLECTING). The composite plate in the simulations is modeled using a single layer of shell elements and the polyurea material is represented in the model by solid elements. Furthermore, the polyurea coatings are assumed to be perfectly bonded to the composite plate and are thus meshed directly to the composite.

The water, air, and explosive charge are modeled with solid elements utilizing the LS-Dyna ALE multi-material element formulation. The water and air utilize the *Mat_Null material definition with the density of the water and air given as 1 g/cm³ and 0.0013 g/cm³ respectively. The Gruneisen EOS is used for the definition of the water with the speed of sound taken to be 149,000 cm/s. A Linear Polynomial EOS defines the air domain in the model with the parameters defined in Table 2. By defining C₀, C₁, C₂, C₃, and C₆ equal to zero, and C₄, and C₅ equal to $\gamma-1$, a gamma law EOS is achieved. Finally, the explosive charge is modeled with the *Mat_High_Explosive_Burn material model combined with the JWL EOS. Although the RP-503 charge contains both RDX (454 mg) and PETN (167 mg), the model assumes a charge comprised of only RDX, with the overall charge weight being maintained. The Material and EOS parameters for the RDX are provided in Tables 3 and 4.

Table 2 Air EOS parameters

C0	0
C1	0
C2	0
C3	0
C4	0.4
C5	0.4
C6	0

Table 3 RDX material parameters

ρ (g/cm ³)	1.77
D (cm/s)	850e3
Chapman–Jouget pressure (dyn/cm ²)	3.41e13

Table 4 RDX EOS (JWL) parameters [37]

A	7.78e12 (dyn/cm ²)
B	7.07e10 (dyn/cm ²)
R1	4.485
R2	1.068
ω	0.3
E _o	5.93e10
V _o	1.0

5 Far Field UNDEX Response of Flat Composite Plates

The response of flat E-Glass/Epoxy plates subjected to far field explosive loading, including the effects of the polyurea coatings is presented in the following section. In the investigation, 5 unique panel configurations are considered as shown in Fig. 7. The goal is to determine the effects of both coating thickness and position with respect to the incoming shock wave. The response of the each of the composite plates, coated and uncoated, is characterized in terms of the transient displacements of the back face of the panel and the deformation mechanisms during the displacement. The correlation between the experiments and numerical models is discussed.

The center point displacement–time history as obtained from the DIC data for the five-panel configurations tested is shown in Fig. 8. In general, the response of both the coated and uncoated panels is approximately the same in terms of peak center point deflection. However, it can be seen that overall the panel with the thicker coating (4.8 mm) located on the back provides a slightly improved response as compared to the baseline. Conversely, the thin coating (2.4 mm) on the front face results in a minor degradation in the transient panel response as compared to the uncoated composite plate. These trends, although not as pronounced, are in agreement with previous observations of experimental data [25]. Similar to the current investigation these studies also showed that, up to a certain thickness, a coating on the front face (towards loading) of a panel under shock loading can degrade the performance of the plate as compared to a panel with no coating at all. Furthermore, a thicker coating on the back face can improve the response of the panel subjected to shock loading. Potential reasons for the lack of significant differentiation of the experimental peak displacements include: (1) the coating

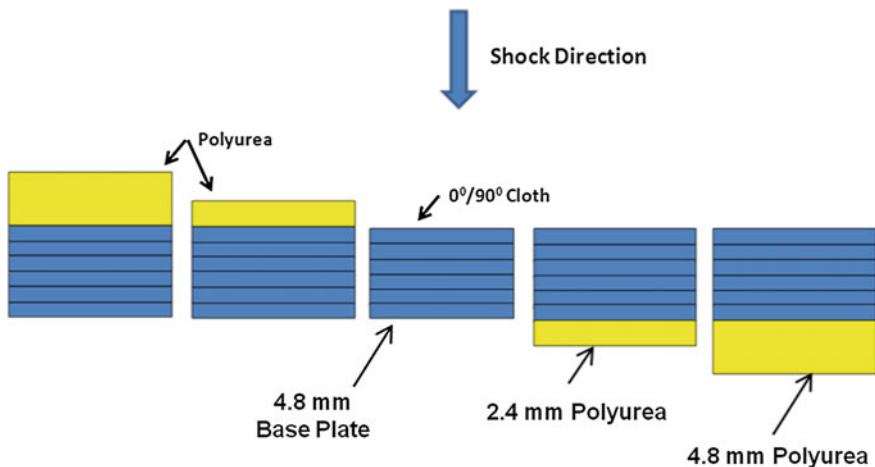


Fig. 7— Composite plate construction—schematic (not to scale)

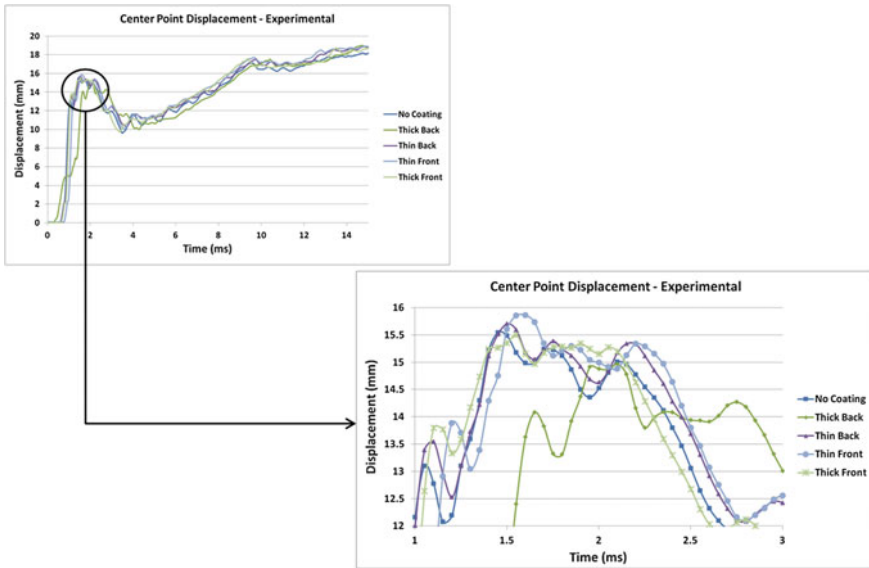


Fig. 8 Time history deformation comparison

thicknesses chosen for this study are not sufficient to meaningfully improve the shock response of the plates, or (2) the in-plane strains realized by the coatings during deformation are not sufficient for the coating to experience the significant strain stiffening as seen in the material characterization.

The deformation of the uncoated composite plate as measured along a horizontal cut through the center point (c) is shown in Fig. 9b. The deformed shape along the cross-section is shown for 5 distinct points in time as indicated by the black dots in the time history in the upper Fig. 9a. From this figure, it is shown that for a plate subjected to a shock front with a plane wave profile, the plate motion initiates at the outer edge and progresses inwards. During the early deformation phase, a knee-like hinge develops at the outer edge as seen for the 0.9 ms deformation contour. As this hinge continues to progress toward the center point the deformation tends toward a mode I plate flexure. The significant observation is that the expected mode I flexure deformation profile does take a finite time to develop and is not the initial deformation mechanism.

The finite-element simulation of the shock tube testing allows for a visual full field representation of the interaction between the pressure wave and the composite plate. The pressure field in the fluid as it interacts with and loads the plate, for the case of the plate with the 4.8 mm polyurea coating is shown on the left side of Fig. 10. The associated plate response is shown in right side of the figure. Figure 10 illustrates several key points. First, although the pressure wave is uniform (planar) prior to its impact with the test plate, the pressure becomes both complex and nonuniform when it interacts with and loads the plate itself. It is evident that there is

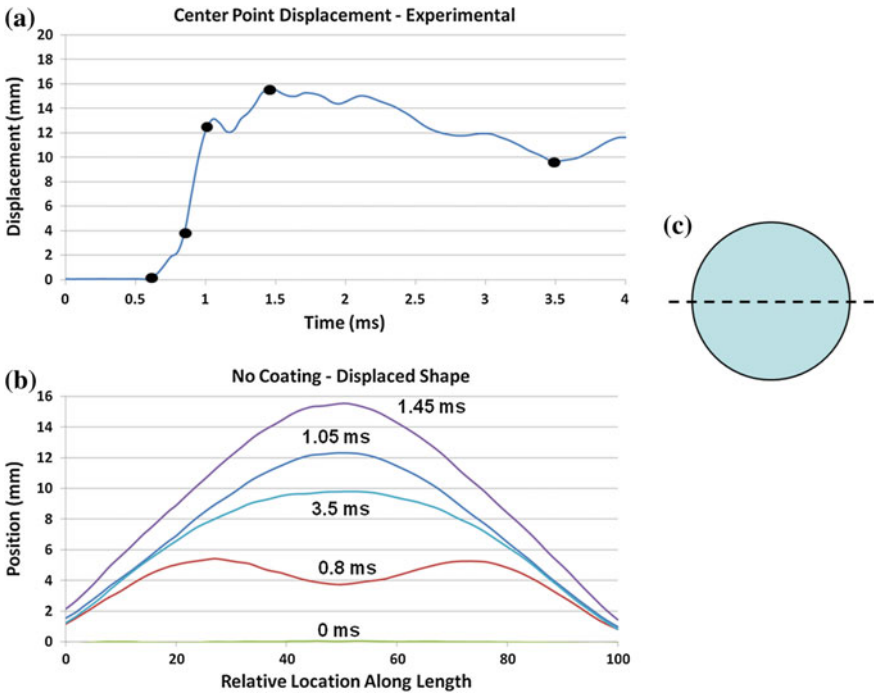


Fig. 9 Plate deformation profiles for centerline

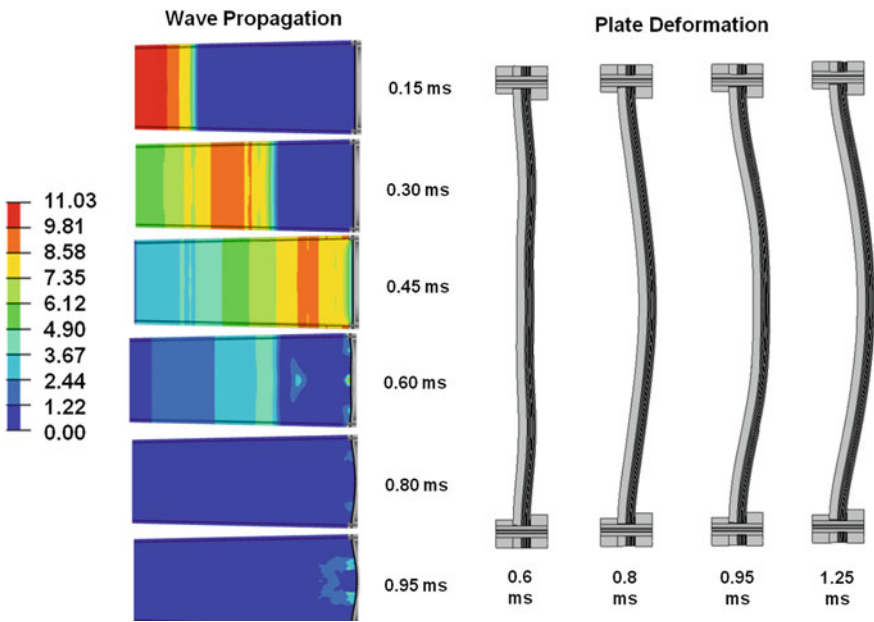
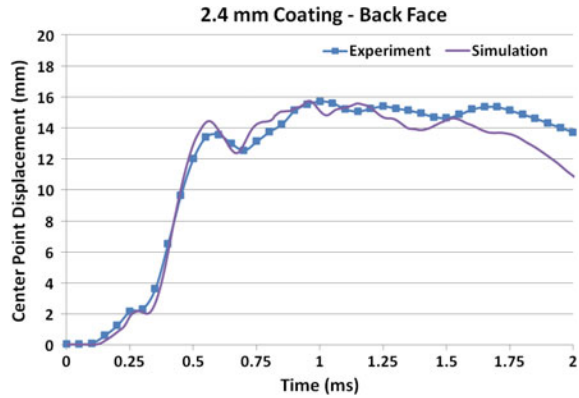


Fig. 10 Fluid structure interaction (contours of MPa) and associated plate response

Fig. 11 Computational model correlation for 2.4 mm back face coating



a low-pressure area that develops in the center of the plate while the clamped edge is loaded with high pressure. The second point is that the loading of the plate and the associated response can be separated into two distinct time regimes. The plate does not start to deform until 0.6 ms which roughly corresponds to the point in time at which the pressure wave is nearly fully reflected. Furthermore, from the cross-section view of the plate deformation it is seen that plate in the simulation also develops a hinge which propagates inwards from the clamped edge. These are the same deformation mechanisms which were observed from the DIC data of the experiments.

The center point displacement data comparison between the experimental and numerical simulation for the CST test performed with a thin (2.4 mm) coating on the back face of the composite panel is shown in Fig. 11. From this graphical comparison, it is seen that there is a high level of correlation between the experimental results and the computational simulations. This level of agreement between the test and finite-element data demonstrates that the computational methodology utilized to simulate the testing is suitable for the accurate predictions of these types of loading conditions.

6 Near Field UNDEX Response of Flat Composite Plates

The effects of polyurea coatings on the near field UNDEX response of flat E-Glass/Epoxy plates subjected to near field explosive loading is presented in the following section. Based on the previously observed results of greater performance obtained when the coating is applied to back face of the structure, only a rear face coating is considered for this part of the study. In addition to the coated panel, a thicker structural configuration is also considered. The 3 unique panel configurations are shown in Fig. 12. The goal is to determine the relative effects of both a rear face coating and a thicker structural laminate.

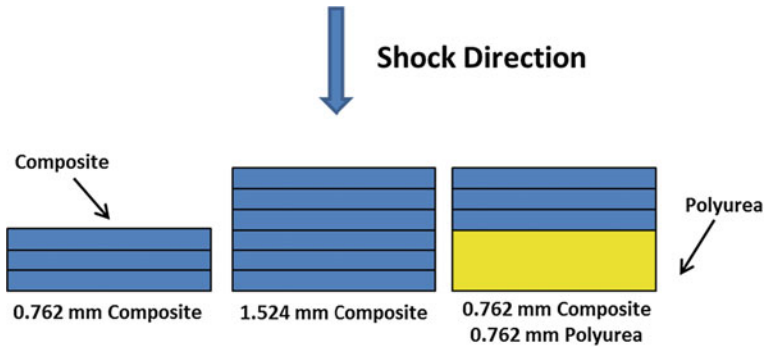
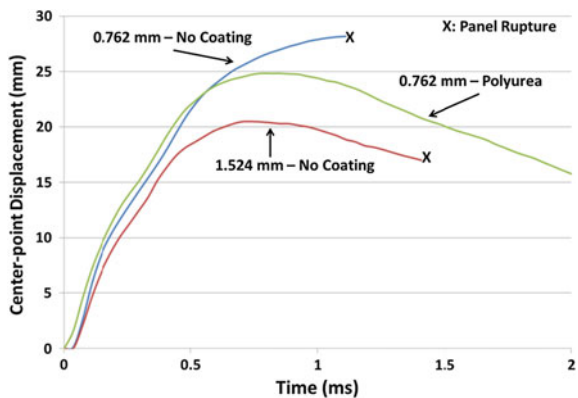


Fig. 12 Composite plate construction—schematic (not to scale)

The center-point displacement for each respective plate configuration is shown in Fig. 13. From this figure, it is observed that there are several distinct differences in the overall plate response as influenced by the plate construction. It is evident that, as compared to the baseline 0.762 mm plate, increasing the plate thickness or including a polyurea coating reduces the peak overall deflection for a given level of loading. It is noted that the center-point velocity during the initial deflection is nearly constant for each configuration. The main difference is the time that it takes for the plate to arrest its outward motion and begin to recover, with the 1.524 mm uncoated and the 0.762 mm polyurea coated plates arresting their outward motion ~ 0.25 ms sooner than the baseline 0.762 mm plate. The center-point deflection comparison between the 1.524 mm uncoated plate and the 0.762 mm plate with a 0.762 mm coating of polyurea indicate that for a plate thickness it is more advantageous to utilize additional structural plies rather than an elastomeric coating. However, when a structure has previously been designed and further thickening of the structural shape is not possible, the application of a polyurea coating can improve the transient response to shock loading. A second primary difference in the

Fig. 13 Plate center-point deflections

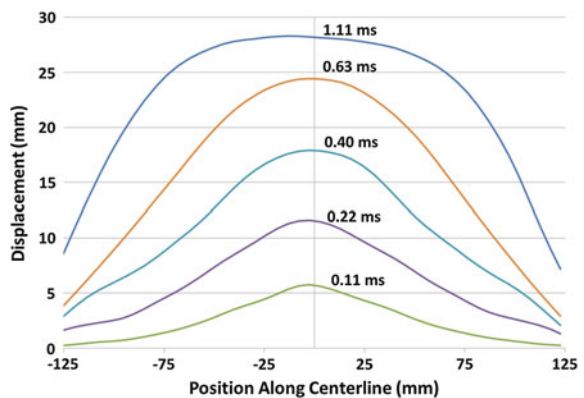


response of the plate configurations is the onset of material damage. Both the uncoated 0.762 and 1.524 mm specimens experienced significant through thickness tearing at the plate boundaries. It is further observed that although the 0.762 mm plate with the polyurea coating did experience larger deflections than the 1.524 mm uncoated plate, there was no edge tearing of the plate itself. Thus in terms of reducing material damage itself, the polyurea coatings offer an advantage over a thicker uncoated plate.

The deformation history of the baseline 0.762 mm uncoated composite plate as measured along a horizontal cut through the center of the plate is shown in Fig. 14. From this figure, it is seen that for a plate subjected to a centralized near field UNDEX loading, the deformation is initially dominated by localized deflections at the center with minimal deflection near the boundaries. As the plate responds to the pressure loading, it gradually transitions to an overall plate flexure mode as shown by the cross-sectional shape at 0.63 and 1.11 ms. The significant observation is that the initial plate deformation is governed by the highly localized pressure loading and then subsequently shifts to a mode I flexure deformation profile later in time.

The center-point time history correlation between the experimental data and the corresponding computational simulation for each respective plate configuration is shown in Fig. 15. The correlations presented in the figure show that there is a high level of correlation between the experiment and simulations, both temporally and in terms of displacement magnitudes. The simulation and experiment results exhibit consistent results in the early time frame of the event (0–0.4 ms) in terms of displacement and velocity, with some deviation beyond this point, although the deviation is somewhat minor. Additionally, for both of the uncoated plates (0.762 and 1.524 mm) it is seen that the onset of edge tearing occurs slightly later (0.1 ms) in time as compared to the experimental results. The timing differences in the onset of damage are expected as the model assumes a uniform plate in terms of material properties and does not account for manufacturing variability or minor internal defects which can contribute to the onset of damage or slightly weaker/stronger areas of the plates as compared to the gross material strengths. That the model is

Fig. 14 Plate deformation—horizontal centerline



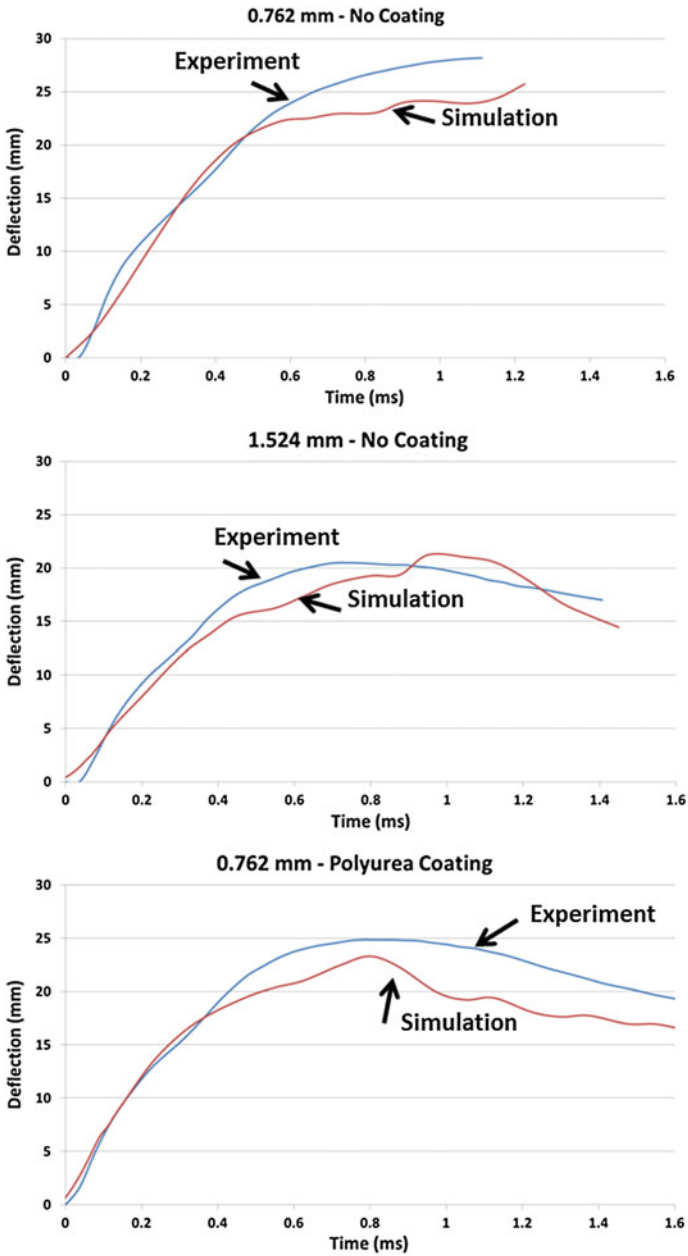


Fig. 15 Center-point displacement model correlation

able to predict the onset of damage in a consistent manner as observed during the testing, namely edge tearing, is encouraging.

7 Summary

This research has studied the response of E-Glass/Epoxy composite plates subjected to UNDEX loading, specifically far and near field conditions. The work consists of experimental testing with corresponding numerical simulations. The primary objectives of the study were to (1) determine the effects of polyurea coatings on the transient response and damage mechanisms of the plates during loading and (2) develop a computational modeling methodology that is able to accurately simulate the behavior of the plates. The relevant findings resulting from the present study are presented below.

- (1) Experimental methods have been developed which subject flat composite plates to loading conditions representative of underwater explosions. Far field loading conditions are generated through the use of a conical shock tube facility which replicates the free field expansion of pressure waves resulting from the explosion. A water-filled blast chamber is utilized for the controlled detonation of small charges in close proximity to the plates to replicate near field loading conditions. In all experiments the real-time dynamic response of the back face of the specimens is captured through the use of high-speed photography coupled with the digital image correlation technique.
- (2) A computational modeling methodology, utilizing the commercial finite-element code LS-Dyna, has been developed that is able to accurately simulate the response of the composite material and polyurea coatings subject to UNDEX conditions. Unique modeling methods have been employed for the simulation of the far and near field loading experiments. All simulations include explicit representations of the plate, coating, and a sufficient amount of the surrounding fluid to accurately capture the fluid structure interaction between the pressure wave and structure. The models are shown to be able to simulate the dynamic loading of the plate and the corresponding transient response.
- (3) The effects of polyurea surface coatings have been studied to determine the effects of parameters including coating thickness and location with respect to the incident shock front. In general, it was shown that greater performance increases are obtained when the back face of the panels are coated as compared to the front face in terms of peak deflections and velocity decay times. Furthermore, as the coating thicknesses were increased the performance was further increased but at the cost of added weight and panel thickness.

The work discussed in this chapter has provided a basis for experimental and computation techniques which can be applied to the study of the dynamic response of composite materials subjected to underwater explosive loading conditions. However, there remains a significant body of work to be completed in this area before the dynamic response of these materials matures to an equivalent level of understanding as that for metallic materials. This work includes further experimental and computational studies as well as validation efforts which correlates the

two. These efforts will ultimately lead to validated modeling practices that can be applied during the design phase of composite structures.

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References

1. Mouritz, A. P., Gellert, E., Burchill, P., & Challis, K. (2001). Review of advanced composite structures for naval ships and submarines. *Composite Structures*, 53, 21–41.
2. Latourte, F., Gregoire, D., Zenkert, D., Wei, X., & Espinosa, H. (2011). Failure mechanisms in composite plates subjected to underwater impulsive loads. *Journal of the Mechanics and Physics of Solids*, 59, 1623–1646.
3. Espinosa, H., Lee, S., & Moldovan, N. (2006). A novel fluid structure interaction experiment to investigate deformation of structural elements subjected to impulsive loading. *Experimental Mechanics*, 46(6), 805–824.
4. Schiffer, A., & Tagarielli, V. (2015). The Response of circular composite plates to underwater blast: Experiments and Modeling. *Journal of Fluids and Structures*, 52, 130–144.
5. Avachat, S., & Zhou, M. (2014). Response of cylindrical composite structures to underwater impulsive loading. *Procedia Engineering*, 88, 69–76.
6. Avachat, S., & Zhou, M. (2015). High-speed digital imaging and computational modeling of dynamic failure in composite structures subjected to underwater impulsive loads. *International Journal of Impact Engineering*, 77, 147–165.
7. LeBlanc, J., & Shukla, A. (2010). Dynamic response and damage evolution in composite materials subjected to underwater explosive loading: An experimental and computational study. *Composite Structures*, 92, 2421–2430.
8. LeBlanc, J., & Shukla, A. (2011). dynamic response of curved composite plates to underwater explosive loading: Experimental and computational comparisons. *Composite Structures*, 93, 3072–3081.
9. Franz, T., Nurick, G., & Perry, M. (2002). Experimental investigation into the response of chopped-strand mat glassfibre laminates to blast loading. *International Journal of Impact Loading*, 27, 639–667.
10. Mouritz, A. P. (1995). The effect of underwater explosion shock loading on the fatigue behaviour of GRP laminates. *Composites*, 26, 3–9.
11. Dear, J., & Brow, S. (2003). Impact damage processes in reinforced polymeric materials. *Composites Part A Applied Science and Manufacturing*, 34, 411–420.
12. Matzenmiller, A., Lubliner, J., & Taylor, R. L. (1995). A constitutive model for anisotropic damage in fiber-composites. *Mechanics of Materials*, 20, 125–152.
13. Zako, M., Uetsuji, Y., & Kurashiki, T. (2003). Finite element analysis of damaged woven fabric composite materials. *Compos Sci Technol*, 63, 507–516.
14. Dyka, C. T., & Badaliane, R. (1998). Damage in marine composites caused by shock loading. *Compos Sci Technol*, 58, 1433–1442.
15. O'Daniel, J. L., Koudela, K. L., & Krauthammer, T. (2005). Numerical simulation and validation of distributed impact events. *International Journal of Impact Engineering*, 31, 1013–1038.

16. McGregor, C. J., Vaziri, R., Poursartip, A., & Xiao, X. (2007). Simulation of progressive damage development in braided composite tubes under axial compression. *Compos Part A*, 38, 2247–2259.
17. Williams, K. V., & Vaziri, R. (2001). Application of a damage mechanics model for predicting the impact response of composite materials. *Computers & Structures*, 79(2001), 997–1011.
18. Gama, B., Xiao, J., Haque, M., Yen, C., & Gillespie, J. (2004). *Experimental and numerical investigations on damage and delamination in thick plain weave S-2 glass composites under quasi-static punch shear loading*. Center for Composite Materials, University of Delaware.
19. Xiao, J., Gama, B., & Gillespie, J. (2007). Progressive damage and delamination in plain weave S-2 glass/SC-15 composites under quasi-static punch-shear loading. *Composite Structures*, 78, 182–196.
20. Donadon, M. V., Iannucci, L., Falzon, B. G., Hodgkinson, J. M., & de Almeida, S. F. M. (2008). A progressive failure model for composite laminates subjected to low velocity impact damage. *Computers & Structures*, 86, 1232–1252.
21. Hosseinzadeh, R., Shokrieh, M. M., & Lessard, L. (2006). Damage behavior of fiber reinforced composite plates subjected to drop weight impacts. *Composites Science and Technology*, 66, 61–68.
22. Batra, R. C., & Hassan, N. M. (2007). Response of fiber reinforced composites to underwater explosive loads. *Composites Part B: Engineering*, 38, 448–468.
23. Chan, S., Fawaz, Z., Behdinan, K., & Amid, R. (2007). Ballistic limit prediction using a numerical model with progressive damage capability. *Composite Structures*, 77, 466–474.
24. Hodge, N. (2004). Military experimenting with 'spray on' armor for humvees. *Defense Today*, 25.
25. LeBlanc, J., Gardner, N., & Shukla, A. (2013) Effect of polyurea coatings on the response of curved e-glass/vinyl ester composite plates to underwater explosive loading. *Composites Part B: Engineering*, 44, 565–574.
26. LeBlanc, J., & Shukla, A. (2015). Response of Polyurea Coated flat composite plates to underwater explosive loading. *Journal of Composite Materials*, 49, 965–980.
27. Tekalur, A., Shukla, A., & Shivakumar, K. (2008). Blast resistance of polyurea based layered composite materials. *Composite Structures*, 84, 271–281.
28. Gardner, N., Wang, E., Kumar, P., & Shukla, A. (2012). Blast mitigation in a sandwich composite using graded core and polyurea interlayer. *Experimental Mechanics*, 52, 119–133.
29. Amirkhizi, A., Isaacs, J., McGee, J., & Nemat-Nasser, S. (2006). An experimentally-based viscoelastic constitutive model for polyurea, including pressure and temperature effects. *Philosophical Magazine*, 86, 5847–5866.
30. Amini, M. R., Isaacs, J. B., & Nemat-Nasser, S. (2010). Experimental investigation of response of monolithic and bilayer plates to impulsive loads. *International Journal of Impact Engineering*, 37, 82–89.
31. Xue, L., Mock, W., & Belytschko, T. (2010). Penetration of DH-36 steel plates with and without polyurea coating. *Mechanics of Materials*, 42, 981–1003.
32. Gruzicic, M., Pandurangan, B., He, T., Cheeseman, B. A., Yen, C. F., & Randow, C. L. (2010). Computational investigation of impact energy absorption capability of polyurea coatings via deformation-induced glass transition. *Materials Science and Engineering: A*, 527, 7741–7751.
33. Bahei-El-Din, Y. A., Dvorak, G. J., & Fredricksen, O. J. (2006). A blast-tolerant sandwich plate design with a polyurea interlayer. *International Journal of Solids and Structures*, 43, 7644–7658.
34. Coombs, A., & Thornhill, C. K. (1967). An underwater explosive shock gun. *Journal of Fluid Mechanics*, 29, 373–383.
35. Poche, L., & Zalesak, J. (1992). *Development of a water-filled conical shock tube for shock testing of small sonar transducers by simulation of the test conditions for the heavyweight MIL-S-901D (Navy)*. NRL Memorandum Report 7109, 10 October 1992.

36. LeBlanc, J., Shillings, C., Gauch, E., Livolsi, F., & Shukla, A. (2016). Near field underwater explosion response of polyurea coated composite plates. *Experimental Mechanics*, *56*, 569–581.
37. Dobratz, B. (1972). *Properties of chemical explosives and explosive simulants*. Lawrence Livermore National Laboratory.