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FINAL TECHNICAL REPORT

***'Dynamic Response and Failure Mechanisms of Layered Ceramic-
Elastomer-Polymer/Metal Composites'***

ONR Grant No: N00014-06-1-0340

Period of Performance: January 2006 – December 31, 2009

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I. ABSTRACT

A thorough study through a combination of ballistic and impact experiments, microscopic failure characterization, and numerical simulations has been carried out in order to decipher the underlying mechanisms involved in the interaction between a blast and/or a blast-induced high-velocity projectile and advanced ceramic-polymer and metal-polymer composites, resulting in an improved ballistic efficiency and impact- and blast-resistant structural system. The work includes: 1. Systematic experimental characterization of each material constituent of interest, i.e., polyurea and DH-36 steel, over broad ranges of deformation rates, strains, and temperature of interest. 2. Physics-based constitutive modeling of the dynamic response and failure modes of each material constituent of interest. 3. Numerical simulations of the dynamic response and failure modes of each material constituent of interest. 4. Controlled quantitative ballistic experiments with high-speed photography to document the interaction between a high-velocity projectile and/or a pressure pulse and composite structural targets consisting of bi- and multi-layered constituents. 5. Simulation of a selected set of controlled quantitative (independent) experiments to verify the numerical codes.

II. TECHNICAL SECTION

Progress Statement:

A series of high-velocity impact and ballistic experiments has been performed on several metal-metal, metal-polyurea-metal and polyurea-ceramic composites. New steel plate designs with different thicknesses were employed to avoid tearing of the sample at its supporting ring. New experiments support the hypothesis that the steel-polyurea sandwich samples show a noticeably better performance against blast loads, as compared with that of bare steel. The existing 3D finite element model has been improved to analyze this phenomenon in depth. An axi-symmetric model has also been generated that allows for very fine-mesh simulations. New penetration experiments have also been performed on some newly-fabricated ceramic-polyurea-ceramic sandwich systems. These experimental results suggest that the use of polyurea in ceramic-polyurea composites to improve the ballistic resistance is not as effective as the use of other previously tested materials such as E-glass/epoxy or carbon-fiber/epoxy, whereas the reverse is the case for polyurea-steel layers and sandwich structures.

Technical Summary:

To study the effect of polymers (which are well-known energy absorbers) on the performance of sandwich structures under blast loads, a set of experiments was performed on circular polyurea-steel sandwich samples, using a 3" Hopkinson bar setup. Using an

experimentally-based material model for polyurea, the entire experiment was numerically modeled and analyzed in LS-DYNA and the results are compared with the experimental results.

Experiments:

A 3" Hopkinson bar setup with Aluminum bars was used for the experiments. Three different configurations for the circular sandwich structures were considered: steel-steel, steel-polyurea-steel and steel-polyurea-steel-polyurea. The Naval structural steel, DH-36, is used to manufacture the samples. The sandwich structure is placed between a cylindrical layer of soft polyurethane and a hollow steel ring. When the gun is triggered, high-pressure gas accelerates the projectile through a barrel towards the target. The projectile, which is made of aluminum, impacts the target at a high velocity, which is accurately measured by two magnetic sensors placed at the end of the barrel. Polyurethane, which is nearly incompressible, is now confined between the projectile and the sample. This subjects the sample to a pressure pulse applied to the sample. The history of transmitted force from the sample to the output bar is recorded by two strain gages mounted on the Hopkinson bar.



Figure 1- Sandwich structures

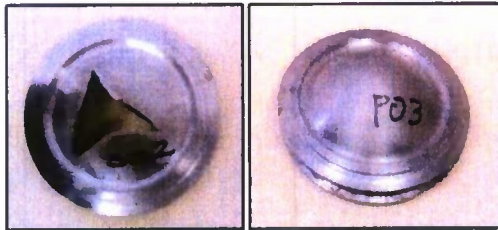


Figure 2 - Samples after the Impact. Right: with polyurea, Left: without polyurea

Our experimental results reveal that when polyurea is cast between the steel plates, the performance of the sandwich structure is noticeably improved. In all cases with polyurea, the steel plate facing the blast does not experience fracture (Figure 2 - right), whereas with the same amount of input energy, both front and back plates are severely fractured from the center in the absence of polyurea (Figure 2 - left). This outcome has been investigated numerically in a

finite element framework.

Finite Element Model:

A better understanding of the sandwich-structure experiment has been achieved using computational techniques. Our experimental measurements and observations include high-speed photography of the impact and penetration process, and examination of the final state of the deformed sample. However, a quantitative assessment of the

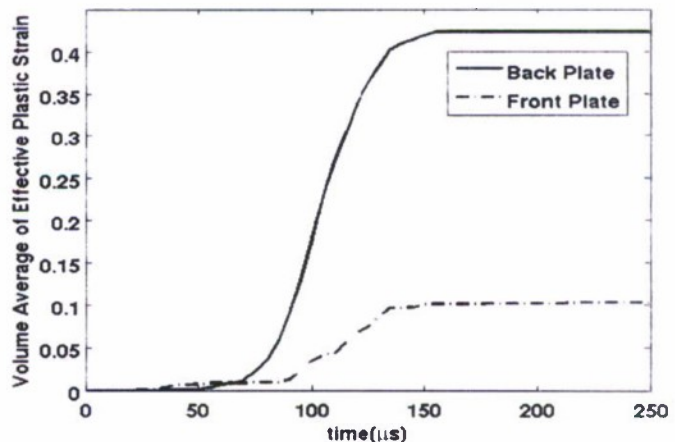


Figure 3 - Average effective plastic strain at the center of front and back plates 3

entire process is highly desirable. Therefore, a 3D finite element model of the experiment has been developed suitable for explicit analysis in LS-DYNA. Proper material models for this model have been used which can capture the pressure, temperature, and rate sensitivities.

Our simulation results show a large difference between the plastic deformation of the front plate, which faces the blast load, and the back plate (Figure 2). This explains why the front face survives the blast, while the back face acts like a sacrificial layer and absorbs a large amount of energy to save the front layer.

New samples with different steel plate thicknesses were made and tested. The new samples were thinner and have been tested to undergo the desired deformation when exposed to impact loadings. The new tests suggest that the performance of the sandwich structure against impact loading is consistently better than the performance of the bare steel.

The finite element model has been improved to achieve a better match between the numerical and experimental results. Also, an axi-symmetric model with a finer mesh has been developed which shows similar results.

Abstracts - Archival Publication:

'Experimental investigation of response of monolithic and bilayer plates to impulsive loads,' M.R. Amini, J.B. Isaacs, S. Nemat-Nasser

Abstract: This article presents the results of a series of experiments performed to assess the dynamic response of circular monolithic steel and steel-polyurea bilayer plates to impulsive loads. A convenient technique to enhance the energy absorption capability of steel plates and to improve their resistance to fracturing in dynamic events, is to spray-cast a layer of polyurea onto the plates. Since polyurea readily adheres to metallic surfaces and has a short curing time, the technique may be used to retrofit existing metallic structures to improve their blast resistance. We have examined the effectiveness of this approach, focusing on the question of the significance of the relative position of the polyurea layer with respect to the loading direction; i.e., we have explored whether the polyurea layer cast on the front face (the impulse-receiving face) or on the back face of the steel plate would provide a more effective blast mitigating composite. The experimental results suggest that the polyurea layer can have a significant effect on the response of the steel plate to dynamic impulsive loads, both in terms of failure mitigation and energy absorption, if it is deposited on the back face of the plate. And, remarkably, when polyurea is placed on the front face of the plate, it may actually enhance the destructive effect of the blast, promoting (rather than mitigating) the failure of the steel plate, depending on the interface bonding strength between the polyurea and steel layers. These experimental results are supported by our computational simulations of the entire experiment, employing realistic physics-based constitutive models for the steel (DH-36, in the present work) and polyurea [Amini MR, Amirkhizi AV, Nemat-Nasser S. Numerical modeling of response of monolithic and bilayer plates to impulsive loads. *J. Impact Engr.*, 2010].

'Numerical modeling of response of monolithic and bilayer plates to impulsive loads,'

M.R. Amini, A.V. Amirkhizi, S. Nemat-Nasser

Abstract: In this paper, we present and discuss the results of our numerical simulation of the dynamic response and failure modes of circular DH-36 steel plates and DH-36 steel-polyurea bilayers, subjected to impulsive loads in reverse ballistic experiments. In our previous article, we reported the procedure and results of these experiments [MR Amini, JB Isaacs, and S Nemat-Nasser. Experimental investigation of response of monolithic and bilayer plates to impulsive loads. *J. Impact Engr.*, 2010]. For the numerical simulations, we have used physics-based and experimentally-supported temperature- and rate-sensitive constitutive models for steel and polyurea, including in the latter case the pressure effects. Comparing the simulation and the experimental results, we focus on identifying the potential underpinning mechanisms that control the deformation and failure modes of both monolithic steel and steel-polyurea bilayer plates. The numerical simulations reveal that the bilayer plate has a superior performance over the monolithic plate if the polyurea layer is cast on its back face (opposite to the blast-receiving side). The presence of the polyurea layer onto the front face (blast-receiving side) amplifies the initial shock loading and thereby enhances the destructive effect of the blast, promoting (rather than mitigating) the failure of the steel plate. In addition, the interface bonding strength between polyurea and steel is examined numerically and it is observed that the interface bonding strength has a significant effect on the performance of the steel-polyurea bilayer plates. The numerical simulations support the experimentally observed facts provided the entire experiment is simulated, employing realistic physics-based constitutive models for all constituents.

'Micromechanisms of ductile fracturing of DH-36 steel plates under impulsive loads and influence of polyurea reinforcing,' M. R. Amini and S. Nemat-Nasser

Abstract: Micromechanisms of ductile fracturing of DH-36 steel plates subjected to blast-induced pressure loads are studied experimentally using specially designed dynamic testing facilities. The sample geometry is such that it undergoes controllable fracturing, generally initiated near its center and grows first circumferentially and then radially. Selected fractured samples are sectioned normal to the fracture surfaces, at various intervals along the length of the fracture which extends into the necked and finally to the uniformly deformed material. The thickness profile of the sample at each cross section is analyzed using optical and scanning electron microscopy. In this manner, we have been able to examine the microstructural evolution that has taken place, from necking inception to fracture initiation and growth, leading to a better understanding of the underpinning mechanisms of the fracturing of this material. The observed ductile fracture involves void nucleation, and void growth and coalescence, creating dimpled fracture surfaces. The examination of the microstructure of the deformed steel samples also revealed that the microstructure does not change significantly during the deformation and that there are no shearbands developing in and around the fracture zones. Based on the observed micro-scale deformation, a finite-element model was developed to further study the fracturing process, using a physics-based and experimentally-supported temperature- and rate-sensitive constitutive model for DH-36 steel. The finite element model was capable of predicting the fracture process of the steel plates rather well. Additional finite element

simulations are performed to investigate the effect of the polyurea coating on the fracturing and fracture resistance of the plates. These also correlated well with the experimental results.

'Numerical modeling of effect of polyurea on response of steel plates to impulsive loads in direct pressure-pulse experiments,' M.R. Amini, J. Simon, S. Nemat-Nasser

Abstract: Results of computational modeling and simulation of the response of monolithic DH-36 steel plates and bilayer steel-polyurea plates to impulsive loads in direct pressure-pulse experiments are presented and discussed. The corresponding experiments and their results are presented in an accompanying paper. The entire experimental setup is modeled using the finite-element code, LS-DYNA, in which a physics-based temperature- and strain rate-sensitive constitutive model for DH-36 steel, developed by Nemat-Nasser and Guo (Thermomechanical response of DH-36 structural steel over a wide range of strain rates and temperatures. *Mech. Mat.*, 35, 1023–1047, 2003) and an experimentally supported temperature-, rate-, and pressure-sensitive constitutive model for polyurea, developed and incorporated into the computer code, LS-DYNA, by Amirkhizi et al. 2006 (An experimentally-based viscoelastic constitutive model for polyurea, including pressure and temperature effects. *Phil. Mag. and Phil. Mag. Letters* 86 (36), 5847–5866.), have been implemented. The transient response of the plates under impulsive pressure loads is studied, focusing on the effects of the relative position of polyurea with respect to the loading direction, the thickness of the polyurea layer, and the polyurea-steel interface bonding strength. The numerical simulations of the entire experiment support the experimentally observed results reported by Amini et al. 2010 (Numerical modeling of response of monolithic and bilayer plates to impulsive loads. *J. Impact Engr.* 37 (1), 90–102.).

'Investigation of effect of polyurea on response of steel plates to impulsive loads in direct pressure-pulse experiments,' M.R. Amini, J. Isaacs, S. Nemat-Nasser

Abstract: We summarize the results of the response of monolithic steel plates and steel-polyurea bilayer plates to impulsive blast loads produced in direct pressure-pulse experiments, focusing on the deformation and failure modes of the plates. In these experiments, an impulsive pressure pulse is applied to a steel plate through water or soft polyurethane that simulates shock loading with a peak pressure of ~80 MPa and duration of ~50 μ s, followed by a cavitation period and a post-cavitation peak pressure of ~40 MPa and ~400 μ s duration. The pressure pulse is produced by a projectile that impacts either a confined water- or soft polyurethane-layer which in turn transmits the pulse and loads the sample supported by a hollow steel cylinder. Using high-speed photography, the deformation and fracturing of some of the plates are also captured. In addition, the total force acting on the steel plate is measured as a function of time in several selected cases. The experimental results suggest that the presence of polyurea on the back face (opposite to the load-receiving side) of the steel plates can enhance the energy absorption of the plates and help to mitigate their failure. On the other hand, when polyurea is placed on the front face (load-receiving side), it will magnify the initial shock effect and promote failure. These experimental results are paralleled by numerical simulations of the entire experiment, employing physics-based models for the DH-36 steel and polyurea (Amini et al.,

Numerical modeling of effect of polyurea on response of steel plates to impulsive loads in direct pressure-pulse experiments. *Mech. Mat.*, 42, 615– 627, 2010).

III. SCIENTIFIC AND TECHNICAL PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD

Sia Nemat-Nasser (PI) – MAE Faculty and Director, CEAM
Alireza Vakil Amirkhizi - Asst. Research Scientist

Technical Personnel:

Jon Isaacs – Sr. Development Engineer

Graduate Student Researchers:

Mahmoud R. Amini, PhD

[Degree Conferred Fall 2007, Thesis Titled “Effect of Polyurea on Dynamic response and Fracture Resistance of Steel Plates under Impulsive Loads”]

Ahsan Samiee, PhD. Degree to be conferred in 2010

Undergraduate Student Researchers:

Jeffrey Simon (2006-2007)

IV. PUBLICATIONS

Journal Publications Appearing in Print

Amini, M.R, J. Isaacs and S. Nemat-Nasser, “Experimental Investigation of Response of Monolithic and Bilayer Plates to Impulsive Loads” *J. Impact Engr.*, Vol. 37. No. 1 (2010) 82-89. ONR grant not cited in error.

Amini, M.R, A.V. Amirkhizi and S. Nemat-Nasser, “Numerical Modeling of Response of Monolithic and Bilayer Plates to Impulsive Loads,” *J. Impact Engr.*, Vol. 37. No. 1 (2010) 90-102. ONR grant not cited in error.

Amini, M.R. and S. Nemat-Nasser, “Micromechanisms of Ductile Fracturing of Dh-36 Steel Plates under Impulsive Loads and Influence of Polyurea Reinforcing,” *Intl J. Fracture*, Vol. 162 (2010) 205-217.

Amini, M.R., J. Simon and S. Nemat-Nasser, “Numerical Modeling of Effect of Polyurea on Response of Steel Plates to Impulsive Loads in Direct Pressure-Pulse Experiments,” *Mech. Mat.*, Vol. 42, No. 6 (2010) 615-627. ONR grant not cited in error.

Amini, M.R., J. Isaacs and S. Nemat-Nasser, "Investigation of Effect of Polyurea on Response of Steel Plates to Impulsive Loads in Direct Pressure-Pulse Experiments," *Mech. Mat.*, Vol. 42, No. 6 (2010) 628-639. ONR grant not cited in error.

Non-Referred Publications and Published Technical Reports

Samiee, A., J. Isaacs and S. Nemat-Nasser, "Performance of polymer-steel sandwich structures under blast loads," *Proceedings of Electroactive Polymer Actuators and Devices (EAPAD) 2009, SPIE's 16th Annual International Conference on Smart Structures and Materials*, Vol. 7287 (2009) 72872E1-E5. [Conference Proceeding]

Samiee, A., J. Isaacs and S. Nemat-Nasser, "Ballistic Performance of Polyurea-coated Armor Grade Ceramic Tiles," *Proceedings of Electroactive Polymer Actuators and Devices (EAPAD) 2010, SPIE's 17th Annual International Conference on Smart Structures and Materials*. Vol. 7644 (2010) 76441Y-1-76441Y-7. [Conference Proceeding]

Samiee, A., A.V. Amirkhizi and S. Nemat-Nasser, "Performance of Polymer-steel Bi-layers under Blast," *Proceedings SEM Annual Conference and Exposition on Experimental and Applied Mechanics*, June 7-10, 2010, Indianapolis, IN, ISBN: 978-1-935116-05-9 (2010). [Conference Proceeding]

V. PRESENTATIONS

Nemat-Nasser, S. "Experimentally-based Viscoelastic Constitutive Model for Simulation of Impact response of Polyurea," *9th USNCCM – T. Oden 70th B-day Symposium*, San Francisco, CA, July 2007.

Nemat-Nasser, S., "Experiments and Constitutive Modeling of Three Dimensional Response of Polyurea," *ASME IMECE Annual Conference*, Seattle, WA, Nov. 2007.

Nemat-Nasser, S. "Polyurea: Characterization, Modeling, and Dynamic Performance Evaluation," *Mechanics of Time Dependent Materials Conference*, Monterey CA April, 2008.

Nemat-Nasser, S., "Dynamic Properties of Elastomer-based Nano-structures Composites," *SEM IX International Conference*, Orlando, FL, May-June, 2008.

Nemat-Nasser, S., "Temperature- and Pressure-Dependent Viscoelastic Model for Polyurea and Comparison with Experimental Data," *SEM IX International Conference*, Orlando, FL, May -June, 2008.

Samiee, A., "Performance of Polymer-steel Sandwich Structures under Blast Loads," *Proceedings of Electroactive Polymer Actuators and Devices (EAPAD) 2009, SPIE's 16th Annual International Conference on Smart Structures and Materials*, San Diego, CA, March 2009.

Samiee, A, "Ballistic Performance of Polyurea-coated Armor Grade Ceramic Tiles," *Proceedings of Electroactive Polymer Actuators and Devices (EAPAD) 2010, SPIE's 17th Annual International Conference on Smart Structures and Materials. In-Press, San Diego, CA, March 2010.*

Samiee, A., "Performance of Polymer-steel Sandwich Structures under Impact Loadings", *International Conference on Computational & Experimental Engineering and Sciences, Las Vegas, NV, March 2010.*

Samiee, A., "Performance of Polymer-steel Bi-layers under Blast," *Proceedings SEM Annual Conference and Exposition on Experimental and Applied Mechanics, Indianapolis, IN, June 2010.*

VITAL STATISTICS:

Number of Conferred PhD's: 1

Number of Ph.D. Degrees to be Conferred: 1

Number of Conferred Masters Degrees: 0

Number of Graduate Students: 2

Number of Publications and Reports: 8