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Report Title

Dynamic Compressive Responses and Flow Behavior of Damaged Ceramics under Confinement

ABSTRACT

We developed a novel dynamic loading/reloading experimental technique modified from a split Hopkinson pressure bar (SHPB) to determine the dynamic properties and to record the damage/failure modes in the ceramic specimen, in which a ceramic specimen was loaded by two consecutive stress pulses. The first pulse determines the dynamic response of the intact ceramic material and then crushes the specimen to a desired damage level. The second pulse then determines the dynamic compressive constitutive behavior of the damaged but still interlocked ceramic specimen. The first pulses were slightly varied to control the damage levels in the ceramic specimen while the second pulse was maintained identical. The damage modes in a hot-pressed silicon carbide (SiC-N) specimen have been correlated to its dynamic compressive response at high strain rates. The results show that the compressive strengths of damaged ceramics depend on a critical level of damage, below which the specimen retains its load-bearing capacity and only axial cracks are observed in the specimen. When the specimen is critically damaged, axial cracks and isolated pulverized regions are observed. When the specimen id damaged beyond the critical level, the ceramic specimen is crushed into cracked particles with pulverized (comminuted) materials along the particle boundaries, which displays a granular flow behavior in its stress-strain curve.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Rojas, R. R., and Chen, W., 2003, “Instrumented Low-speed Penetration into Granular Alumina,” Instrumentation, Measurements, and Metrology, vol. 3, No. 3-4, pp. 213-236.

Chen, W. and Luo, H., 2004, “Dynamic Compressive Responses of Intact and Damaged Ceramics from a Single Split Hopkinson Pressure Bar Experiment,” Experimental Mechanics, vol. 44, No. 3, pp. 295-299.

Luo, H. and Chen, W., 2004, “Dynamic Compressive Responses of Intact and Damaged AD995 Alumina,” International Journal of Appied Ceramic Technology, vol. 1, issue 3, pp. 254-260.

Krashanitsa, R. and Shkarayev, S., 2004, “Theoretical Study of the Dynamic Response of Bars Composed of Dissimilar Materials,” Physicochemical Mechanics of Materials, Vol. 40, No. 6, 73-84.

Luo, H., Chen, W., and Rajendran, A. M., 2006, "Dynamic Compressive Response of Damaged and Interlocked SiC-N Ceramics," Journal of The American Ceramic Society, vol. 89 [1], pp. 266-273.

Number of Papers published in peer-reviewed journals: 5.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Chen, W. and Luo, H., 2003, “Dynamic Compressive Testing of Intact and Damaged Ceramics,” 27th Annual Cocoa Beach Conference and Exposition on Advanced Ceramics and Composites, January, 26-31, Cocoa Beach, FL, U.S.A.

Luo, H. and Chen, W., 2004, “Dilatation of AD995 Alumina Impacted by Two Consecutive Stress Pulses during a SHPB Experiment,” Proceedings of the 2004 International Conference on Computational & Experimental Engineering & Sciences, 26-29 July, pp. 69-74.

Luo, H. and Chen, W., 2006, “Damage Modes Correlated to the Dynamic Response of SiC-N,” 30th International Conference and Exposition on Advanced Ceramics and Composites, January, 22-27, Cocoa Beach, FL, U.S.A., 8 pages on CD.

Number of Papers published in non peer-reviewed journals: 3.00

(c) Papers presented at meetings, but not published in conference proceedings (N/A for none)

"Valid Split Hopkinson Pressure Bar Experiments with Ceramic Materials," Ceramic Armor Work Group Meeting, Minneapolis, MN, October 29-30, 2002.

"Determination of Dynamic Behavior of Intact and Crushed AD995 with a Single Experiment," 2nd International Conference on Structural Stability and Dynamics, Singapore, December 16-18, 2002.

"Transformation Toughening of a Calcium Zirconate Matrix by Dicalcium Silicate under Ballistic Impact," 27th Annual Cocoa Beach Conference and Exposition on Advanced Ceramics and Composites, Cocoa Beach, FL,January 26-31, 2003.

"Determining Dynamic Compressive Behavior of Intact and Damaged Ceramics with a Single SHPB Experiment," 16th U.S. Army Symposium on Solid Mechanics, Charleston, SC, May 4-7, 2003.

"The Effect of Radial Inertia on Sample during SHPB Experiments," 2003 SEM Annual Conference and Exposition on Experimental and Applied Mechanics, Society of Experimental Mechanics, June 2-4, Charlotte, NC, 2003.

"Dynamic Compressive Response of Damaged Ceramics," 2003 SEM Annual Conference and Exposition on Experimental and Applied Mechanics, Society of Experimental Mechanics, June 2-4, Charlotte, NC. 2003.

"Theoretical Study of the Dynamic Response of Bars Composed of Dissimilar Materials," Proceedings of 2003 ASME Congress and Symposium on the Dynamic Behavior of Advanced Materials and Structures, ASME International Mechanical Engineering Congress and RD&D Expo, Washington, D.C., November 15-21, 2003.

"The Effect of Radial Inertia on Brittle Samples During the Split Hopkinson Pressure Bar Test," Society for Experimental Mechanics 2004 Annual Meeting on Experimental and Applied Mechanics, Costa Mesa, CA, 7-10 June 2004.

"Identification of Parameters of Constitutive Relations for Ceramics Subjected to Impact Load," ASME International Mechanical Engineering Congress, Anaheim, CA, November 13-19, 2004.

"Pulse Shaping Techniques to Obtain Elastic-Plastic Material Properties with a Split Hopkinson Pressure Bar," Society for Experimental Mechanics 2004 Annual Meeting on Experimental and Applied Mechanics, Costa Mesa, CA, 7-10 June 2004.

"Dynamic Behavior of Bars Composed of Dissimilar Materials," 41st Annual Technical Meeting of the Society of Engineering Science, October 10-13, 2004, Lincoln, NE.

"Dynamic Compressive Response of Damaged Materials," 41st Annual Technical Meeting of the Society of Engineering Science, October 10-13, 2004, Lincoln, NE.

"Pulse Shaping Techniques to Obtain Elastic-Plastic Material Properties with a Split Hopkinson Pressure Bar," ASME 2004 International Mechanical Engineering Congress and Exposition, Anaheim, CA, November 13-19, 2004.

"Dilatation of AD995 Alumina Impacted by Two Consecutive Stress Pulses during a SHPB Experiment," Symposium on Advanced Computational Algorithms for Shock, Impact and Penetration Problems," ICCES'04 International Conference on Computational & Experimental Engineering & Sciences, Madeira, Portugal, 26-29 July 2004 (keynote lecture).

"Computational Study of Dynamic Response and Flow Behavior of Damaged Ceramics," Proceedings of 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Austin, TX, April 18-21, 2005.

"Dynamic Compressive Behaviors of Armor Ceramics Impacted by Consecutive Stress Pulses," Shock Loading Symposium, Plasticity 2005: The Eleventh International Symposium on Plasticity and Its Current Applications, Kauai, Hawaii, 3-9 January 2005 (Keynote lecture).

Number of Papers not Published: 16.00

(d) Manuscripts

Krashanitsa, R., Luo, H., Chen, W., and Shkarayev S. 2006, "Image Processing method for Damage Quantification in Ceramics," Experimental Mechanics, submitted.

Number of Manuscripts: 1.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED	
Raul Rojas	1.00	No
Huiyang Luo	1.00	No
Roman Krashanitsa	1.00	No
FTE Equivalent:	**3.00**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Weinong Chen	0.08	No
Sergey Shkarayev	0.08	No
FTE Equivalent:	**0.16**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Personnel receiving masters degrees

NAME	
Raul Rojas	No
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Huiyang Luo	No
Roman Krashanitsa	No
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

2005 Project Summary – 42710-EG

Dynamic Compressive Responses and Flow Behavior of Damaged Ceramics under High Confinement

PI: Weinong Wayne Chen
Department of Aerospace and Mechanical Engineering
The University of Arizona, Tucson, AZ 85721-0119

Research objectives

During a penetration process through a ceramic armor, the pulverized but still interlocked ceramic is the only material that is in direct contact with the penetrator. However, the mechanical response of this specific ceramic layer to impact loading is unavailable. The objective of this research program is to fill in the urgent needs for valid dynamic properties of damaged but interlocked ceramics by (1) developing a dynamic multiaxial compression technique that can accurately determine the dynamic behavior of such ceramics under valid testing conditions, and (2) performing dynamic experiments on damaged/interlocked armor ceramics at various strain rates and confinement levels, and consequently developing dynamic constitutive models for armor performance simulation and assessment.

Approach

An inter-related experimental and analytical investigation is planned to develop a fundamental understanding and accurate description of the dynamic constitutive and flow behavior of damaged ceramic materials under impact loading conditions. The proposed research will consist of four major tasks: construction of a modified split Hopkinson pressure bar with an integrated high-confinement pressure chamber, experimental determination of the constitutive behavior of damaged ceramics at a variety of damage and confinement levels, analytical modeling of the experimental results with proper damage parameters, and the dynamic flow behavior as a function of resistance to the ceramic ejection.

Significance – Army value

Ceramic tiles are key components in the armor of U.S. Army's Future Combat Systems (FCS) and in the personnel protection systems of Objective Force Warriors (OFW). Upon impact, the ceramic armor that is in direct contact with the impactor will pulverize. This pulverized layer of ceramic significantly affects the impact resistance of the ceramic armor. As pointed out in the "Ceramic Armor Material by Design Symposium" organized by ARL at PAC RIM IV in November 2001, knowledge on the behavior of damaged ceramics is critical to ceramic armor development. The results of this research program will provide qualitative understanding and quantitative experimental data to satisfy the urgent needs of FCS and OFW.

Accomplishments

Our research is mainly focused on the development of novel experimental techniques such that the impact response of damaged ceramics can be determined and understood. During the past year, we used a high-precision, heavy-duty split Hopkinson pressure bar (SHPB) and conducted novel dynamic loading/reloading experiments for obtaining the dynamic compressive responses of intact and damaged silicon carbide armor ceramic in a single experiment. Research effort has been invested to develop the pulse-shaping techniques that are necessary to conduct the experiments under valid dynamic testing conditions, so that the resultant experimental data are valid and accurate.

The research preparation for characterizing the dynamic compressive responses of damaged ceramics under multiaxial compression has made steady progress. The construction for the confining pressure system is near completion. The experimental technique for preserving a damaged but interlocked ceramic sample is being explored.

Technology Transfer

The P.I. has long-term technology transfer activities and collaborations with the U.S. Army Research Laboratory (ARL), Aberdeen Proving Ground, MD. Dr. Tusit Weerasooriya of ARL plans to obtain the experimental technique for loading intact/damaged ceramic samples in a single experiment. The experimental data have been transferred to the Armor/Structure Program at TARDEC and Army HPC Research Center. The P.I. of this program, Dr. Chen, will work at ARL again in the summer of 2005 under a Summer Faculty Program. In addition, a computational group at Sandia National Laboratories, Albuquerque, NM, working on a DoD program has requested and obtained part of our experimental data for simulations.

Journal Publications

Rojas, R. R., and Chen, W., 2003, "Instrumented Low-speed Penetration into Granular Alumina," *Instrumentation, Measurements, and Metrology*, vol. 3, no. 3-4, pp. 213-236.

Chen, W. and Luo, H., 2004, "Dynamic Compressive Responses of Intact and Damaged Ceramics from a Single Split Hopkinson Pressure Bar Experiment," *Experimental Mechanics*, vol. 44, No. 3, pp. 295-299.

Luo, H. and Chen, W., 2004, "Dynamic Compressive Behavior of Intact and Damaged AD995 Ceramic," *International Journal of Applied CeramicTechnology*, vol. 1, issue 3, pp. 254-260.

Krashanitsa, R. and Shkarayev, S., 2004, "Theoretical Study of the Dynamic Response of Bars Composed of Dissimilar Materials," *Physicochemical Mechanics of Materials*, Vol. 40, No. 6, 73-84.

Luo, H., Chen, W., and Rajendran, A. M., 2005, "Dynamic Compressive Response of Damaged and Interlocked SiC-N Ceramics," *Journal of The American Ceramic Society*, vol. 89 [1], pp. 266-273.

Conference presentations

"Valid Split Hopkinson Pressure Bar Experiments with Ceramic Materials," Ceramic Armor Work Group Meeting, Minneapolis, MN, October 29-30, 2002.

"Determination of Dynamic Behavior of Intact and Crushed AD995 with a Single Experiment," 2nd International Conference on Structural Stability and Dynamics, Singapore, December 16-18, 2002.

"Dynamic Compressive Testing of Intact and Damaged Ceramics," Symposium on Topics in Ceramic Armor, 27th Annual Cocoa Beach Conference & Exposition of the American Ceramic Society, Cocoa Beach, FL, January 26-31, 2003.

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"The Effect of Radial Inertia on Brittle Samples During the Split Hopkinson Pressure Bar Test," *Society for Experimental Mechanics 2004 Annual Meeting on Experimental and Applied Mechanics*, Costa Mesa, CA, 7-10 June 2004.

"Identification of Parameters of Constitutive Relations for Ceramics Subjected to Impact Load," *ASME International Mechanical Engineering Congres*s, Anaheim, CA, November 13-19, 2004.

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"Dynamic Compressive Response of Damaged Materials," *41st Annual Technical Meeting of the Society of Engineering Science*, October 10-13, 2004, Lincoln, NE.

"Pulse Shaping Techniques to Obtain Elastic-Plastic Material Properties with a Split Hopkinson Pressure Bar," *ASME 2004 International Mechanical Engineering Congress and Exposition*, Anaheim, CA, November 13-19, 2004.

"Computational Study of Dynamic Response and Flow Behavior of Damaged Ceramics," *Proceedings of 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Austin, TX, April 18-21, 2005.

Honors

The PI was invited to present Keynote Lectures with the results from this research program at these International Conferences:

"Dilatation of AD995 Alumina Impacted by Two Consecutive Stress Pulses during a SHPB Experiment," Symposium on Advanced Computational Algorithms for Shock, Impact and Penetration Problems," ICCES'04 International Conference on Computational & Experimental Engineering & Sciences, Madeira, Portugal, 26-29 July 2004.

"Dynamic Compressive Behaviors of Armor Ceramics Impacted by Consecutive Stress Pulses," Shock Loading Symposium, Plasticity 2005, Kauai, Hawaii, 3-9 January 2005.