REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
19-07-2018	Final Report	15-Apr-2017 - 14-Apr-2018

4. TITLE AND SUBTITLE

Final Report: Acquisition of State-of-the-Art High-Speed Video Camera for Capturing Dynamic Deformation under Impact loads

5a. CONTRACT NUMBER
W911NF-17-1-0192

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611103

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

University of Massachusetts - North Dartmo
285 Old Westport Rd.

North Dartmouth, MA 02747 -2300

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
69992-EG-RIP.3

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Vijaya Chalivendra
					19b. TELEPHONE NUMBER 508-679-6896

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

RPPR Final Report
as of 30-Oct-2018

Agency Code:

Proposal Number: 69992EGRIP **Agreement Number: W911NF-17-1-0192**

INVESTIGATOR(S):

Name: Vijaya Chalivendra
Email: vchalivendra@umassd.edu
Phone Number: 5086796896
Principal: Y

Name: Yong Ku Kim ykim@umass
Email: Ykim@umassd.edu
Phone Number: 5089957242
Principal: N

Organization: **University of Massachusetts - North Dartmouth**
Address: 285 Old Westport Rd., North Dartmouth, MA 027472300
Country: USA
DUNS Number: 799477427 EIN: 043167352

Report Date: 14-Jul-2018 Date Received: 19-Jul-2018
Final Report for Period Beginning 15-Apr-2017 and Ending 14-Apr-2018
Title: Acquisition of State-of-the-Art High-Speed Video Camera for Capturing Dynamic Deformation under Impact loads
Begin Performance Period: 15-Apr-2017 **End Performance Period:** 14-Apr-2018
Report Term: 0-Other

Submitted By: Vijaya Chalivendra Email: vchalivendra@umassd.edu
Phone: (508) 679-6896

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0 **STEM Participants:** 0

Major Goals: 1. Use high-speed video camera along with linear impactor instrumented with high-end accelerometers to investigate the deflection of military helmets mounted on a magnesium head under impact loads. Use the deformation information to verify the numerical models to be developed in coming years.
2. Utilize split Hopkinson pressure bar technique along with high-speed video camera to investigate the damage in both compression and indirect tension at both medium and high strain rates.
3. Employ modified Hopkinson pressure bar system along with high-speed video camera to investigate the crack initiation and propagation in laminated composites reinforced with short flocked fibers along through thickness direction.

Accomplishments: 1. Dynamic fracture of laminated composites reinforced with short fibers along the thickness direction: Experiments were conducted to investigate the crack dynamics of laminated composites. Currently working on capturing electro-mechanical response along with high speed imaging to correlate crack propagation due to damage to in-situ change in electrical resistance.

2.Dynamic deformation studies of novel energy absorbing materials for military helmets: Fiber based novel layered materials to be used in military helmet pads are investigated for deformation and constitutive response under impact loading conditions using split Hokinson pressure bar along with acquired high-speed video camera.

3. Impact loading of military helmets with novel padding materials for mitigating traumatic brain injuries: Novel padding materials for army helmet is currently investigated for their performance against rotational loading conditions. Experiments were performed to understand the deflection and angular acceleration of helmets for various positions of the helmets.

Training Opportunities: One graduate student was trained on the acquired high-speed video camera.

Results Dissemination: Rabbi, M.F., Chalivendra, V.B. and Li, D. Dynamic Fracture Characterization of 3D printed materials, SEM Annual Conference & Exposition, Greenville, SC, June 4-7, 2018.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: PI is currently collaborating with Dr. Asha Hall, Dr. Haile Mulugeta, and Dr. Latha Narajan from Army Research Laboratory, Aberdeen Proving Ground, Maryland on a cooperative agreement (W911NF-17-2-0198).

PARTICIPANTS:

Participant Type: PD/PI
Participant: Vijaya B Chalivendra
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co PD/PI
Participant: Yong k Kim
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 5-Submitted
Conference Name: 2018 SEM Annual Conference and Exposition on Experimental and Applied Mechanics
Date Received: 26-May-2018 Conference Date: 04-Jun-2018 Date Published:
Conference Location: Greenville, SC, USA
Paper Title: Dynamic Fracture Characterization of 3D printed materials
Authors: Md Fazlay Rabbi, Dapeng Li, Vijaya Chalivendra
Acknowledged Federal Support: **Y**

Final Report for DURIP Grant (W911NF-17-1-0192)
Attention: Dr. Ralph A. Anthenien Jr.
Program Manager, Propulsion & Energetics
Chief, Mechanical Sciences Division
U.S. Army Research Office

Acquisition of State-of-the-Art High-Speed Video Camera for Capturing Dynamic Deformation under Impact loads

<u>Technical Point of Contact and Principal Investigator</u>

Vijaya B. Chalivendra
Professor, Mechanical Engineering Department,
University of Massachusetts, North Dartmouth, MA 02747
Phone: 508-910-6572, Fax: 508-999-881, E-mail: vchalivendra@umassd.edu

Objective

In the proposed project, acquired high-speed video camera is to investigate the real-time deformation of military helmet pads, damage evolution of composite materials and crack dynamics of composite materials under impact loading conditions. The unanswered questions of this research are: (i) Is the deformation of novel flocked (through thickness reinforced) energy absorbing materials (FEAM) based padding materials heterogeneous?, (ii) What are the damage initiation mechanisms in flocked composite materials under dynamic loads?, (iii) What are crack-tip velocities and acceleration (if any) in the flocked composites under dynamic loading conditions?, and (iv) How is the real-time deflection of head equipped with military helmets under impact loads?

Approach

- Use high-speed video camera along with linear impactor instrumented with high-end accelerometers to investigate the deflection of military helmets mounted on a magnesium head under impact loads. Use the deformation information to verify the numerical models to be developed in coming years.
- Utilize split Hopkinson pressure bar technique along with high-speed video camera to investigate the damage in both compression and indirect tension at both medium and high strain rates.
- Employ modified Hopkinson pressure bar system along with high-speed video camera to investigate the crack initiation and propagation in laminated composites reinforced with short flocked fibers along through thickness direction.

Equipment Procured

The acquired instrument through this DURIP grant is Shimadzu Hyper Vision HPV-X2, which is the state-of-the-art high speed video camera with high end specifications such as 10 million frames per second, 100,000 pixels resolution (400 horizontal × 250 vertical), with maximum 256 frames, and with exposure time as low as 10ns. The image of the high-speed video camera is shown in **Figure 1**. Along with this camera, a control unit, a set of focusing lens, a white LED light source, and a tripod are also included. The has a warranty period of 1 year.

Figure 1: Image of High-speed video camera acquired through DURIP grant

Relevance to Army

Proper understanding of real-time deformation of padding materials will help to design military helmets to withstand both linear and angular accelerations. Currently used military helmet pads use foam materials and they do excellent job in mitigating the effect of linear acceleration. However, FEAM based padding materials can withstand both linear and angular acceleration due to the fact that flocked fibers in FEAM can buckle as well as promote frictional dissipation energy during contact between two neighboring flocked fibers under rotational load.

Through thickness reinforced laminated composites offer superior fracture toughness due to crack bridging and hence can used as damage resistant materials for army structures and for body armor applications.

Accomplishments for Reporting Period

1. Dynamic fracture of laminated composites reinforced with short fibers along the thickness direction: This project is sponsored as a cooperation agreement (W911NF-17-2-0198) with Army Research Laboratory, Aberdeen Proving Ground, Maryland. For dynamic fracture characterization of glass fiber/epoxy composites, a modified split Hopkinson pressure bar consisting of a striker bar and a solid incident bar made of margining steel is used to load a three point bend specimen (as shown **Figure 2**).

Figure 2: Experimental set up that shows the position of high speed video camera and light source with respect to specimen under dynamic loading conditions

A copper pulse shaper with 1.2 mm is used for obtaining dynamic force equilibrium. When the sticker bar impacts the incident bar, a compressive pulse, known as incident pulse was generated which traveled through the incident bar to bar specimen interface. After reaching the specimen, incident pulse transmitted to the specimen and loaded the crack tip. A high speed camera HPVX with 10,000,000 frames/second was used to observe the real time crack initiation and propagation. Picture of the actual test setup is shown in **Figure 2**. Using one dimensional wave theory, the force applied on specimen can be obtained according to the following equation (1)

$$F(t) = AE[\varepsilon_i(t) + \varepsilon_r(t)] \quad (1)$$

By using beam theory, general expression for mode-I and mode-II can be expressed as:

$$G_I = \frac{1}{4}\frac{F^2(a+h)^2}{BEI} \tag{2}$$

$$G_{II} = \frac{3}{16}\frac{F^2(a+h)^2}{BEI} \tag{3}$$

The dimensions of glass fiber/epoxy specimen used in this study are 76.2 mm length, 25.4 mm in width and 4.5 mm in thickness. During the fabrication process, a pre crack was created by inserting a 25.4 mm long scotch tape into mid thickness from the opening edge. After the curing, a diamond blade saw was used to take out a 15.24mm long strip from the upper half section to make a mixed mode opening notch flexure (MONF) specimen.

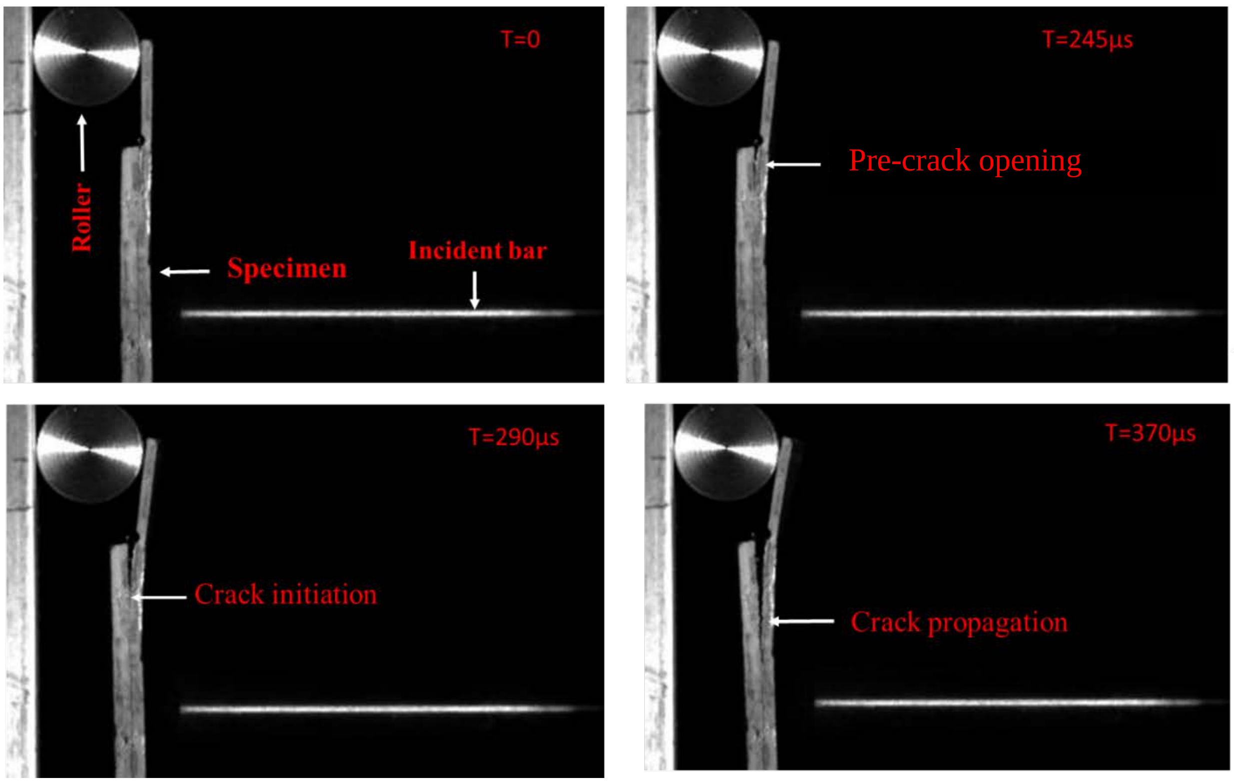

Figure 3: Real time imaging of dynamic fracture of glass fiber reinforced composite test specimen

The preliminary set of dynamic fracture experiments were conducted using high-speed imaging as shown in **Figure 3**. It is shown from the figure that, pre crack started to open at 245µs after the impact, took around 45µs to open the crack from pre-crack tip and then propagated along the mid plane thickness. We plan to include electrical response along high-speed imaging in composites embedded with CNTs and reinforced with short carbon fiber between the laminates to investigate the damage evolution under impact loads.

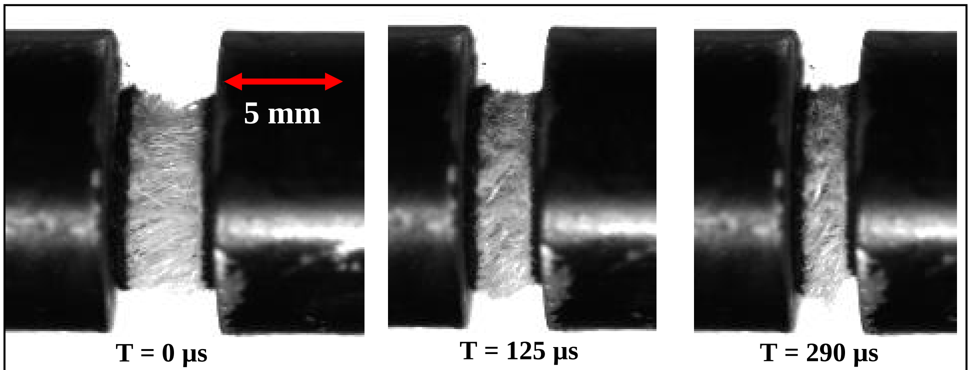

Figure 4. High-speed imaging of a FEAM layer under impact loads using SHPB experimental setup

2. Dynamic deformation studies of novel energy absorbing materials for military helmets:

PIs research group is interested in developing novel padding materials for military helmets to mitigate traumatic brain injuries of combating soldiers when they were subjected to blast loading conditions. To this effect, we are using novel fiber based energy absorbing materials against the foam based materials currently in use. To understand the impact response of these novel materials, we tested compressive response of single layer of fiber based energy absorbing materials using split Hopkinson pressure bar system along with high-speed video camera acquired through this grant.

Figure 4 shows the deformation of fiber based energy absorbing material undergoing compression shown at T= 125 µs and under shear deformation at T= 290 µs. The images were taken with a 200,000 frames/second framing rate at an exposure time of 1 µs. The sudden shift in deformation shape in the flock fibers from impact compression to shear loading conditions is clearly demonstrated. It appears that the inter-fiber friction mode of impact energy absorption (IEA) is the prominent mechanism of these novel materials.

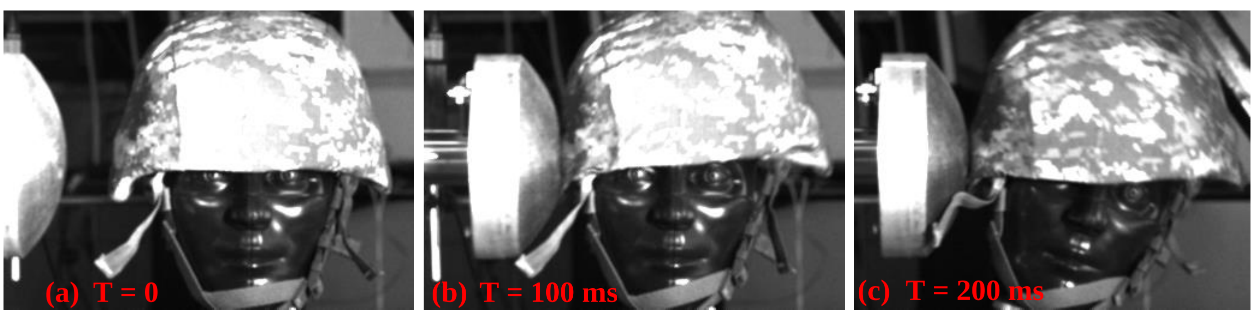

Figure 5: Real-time imaging military helmet under impact with high-speed camera at 500 frames/second

3. Impact loading of military helmets with novel padding materials for mitigating traumatic brain injuries: A custom designed linear impactor is used to create well-controlled impact conditions on military helmets. **Figure 5** shows the real-time images of military helmet under impact with high-speed camera at a framing rate of 50 frames/second. We plan to use novel fiber based padding materials that can withstand shear deformation under inclined impacts at various angles. We are currently pursuing experimental studies to generate preliminary data to submit full proposal to Army Research Office.

Collaborations and Technology Transfer

PI is currently collaborating with Dr. Asha Hall, Dr. Haile Mulugeta, and Dr. Latha Narajan from Army Research Laboratory, Aberdeen Proving Ground, Maryland on a cooperative agreement (W911NF-17-2-0198).

Resulting Journal Publications during Reporting Period

None, but the manuscripts are in preparation for submission in summer 2018.

Graduate Students Involved During Reporting Period

None, because no personnel was funded from this DURIP grant.

Awards, Honors and Appointments

None