AFRL-AFOSR-UK-TR-2020-0009

Damage tolerant mechanisms of natural biomaterials for design of novel engineered bio-inspired composites

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04/30/2020
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
Air Force Office of Scientific Research
European Office of Aerospace Research and Development
Unit 4515 Box 14, APO AE 09421

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
30-04-2020

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
01 Apr 2017 to 30 Sep 2018

4. TITLE AND SUBTITLE
Damage tolerant mechanisms of natural biomaterials for design of novel engineered bio-inspired composites

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-17-1-0214

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Katherine Brown

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
THE CHANCELLOR, MASTER AND SCHOLARS OF THE UNIVERISTY OF CAMBRIDGE
THE OLD SCHOOLS
CAMBRIDGE, CB2 1TN GB

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
EOARD
Unit 4515
APO AE 09421-4515

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR IOE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-UK-TR-2020-0009

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This one-year grant is complete and the final report received. This project was built on research undertaken by the Brown group at the University of Cambridge that involved understanding how soft biological materials respond to mechanical damage. This work required the development of experimental techniques different than the ones typically used for hard synthetic materials. The key focus of this project was the retrofitting of a split-Hopkinson pressure bar for use with soft materials. The Tensile Hopkinson Bar system has been entirely retrofitted to an easier-to-use, more modular configuration. The gas gun now sits on a steel rail system to which multiple ring mounts can be clamped. The mobility of the mounts facilitates testing of samples with a wide range of geometries with varied gripping methods. Tests with plastics including polyethylene were conducted. Due to attendant changes in the opacity of the samples under testing, these experiments were visualized with high-speed videography to assess changes to the strain states of the samples, which can be coupled to information from the strain gauges present on the bars. Signals from the samples could be detected and differentiated from artefacts caused by the grips. A follow-on grant (FA9550-19-1-7006) was awarded to continue the work.

15. SUBJECT TERMS
biomaterials, damage tolerance, soft materials, split hopkinson pressure bar, bio-inspired composites

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			GIMM, JUNG-HWA
Unclassified	Unclassified	Unclassified	SAR		19b. TELEPHONE NUMBER *(Include area code)* 703-696-9542

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

Damage tolerant mechanisms of natural biomaterials for design of novel engineered bio-inspired composites

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Need: Many natural lightweight biomaterials such as scales, horn, and skin are composed of layers of different structures that work together to impart properties such as strength, toughness and/or tear resistance. The purpose of this project is to understand how the molecular structures that make up these layered biomaterials contribute to damage-tolerant properties. In this project, experimental platforms traditionally used to study dynamic mechanical responses of hard materials such as metals will be adapted to study these properties of soft materials at a variety of length-scales. Studies of mechanical properties will be complemented by imaging studies including high-speed photography, optical and electron microscopy, and helium ion microscopy. Molecular components and their structural organizations that play roles in damage tolerance will be identified and used in collaborative modeling studies to design new artificial materials with similar mechanical properties.

Introduction: This project is built on research undertaken by the Brown group at the University of Cambridge that involves understanding how soft biological materials respond to mechanical damage [1-9]. The overall aim of this project is to design bio-inspired materials that are lightweight and tough. Evaluation of impact-resistant and damage-resistant structures requires dynamic testing, including testing with Hopkinson bars, drop weight towers, gas guns, and explosive devices. The Cavendish Laboratory (Physics Department) at Cambridge University has led research in this field and recently, this project expands the focus to include biological materials. This work has required the development of experimental techniques that are different than the ones typically used for hard synthetic materials. This work has been funded by the UK Royal British Legion through the Centre for Blast Injury Studies (CBIS) at Imperial College. Dr. Brown has benefited from a close collaboration with researchers in the Department of Veterinary Medicine at the University of Cambridge, where natural biomaterials can be sourced and imaged, and the Centre for Blast Injury Studies (CBIS) at Imperial College London, where a complementary compression and tensile Hopkinson bars are available for testing materials. Natural composites, such as shell and skin, display wide-ranging and impressive properties that bridge the gap between toughness and stiffness [6]. This project utilizes biophysical expertise in the Brown group to develop complementary experimental studies on the dynamic responses of natural biomaterials in damage-inducing conditions. The key focus of this project was the retrofitting of a split-Hopkinson pressure for use with soft materials.

Tensile Hopkinson Bar Retrofitting:

The Tensile Hopkinson Bar system has been entirely retrofitted (see Figure 1) to an easier-to-use, more modular state. The gas gun now sits on a steel rail system to which multiple ring mounts can be clamped. The mobility of the mounts facilitates testing of samples with a wide range of geometries with varied gripping methods. The system is currently equipped with a set of titanium bars, selected with the testing of metal samples in mind. A set of titanium grips with threaded mounts have been machined together with associated clamps (see Figure 2).

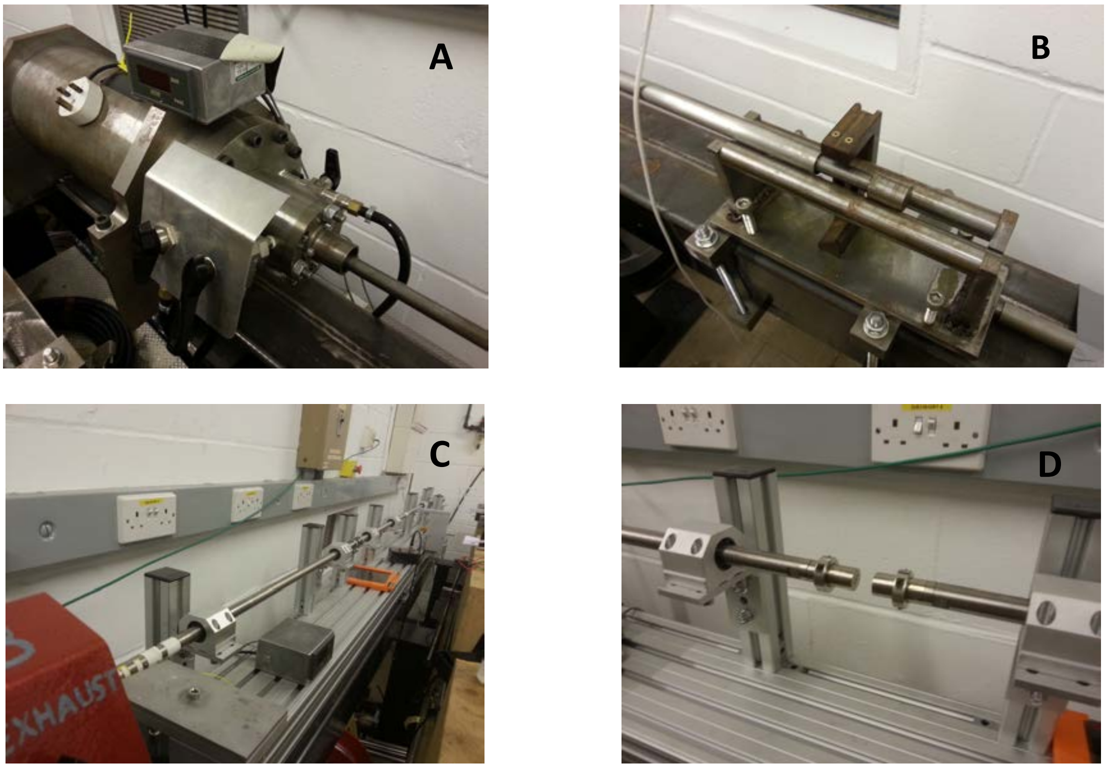

Figure 1: A) Previous gas gun setup. B) Previous sample mount. C) New modular rail system. D) Multipart grips with added clamps designed for biological samples.

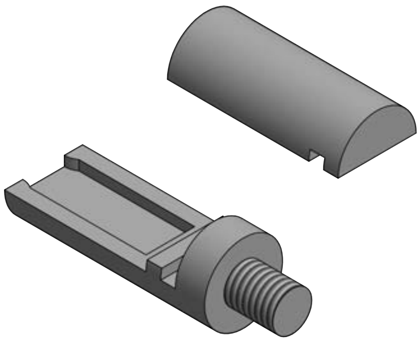

Figure 2: Schematic of the designed grips for biomaterials. A dogbone-shaped sample sits in the recess of the base and is held in place by the head of the grips and an additional circular clamp present in Figure 1 D).

Initial tests with plastics including polyethylene have been conducted. Due to attendant changes in the opacity of the samples under testing, these experiments were visualised with high-speed videography to assess changes to the strain states of the samples which can be coupled to information from the strain gauges present on the bars (see Figure 3). Signals from the samples could be detected and differentiated from artefacts caused by the grips.

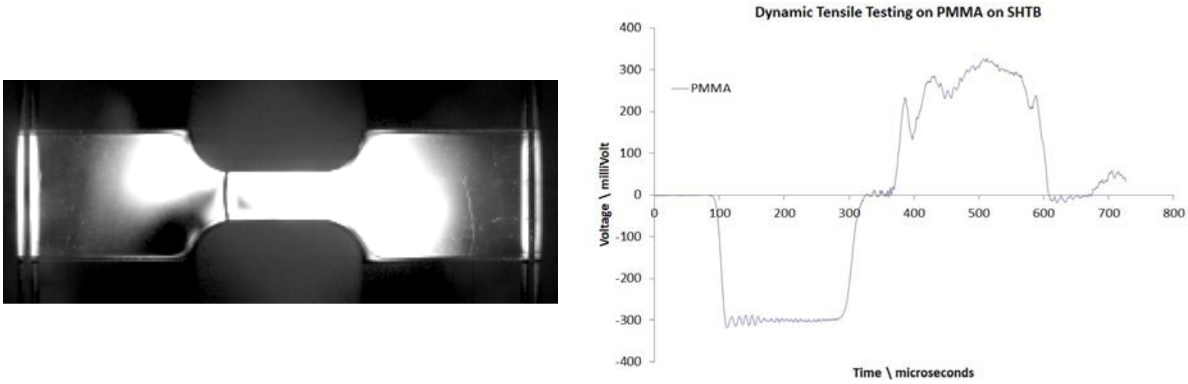

Figure 3 A) & B): A) Image of the fracture of a sample of Polymethyl methacrylate (PMMA) under tension. High speed videography highlights the point at which the sample fractures, 134 µs into this particular test. B) Raw data from the same test on the Split Hopkinson Tensile Bar (SHTB). The 'top-hat' pulse profile, typical of Split Hopkinson Bar tests can be observed. The difference between the input pulse (negative voltage) and the reflected pulse (positive voltage) carries sample information.

Future studies:

Our future work will focus to two key aims:

Aim 1 Develop and optimize tension split-Hopkinson bar systems (SHPBs) for soft material studies. This aim will include the establishment of Digital Image Cross Correlation techniques to determine

(a) the pre-failure localization of stress/strain in samples and;
(b) the limits associated with the onset of failure.

Aim 2 Initiate studies of the responses of natural biomaterials under quasi-static and dynamic conditions in tension and compression. This aim includes the production of baseline measurements against known engineering materials of similar mechanical impedance to the soft biological materials of interest, and the redesign of low-noise, gripping systems suitable for a range of soft materials with varying shapes and tensile properties.

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