REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
14-11-2018	Final Report	1-Jan-2015 - 30-Jun-2018

4. TITLE AND SUBTITLE
Final Report: Shock Mitigation With Ordered Microscale Granular Media

5a. CONTRACT NUMBER
W911NF-15-1-0030

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Washington
Office of Sponsored Programs
4333 Brooklyn Ave NE Box 359472
Seattle, WA 98195 -9472

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)
65959-MS-YIP.11

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:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Nicholas Boechler
UU	UU	UU	UU		19b. TELEPHONE NUMBER
					206-221-6515

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

RPPR Final Report
as of 25-Jun-2020

Agency Code:

Proposal Number: 65959MSYIP | **Agreement Number: W911NF-15-1-0030**

INVESTIGATOR(S):

Name: Ph.D Nicholas Boechler
Email: boechler@uw.edu
Phone Number: 2062216515
Principal: Y

Organization: **University of Washington**
Address: Office of Sponsored Programs, Seattle, WA 981959472
Country: USA
DUNS Number: 605799469 EIN: 916001537

Report Date: 30-Sep-2018 Date Received: 14-Nov-2018
Final Report for Period Beginning 01-Jan-2015 and Ending 30-Jun-2018

Title: Shock Mitigation With Ordered Microscale Granular Media

Begin Performance Period: 01-Jan-2015 **End Performance Period:** 30-Jun-2018
Report Term: 0-Other

Submitted By: Ph.D Nicholas Boechler Email: boechler@uw.edu
Phone: (206) 221-6515

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

STEM Degrees: 1 **STEM Participants:** 2

Major Goals: The objective of this ARO Young Investigator Program proposal is to utilize a combined theoretical, computational, and experimental approach to study high strain rate shock wave propagation in, and the resulting failure of, self-assembled, three-dimensional ordered micro- to nanoscale (100 um to 100 nm) granular media. This combined approach includes nonlinear contact mechanics-based analytical models, discrete element model simulations, and experimental ultrafast photoacoustic pump-probe techniques. While granular materials are known to be highly effective at absorbing shocks from blast and impact, because of the material complexity, many fundamental questions remain open regarding the mechanisms that lead to their shock absorption properties and ultimate failure. This is in part because previous studies have focused on highly complex disordered granular materials (macro- and microscales) or ordered macroscale granular media (which do not take into account critical effects such as the role of interparticle adhesive forces). The proposed approach of simplifying the problem via ordered granular media, while maintaining relevance via micro- to nanoscale grains, is a dramatic shift from previous approaches that will lead to a birth of understanding of the dynamics of granular media and transform the way granular media is studied.

The three major tasks for the project are:

1. Characterize highly nonlinear shock velocities in 3D ordered microscale granular materials.
2. Characterize the decay rate of highly nonlinear shocks in 3D ordered microscale granular materials.
3. Study spall and blast crater failure mechanisms in 3D ordered microscale granular materials.

Accomplishments: Pdf document uploaded.

Training Opportunities: Multiple training opportunities were conducted during the duration of this grant. Graduate students Morgan Hiraiwa and Samuel Wallen met weekly with the PI to discuss research progress. In addition, the students in the group present their findings, on a rotating schedule, in group meetings held every two weeks. In the group meetings the students have an opportunity to work on their scientific communication skills. The graduate students supported by this project authored multiple peer-reviewed journal articles, as listed in the products section of the report.

The graduate students also presented their work at multiple research conferences. Graduate student Morgan Hiraiwa presented his findings at: the ASME 2015 Applied Mechanics and Materials Conference in Seattle, WA; the Materials Research Society (MRS) Fall Meeting 2015, Symposium II: Phonon Transport, Interactions and Manipulations in Nanoscale Materials and Devices-Fundamentals and Applications in Boston, MA; and the ASME 2016 International Mechanical Engineering Congress and Exposition in Phoenix, AZ. Graduate student Samuel Wallen presented his findings at: the ASME 2015 Applied Mechanics and Materials Conference in Seattle, WA; and the 172nd Meeting of the Acoustical Society of America (The 5th Joint meeting of the Acoustical Society of America and the Acoustical Society of Japan) in Honolulu, HI.

Samuel Wallen also successfully defended his thesis entitled "Analytical and Computational Modeling of Mechanical Waves in Microscale Granular Crystals: Nonlinear and Rotational Dynamics" in May 2017, and received his PhD degree in June 2017.

Results Dissemination: The research was disseminated through multiple journal publications as detailed in the Products section of the report. In addition, the following conference presentations were given:

1. PI Boechler as presenter:

Seminar:
- University of Washington, Nanoscience and Molecular Engineering Seminar (5/2015)
- Universite du Maine, LAUM Seminar (10/2015)
- University of California, San Diego, Department of Mechanical and Aerospace Engineering (2/2017)
- Boeing Propulsion Product Development team, Harbor Pointe Technical Center (2/2017)
- Lawrence Livermore National Laboratories (5/2017)
- University of Washington, Nanoscience and Molecular Engineering Seminar (5/2017)

Poster presentations:
- Wallen, S. P., Maznev, A. A., and Boechler, N., Phononics 2015: 3rd International Conference on Phononic Crystals/Metamaterials, Phonon Transport, and Phonon Coupling, pp. 378-379, France (6/2015)
- Boechler, N., Gordon's Research Conference on Multifunctional Materials and Structures, Ventura, CA (2/2016)
- Boechler, N., Gordon's Research Conference on Granular Matter, Easton, MA (7/2016)

Workshop presentations:
- Boechler, N., Biannual Purdue Energetic Materials Summit (PEMS), West Lafayette, IN (5/2017)
- Boechler, N., DENORMS (Designs for Noise Reducing Materilas and Structures) Training School 3, Le Mans University, Le Mans, France (12/2017)

Invited conference presentations:
- Boechler, N., MRS Spring Meeting & Exhibit, Symposium H---Mechanics of Energy Storage and Conversion—Batteries, Thermoelectrics and Fuel Cells, San Francisco, CA (4/2015)
- Boechler, N., SIAM Conference on Applications of Dynamical Systems, Snowbird, UT (5/2015)
- Hiraiwa, M., Khanolkar, A., Eliason, J. K., Wallen, S., Jenks, J., Abi Ghanem, M., Maznev, A. A., Nelson, K. A., and Boechler, N., Phononics 2015: 3rd International Conference on Phononic Crystals/Metamaterials, Phonon Transport, and Phonon Coupling, pp. 300-301, Paris, France (6/2015)
- Boechler, N., International Symposium of Optomechatronics Technology (ISOT), Neuchatel, Switzerland (10/2015)
- Boechler, N., SIAM Conference on Mathematical Aspects of Materials Science, Philadelphia, PA (5/2016)
- Boechler, N., Euromech Colloquium 580 on Strongly Nonlinear Dynamics and Acoustics of Granular Metamaterials, INRIA, Grenoble, France (7/2016)
- Boechler, N., ICTAM2016, 24th International Congress of Theoretical and Applied Mechanics, Contributions to the Foundations of Multidisciplinary Research in Mechanics, pp. 2324-2325, Montreal, Canada (8/2016)
- Boechler, N., Acoustics '17 Boston: The 3rd Joint Meeting of the Acoustical Society of America and the European Acoustics Association, J. Acoust. Soc. Am., Vol. 141, pp. 3734, Boston, MA (6/2017)
- Boechler, N., 2017 International Congress on Ultrasonics, Abstract Book, pp. 65, Honolulu, HI (12/2017)

2. Graduate student Samuel Wallen as presenter:

Conference presentations:
- Wallen, S., Maznev, A. A., and Boechler, N., ASME 2015 Applied Mechanics and Materials Conference, Seattle, WA (7/2015)
- Wallen, S. and Boechler, N., 172nd Meeting of the Acoustical Society of America (The 5th Joint meeting of the Acoustical Society of America and the Acoustical Society of Japan), Honolulu, HI (11/2016)

3. Graduate student Morgan Hiraiwa as presenter:

Conference presentations:
- Hiraiwa, M. and Boechler, N., ASME 2015 Applied Mechanics and Materials Conference, Seattle, WA (7/2015)
- Hiraiwa, M., Khanolkar, A., Wallen, S., Abi Ghanem, M., Eliason, J. K., Vega-Flick, A., Maznev, A. A., Nelson, K. A., and Boechler, N., Materials Research Society (MRS) Fall Meeting 2015, Symposium II: Phonon Transport, Interactions and Manipulations in Nanoscale Materials and Devices-Fundamentals and Applications, Boston, MA

(12/2015)
- Hiraiwa, M. and Boechler, N., ASME 2016 International Mechanical Engineering Congress and Exposition, Phoenix, AZ (11/2016)

Honors and Awards: - PI Boechler received the Young Investigator Program Award in 2016 from the Air Force Office for Scientific Research.
- PI Boechler was elected as Member of the Technical Committee on Vibration and Sound (TCVS), 2016-2019, American Society of Mechanical Engineers
- PI Boechler received the ICU Early Career Award (the “Silver Whistle Award”), 2017, International Congress on Ultrasonics, Honolulu, HI, USA
- Graduate student Samuel Wallen won the student-voted "outstanding teaching assistant award" in the University of Washington Mechanical Engineering Department for the 2016-2017 academic year.

Protocol Activity Status:

Technology Transfer: PI Boechler visited the Army Research Laboratory in July 2015, and presented a talk entitled: "Shock propagation in highly nonlinear microstructured materials: characterization and optimal design".

PARTICIPANTS:

Participant Type: PD/PI
Participant: Nicholas Boechler
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Morgan Hiraiwa
Person Months Worked: 14.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Samuel Wallen
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Phys. Rev. B
Publication Identifier Type: Other Publication Identifier:
Volume: 92 Issue: First Page #: 174303
Date Submitted: 8/31/17 12:00AM Date Published: 11/14/16 12:00AM
Publication Location:
Article Title: Dynamics of a Monolayer of Microspheres on an Elastic Substrate
Authors: S. P. Wallen, A. A. Maznev, and N. Boechler
Keywords: Granular media, self-assembly, dynamics, surface acoustic waves, microspheres, contact mechanics
Abstract: We present a model for wave propagation in a monolayer of spheres on an elastic substrate. The model, which considers sagittally polarized waves, includes: horizontal, vertical, and rotational degrees of freedom; normal and shear coupling between the spheres and substrate, as well as between adjacent spheres; and the effects of wave propagation in the elastic substrate. For a monolayer of interacting spheres, we find three contact resonances, whose frequencies are given by simple closed-form expressions. For a monolayer of isolated spheres, only two resonances are present. The contact resonances couple to surface acoustic waves in the substrate, leading to mode hybridization and ``avoided crossing'' phenomena. We present dispersion curves for a monolayer of silica microspheres on a silica substrate, assuming adhesive, Hertzian interactions, and compare calculations using an effective medium approximation to a discrete model of a monolayer on a rigid substrate. While the effective mediu
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.116.198001
Volume: 116 Issue: First Page #: 198001
Date Submitted: 8/30/16 12:00AM Date Published: 5/1/16 2:00PM
Publication Location:
Article Title: Complex Contact-Based Dynamics of Microsphere Monolayers Revealed by Resonant Attenuation of Surface Acoustic Waves
Authors: M. Hiraiwa, M. Abi Ghanem, S. P. Wallen, A. Khanolkar, A. A. Maznev, N. Boechler
Keywords: Granular media, self-assembly, laser ultrasonics, dynamics, surface acoustic waves, microspheres, contact mechanics
Abstract: We present a model for wave propagation in a monolayer of spheres on an elastic substrate. The model, which considers sagittally polarized waves, includes: horizontal, vertical, and rotational degrees of freedom; normal and shear coupling between the spheres and substrate, as well as between adjacent spheres; and the effects of wave propagation in the elastic substrate. For a monolayer of interacting spheres, we find three contact resonances, whose frequencies are given by simple closed-form expressions. For a monolayer of isolated spheres, only two resonances are present. The contact resonances couple to surface acoustic waves in the substrate, leading to mode hybridization and “avoided crossing” phenomena. We present dispersion curves for a monolayer of silica microspheres on a silica substrate, assuming adhesive Hertzian interactions, and compare calculations using an effective medium approximation (including elasticity of the substrate) to a discrete model of a monolayer on a rigid
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Langmuir
Publication Identifier Type: DOI Publication Identifier: 10.1021/acs.langmuir.6b00982
Volume: 32 Issue: 31 First Page #: 7730
Date Submitted: 8/30/16 12:00AM Date Published: 8/1/16 7:00AM
Publication Location:
Article Title: Laser-Induced Spallation of Microsphere Monolayers
Authors: Morgan Hiraiwa, Melicent Stossel, Amey Khanolkar, Junlan Wang, Nicholas Boechler
Keywords: Granular media, self-assembly, laser ultrasonics, dynamics, spall, microspheres, contact mechanics
Abstract: The detachment of a semi-ordered monolayer of polystyrene microspheres adhered to an aluminum-coated glass substrate is studied using a laser-induced spallation technique. The microsphere?substrate adhesion force is estimated from substrate surface displacement measurements obtained using optical interferometry, and a rigid-body model that accounts for the inertia of the microspheres. The estimated adhesion force is compared with estimates obtained using an adhesive contact model together with interferometric measurements of the out-of-plane microsphere contact resonance, and with estimated work of adhesion values for the polystyrene?aluminum interface. Scanning electron microscope images of detached monolayer regions reveal a unique morphology, namely, partially detached monolayer flakes composed of single hexagonal close packed crystalline domains. This work contributes to the fields of microsphere adhesion and contact dynamics, and demonstrates a unique monolayer delamination morpho
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review E
Publication Identifier Type: DOI Publication Identifier: https://doi.org/10.1103/PhysRevE.95.022904
Volume: 95 Issue: First Page #: 022904
Date Submitted: 8/31/17 12:00AM Date Published: 2/22/17 8:09PM
Publication Location:
Article Title: Discrete Breathers in a Mass-in-Mass Chain with Hertzian Local Resonators
Authors: S. P. Wallen, J. Lee, D. Mei, C. Chong, P. G. Kevrekidis, and N. Boechler
Keywords: Granular media, nonlinear dynamics, discrete breathers, microspheres, localized modes
Abstract: We report on the existence of discrete breathers in a one-dimensional, mass-in-mass chain with linear intersite coupling and nonlinear, precompressed Hertzian local resonators, which is motivated by recent studies of the dynamics of microspheres adhered to elastic substrates. After predicting theoretically the existence of the discrete breathers in the continuum and anticontinuum limits of intersite coupling, we use numerical continuation to compute a family of breathers interpolating between the two regimes in a finite chain, where the displacement profiles of the breathers are localized around one or two lattice sites. We then analyze the frequency-amplitude dependence of the breathers by performing numerical continuation on a linear eigenmode (vanishing amplitude) solution of the system near the upper band gap edge. Finally, we use direct numerical integration of the equations of motion to demonstrate the formation and evolution of the identified localized modes in energy-conserving
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of Applied Physics
Publication Identifier Type: DOI Publication Identifier: http://dx.doi.org/10.1063/1.4963827
Volume: 120 Issue: First Page #: 135107
Date Submitted: 8/31/17 12:00AM Date Published: 10/7/16 7:15PM
Publication Location:
Article Title: Spatial Laplace transform for complex wavenumber recovery and its application to the analysis of attenuation in acoustic systems
Authors: A. Geslain, S. Raetz, M. Hiraiwa, M. Abi Ghanem, S. P. Wallen, A. Khanolkar, N. Boechler, J. Laurent, C
Keywords: Complex wavenumber, granular media, self-assembly, laser ultrasonics, dynamics, surface acoustic waves, microspheres, contact mechanics
Abstract: We present a method for the recovery of complex wavenumber information via spatial Laplace transforms of spatiotemporal wave propagation measurements. The method aids in the analysis of acoustic attenuation phenomena and was applied in three different scenarios: (i) Lamb-like modes in air-saturated porous materials in the low kHz regime, where the method enables the recovery of viscoelastic parameters, (ii) Lamb modes in a Duralumin plate in the MHz regime, where the method demonstrates the effect of leakage on the splitting of the forward S1 and backward S2 modes around the Zero-Group Velocity point, and (iii) surface acoustic waves in a two-dimensional microscale granular crystal adhered to a substrate near 100 MHz, where the method reveals the complex wavenumbers for an out-of-plane translational and two in-plane translational-rotational resonances. This method provides physical insight into each system and serves as a unique tool for analyzing spatiotemporal measurements of p
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Wave Motion
Publication Identifier Type: DOI Publication Identifier: https://doi.org/10.1016/j.wavemoti.2016.08.0
Volume: 68 Issue: First Page #: 22
Date Submitted: 8/31/17 12:00AM Date Published: 8/25/16 9:26AM
Publication Location:
Article Title: Shear to longitudinal mode conversion via second harmonic generation in a two-dimensional microscale granular crystal
Authors: S. P. Wallen and N. Boechler
Keywords: Granular media, nonlinear dynamics, microspheres, contact mechanics
Abstract: Shear to longitudinal mode conversion via second harmonic generation is studied theoretically and computationally for plane waves in a two-dimensional, adhesive, hexagonally close-packed microscale granular medium. The model includes translational and rotational degrees of freedom, as well as normal and shear contact interactions. We consider fundamental frequency plane waves in all three linear modes, which have infinite spatial extent and travel in one of the high-symmetry crystal directions. The generated second harmonic waves are longitudinal for all cases. For the lower transverse-rotational mode, an analytical expression for the second harmonic amplitude, which is derived using a successive approximations approach, reveals the presence of particular resonant and antiresonant wave numbers, the latter of which is prohibited if rotations are not included in the model. By simulating a lattice with adhesive contact force laws, we study the effectiveness of the theoretical analysis for
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Granular Matter
Publication Identifier Type: DOI Publication Identifier: 10.1007/s10035-017-0744-3
Volume: 19 Issue: 62 First Page #:
Date Submitted: 8/31/17 12:00AM Date Published: 7/25/17 2:32AM
Publication Location:
Article Title: Acoustic wave propagation in disordered microscale granular media under compression
Authors: M. Hiraiwa, S. P. Wallen, and N. Boechler
Keywords: Granular media, self-assembly, laser ultrasonics, dynamics, acoustic waves, microspheres, contact mechanics
Abstract: We investigate the effect of dynamic and uniaxial static loading on the wave speeds and rise times of laser generated acoustic waves traveling through a disordered, multilayer aggregate of 2 ?m diameter silica microspheres, where the excited dynamic amplitudes are estimated to approach the level of the static overlap between the particles caused by adhesion and externally applied loads. Two cases are studied: a case where the as-fabricated particle network is retained, and a case where the static load has been increased to the point where the aggregate collapses and a rearrangement of the particle network occurs. We observe increases in wave speeds with static loading significantly lower than, and in approximate agreement with, predictions from models based on Hertzian contact mechanics for the pre- and post-collapse states, respectively. The measured rise time of the leading pulse is found to decrease with increasing static load in both cases, which we attribute to decreased scatt
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 0-Other
Journal: ACS Nano (to be submitted)
Publication Identifier Type: Other Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/31/17 12:00AM Date Published: 8/31/17 2:00PM
Publication Location:
Article Title: Nanoscale contact bridges and their effect on the longitudinal eigenvibration of multilayer colloidal crystals
Authors: M. Abi Ghanem, A. Khanolkar, S. P. Wallen, M. Helwig, M. Hiraiwa, S. Romanov, A. A. Maznev, N. Vog
Keywords: colloidal crystals, microscale granular crystals, laser ultrasonics, acoustics
Abstract: We study the longitudinal contact-based vibrations of colloidal crystals with a defined layer thickness. These colloidal crystals, which may also be thought of as “microscale granular crystals”, consist of close-packed polystyrene particles of diameter 390 nm and are one to twelve layers thick. A laser ultrasonic technique is used to excite and measure longitudinal eigen-modes of the crystals that have out-of-plane motion. From these measurements, we extract particle-substrate and effective interlayer contact stiffnesses in the colloidal crystals, using a discrete, coupled oscillator model, and observe a dependence on fabrication method and number of layers. The extracted stiffnesses are correlated with visual observations of the contacts and measurements of the substrate surface topography after removal of the colloidal particles, and show differences from predictions made using an adhesive elastic contact model. We find that contact bridges of nanometric thickness drastically alter t
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Society of Experimental Mechanics Series, SEM 13th International Congress & Exposition on Experimental and Applied Mechanics
Date Received: 31-Aug-2017 Conference Date: 08-Jun-2016 Date Published: 18-Sep-2016
Conference Location: Orlando, FL
Paper Title: Dynamics of Microscale Granular Crystals
Authors: N. Boechler
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: University of Washington
Date Received: 31-Aug-2017 Completion Date: 6/9/17 9:38PM
Title: Analytical and Computational Modeling of Mechanical Waves in Microscale Granular Crystals: Nonlinearity and Rotational Dynamics
Authors: Samuel Wallen
Acknowledged Federal Support: **Y**

Accomplished under goals: Part of Final Report for "Shock mitigation with ordered microscale granular media" (Grant No. W911NF-15-1- 0030)

Published results:

Note: Figures and captions in this section are taken directly from the publication listed for each sub-section.

1. Wallen, S., Maznev, A., and Boechler, N., "*Dynamics of a Monolayer of Spheres on an Elastic Substrate*" **Physical Review B**, 92, 174303 (2015)

In this work, we developed the analytical model used to describe and analyze the microscale granular system presented in subsection 2, corresponding to Ref. [Hiraiwa, M. et al., Phys. Rev. Lett., 116, 198001 (2016)]. This quasi-one-dimensional (e.g. one-dimensional [1D] chain with two-dimensional [2D] motion) model formed the basis for our 2D microscale granular crystal model developed later in Ref. [Wallen, S. P. et al., Wave Motion, 68, 22 (2017)]. The model contained two translational, and one rotational, degrees of freedom per particle in the 1D chain, linear shear and normal interparticle and particle-substrate stiffnesses, and a deformable, continuum elastic substrate.

2. Hiraiwa, M., Abi Ghanem, M., Wallen, S. P., Khanolkar, A., Maznev A. A., and Boechler, N., "*Complex contact-based dynamics of microsphere monolayers revealed by resonant attenuation of surface acoustic waves*", **Physical Review Letters**, 116, 198001 (2016)

As part of this work, we were the **first** to experimentally characterize the contact-based dynamics of a 2D microscale granular crystal. This was an important first step to characterizing nonlinear acoustic wave propagation in three-dimensional (3D) microscale granular crystals. This includes both advancing our laboratory's microscale granular crystal manufacturing, and laser ultrasonic characterization, capabilities. Measurements of the resonant attenuation of laser-generated surface acoustic waves revealed three collective vibrational modes that involve displacements and rotations of the microspheres, as well as interparticle, and particle-substrate, interactions. To identify the modes, we tuned the interparticle stiffness, which shifted the frequency of the horizontal-rotational resonances while leaving the vertical resonance unaffected. Figure 1 provides a schematic overview of the project. Figure 2 shows the tuning of the acoustic transmission spectra, as a function of evaporated metal deposition at the interparticle contacts.

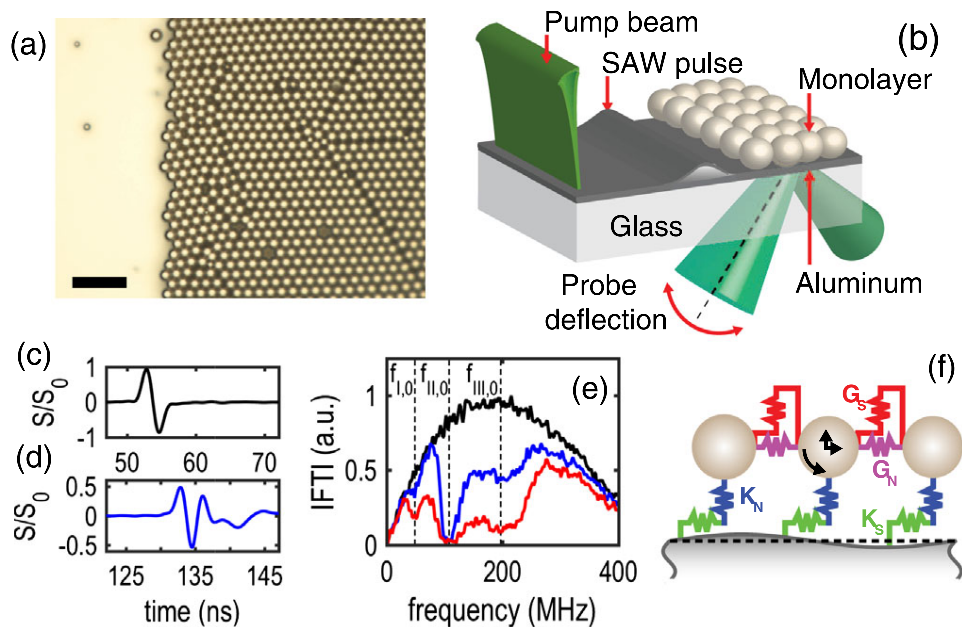

Figure 1: Overview of the experiment. (a) Microscope image of the interface between the monolayer and blank sample regions. The scale bar is 10 μm. (b) Schematic of the laser ultrasonic experimental setup. Normalized signal measured in the (c) blank region and (d) 132 μm inside the monolayer region. (e) Normalized Fourier spectra of the signals in (c) and (d) using the same colors. The red spectrum corresponds to a signal measured 400 μm inside the monolayer region. The vertical dashed lines denote the identified contact resonance frequencies. (f) Schematic of the dynamical model.

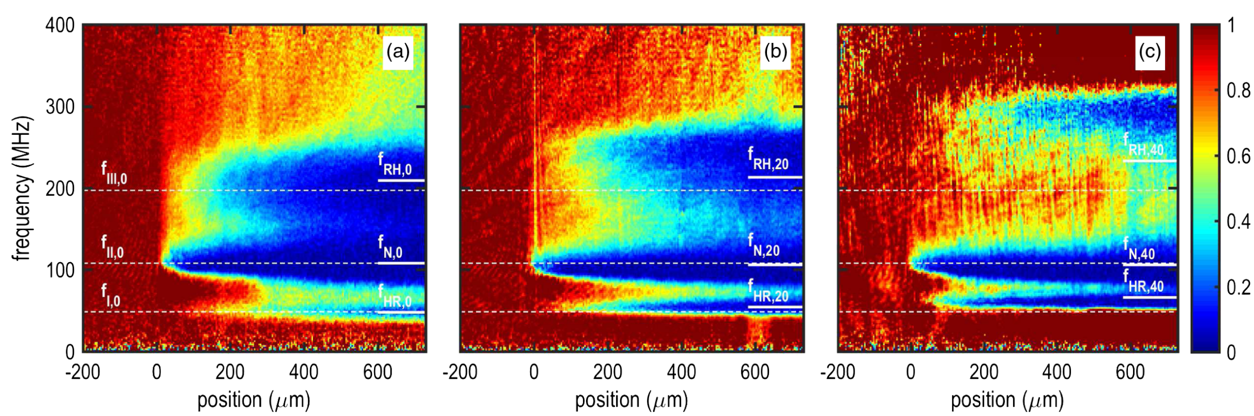

Figure 2: (a)–(c) Transmission spectra showing absorption bands for SAWs propagating across the granular crystal edge. The color bar denotes the magnitude of the transmission coefficient. The horizontal dashed lines denote the identified contact resonance frequencies for the uncoated monolayer. The short horizontal lines on the right of the panels are the fitted contact resonance frequencies. Position denotes the distance from the interface. (a) Uncoated microsphere monolayer. (b) 20 nm of aluminum coating. (c) 40 nm of aluminum coating.

3. Hiraiwa, M., Stossel, M., Wang, J., and Boechler, N., "*Laser-induced spallation of microsphere monolayers*", **Langmuir**, 32, 7730 (2016)

In this work, we experimentally demonstrated a novel fracture morphology that occurs during the laser-induced spallation of 2D microscale granular crystals. This was an important first step towards characterizing highly nonlinear wave (or shock) propagation via high-amplitude laser ultrasonics, and could be conducted in parallel, as our 3D microscale granular crystal manufacturing capabilities were being advanced. An image of the experimental setup and delamination morphology is shown in Figs. 3 and 4 below (respectively).

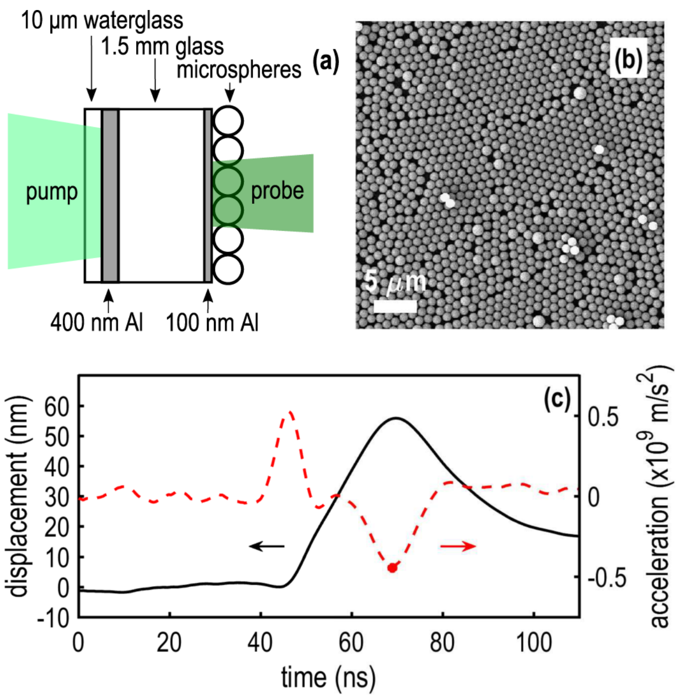

Figure 3: (a) Schematic of the sample and the laser-induced spallation setup. (b) SEM image of an untested monolayer. (c) Measured surface displacement (black solid curve) and calculated surface acceleration (red dashed curve) for a pump energy of 32 mJ. The marker indicates the identified point of maximum tensile force at the microsphere−substrate contact.

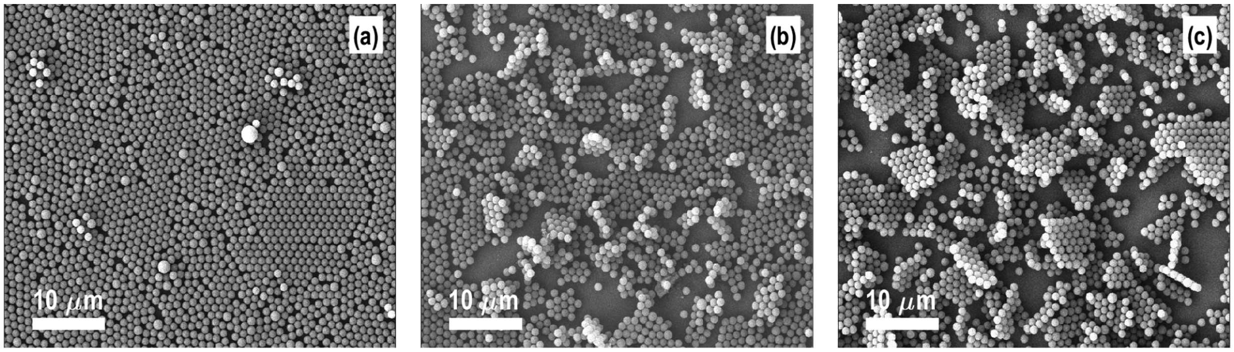

Figure 4: SEM images of a monolayer after excitation, which had surface acceleration (a) below, (b) just above, and (c) significantly above the spallation threshold.

4. Geslain, A., Raetz, S., Hiraiwa, M., Abi Ghanem, M., Wallen, S. P., Khanolkar, A., Boechler, N., Laurent, J., Prada, C., Duclos, A., Leclaire, P., Groby, J.-P., "*Spatial Laplace transform for complex wavenumber recovery and its application in the analysis of attenuation in acoustic systems*", **Journal of Applied Physics**, 120, 135107 (2016)

In this work, using our experimental data from Ref. [Hiraiwa, M. et al., Phys. Rev. Lett., 116, 198001 (2016)], we worked with collaborators developing a method to analyze the dispersion of acoustic waves wherein significant attenuation is present.

5. Wallen, S. P., and Boechler, N., "*Shear to longitudinal mode conversion via second harmonic generation in a two-dimensional microscale granular crystal*", **Wave Motion**, 68, 22 (2017)

Extending the model we developed in Ref. [Wallen, S. et al., Phys. Rev. B, 92, 174303 (2015)], we studied shear-to-longitudinal mode conversion in a 2D microscale granular crystal model. This model formed the basis for our 2D microscale granular crystal computational model developed later, and shown in Ref. [Wallen, S., PhD Thesis, University of Washington (2017)]. The model contained two-translational and one rotational degree of freedom per particle in the hexagonally-close-packed 2D array, as well as nonlinear shear and normal interparticle contact stiffnesses. We observed weakly nonlinear shear-to-longitudinal mode conversion, where the conversion exhibited resonant and anti-resonant wavenumbers. Anti-resonant wavenumbers were found not to exist without the presence of rotations. A schematic of the model is shown in Fig. 5, and the shear-to-longitudinal wave conversion efficiency is shown in Fig. 6.

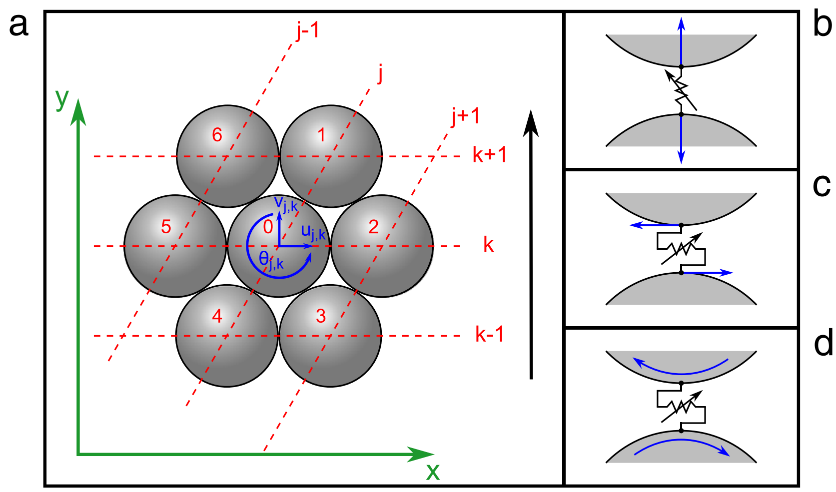

Figure 5: (a) Schematic of the model of a 2D, hexagonally close-packed granular membrane. The black arrow indicates the direction of wave propagation. (b–d) Illustrations of longitudinal, shear, and rotational motions activating normal and shear nonlinear contact springs.

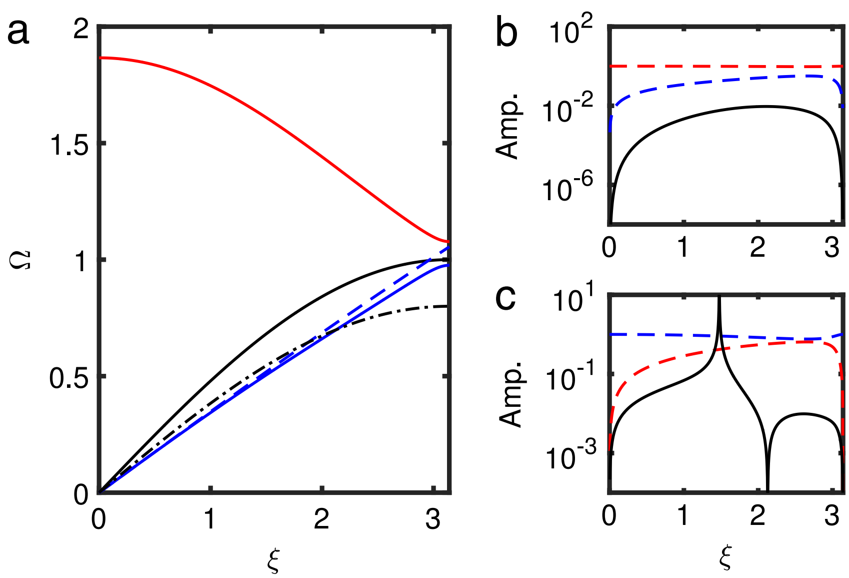

Figure 6: (a) Dispersion of plane waves traveling in the direction indicated in Fig. 1(a). Longitudinal (black), TR (blue), and RT (red) modes are denoted by the solid lines. The blue dashed curve is a frequency- and wave number-doubled representation of the TR mode, which is shown to intersect with the L mode. The black dash-dotted curve defines the antiresonance condition, wherein its intersection with the TR branch denotes the antiresonance frequency and wavenumber. (b, c) Amplitudes of second harmonic longitudinal waves (black solid curves) generated from fundamental waves in the RT and TR modes, respectively. Blue and red dashed curves show the transverse and rotational displacements, normalized such that the sum of squares is unity. The second harmonic amplitudes are normalized by the small parameter ε.

6. Wallen, S. P., Lee, J., Mei, D., Chong, C., Kevrekidis, P. G., and Boechler, N., "*Discrete Breathers in a Mass-in-Mass Chain with Hertzian Local Resonators*", **Physical Review E** 95, 022904 (2017)

In this work, we extended our model of Ref. [Wallen, S. et al., Phys. Rev. B, 92, 174303 (2015)] to include nonlinear particle-substrate interactions, while simplifying our model by removing the interparticle interactions and treating the surface acoustic waves propagating in the substrate as an effective 1D wave. In this system, we studied discrete breathers (DBs, a type of nonlinear intrinsic localized mode). This served as a stepping stone to study other types of nonlinear intrinsic localized modes (like solitary waves), which we expected may exist in higher dimensional systems (such as Ref. [Wallen, S. P. et al., Wave Motion, 68, 22 (2017)]). After predicting theoretically the existence of DBs, we used numerical continuation to compute a family of DBs localized around one lattice site. We then analyzed the frequency-amplitude dependence of a DB near the upper band gap edge, and demonstrated the evolution of their dynamics in dissipative scenarios. Figure 7 shows a schematic of the model, and Fig. 8 and Fig. 9 shows the simulated dynamical evolution of sample breathers and linear eigenmodes at varied amplitudes in non-dissipative and dissipative scenarios, respectively.

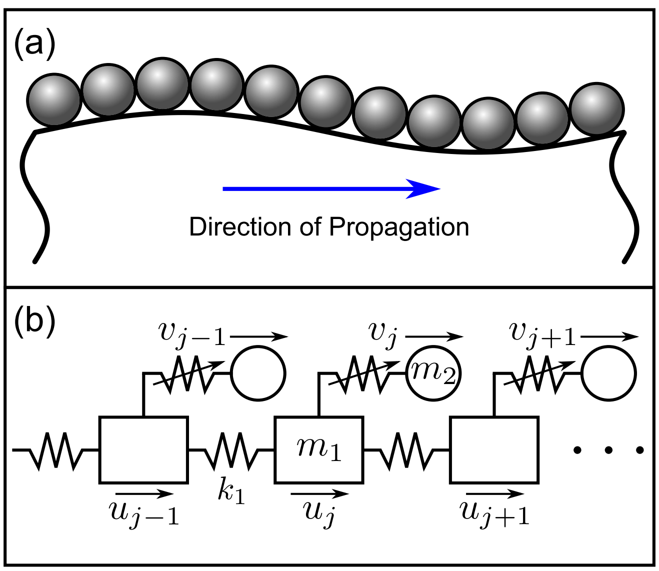

Figure 7: (a) Granular metamaterial composed of a monolayer of microspheres on an elastic half space. (b) Schematic of the 1D, discrete granular metamaterial model.

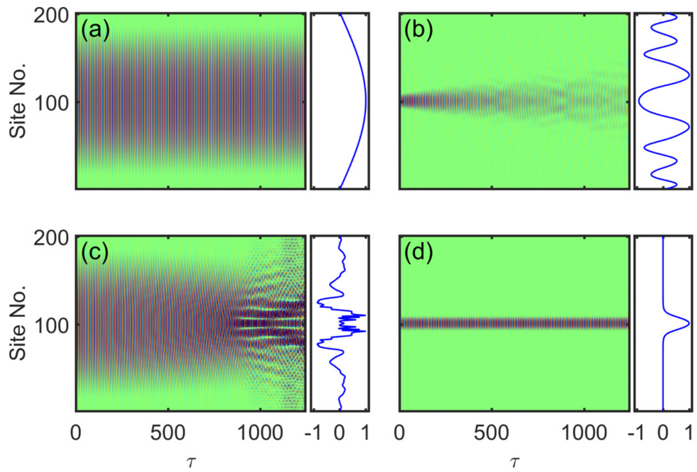

Figure 8: Spatiotemporal plots of the relative displacements of the simulated lattice for high- and low-amplitude excitations, using eigenmode and DB profiles as initial shapes. Side panels contain spatial profiles at the final time step, normalized to the maximum value. (a) Eigenmode shape with low amplitude (approximate periodic solution). (b) DB shape rescaled to low amplitude. (c) Eigenmode shape rescaled to high amplitude. (d) DB shape with high amplitude (exact periodic solution).

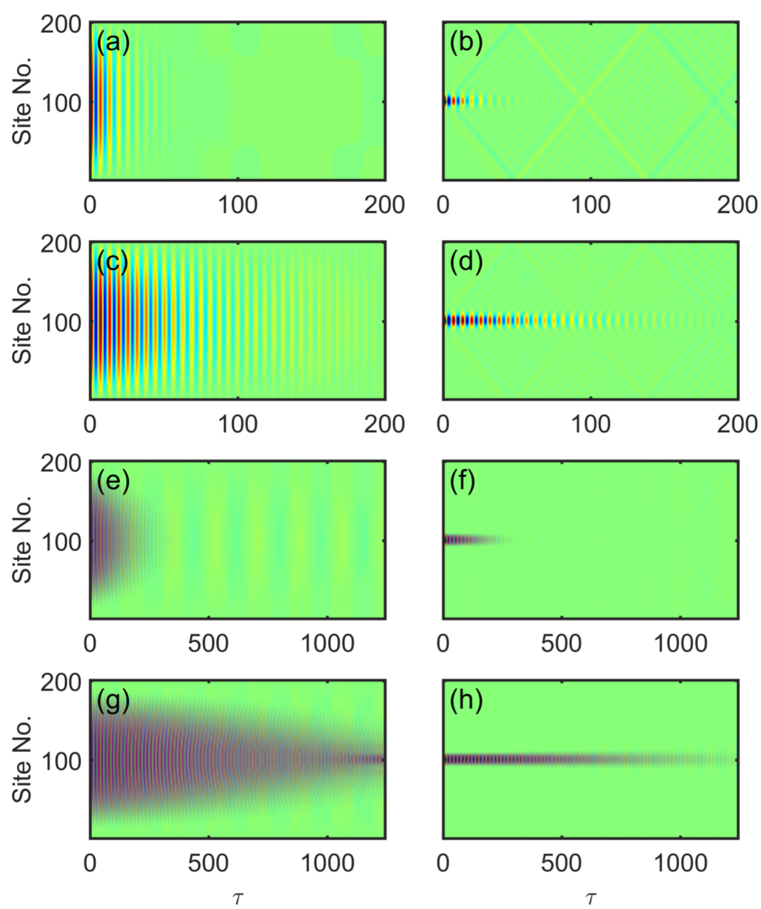

Figure 9: Spatiotemporal plots of the relative displacements of the simulated lattice for several damping coefficients. Left and right panels correspond to the eigenmode (rescaled to high amplitude) and DB excitations.

7. Hiraiwa, M., Wallen, S. P., and Boechler, N., "*Acoustic wave propagation in disordered microscale granular media under compression*", **Granular Matter**, 19, 62 (2017)

In this work, we studied the sound speed tunability with variation of static compression applied to, and wave amplitude in, a disordered monodisperse granular medium composed of 2 um silica particles. We were the **first** to demonstrate nonlinear effects (consistent with Hertzian models) in such a 3D monodisperse microscale granular medium. We observed significant effects from the evaporative manufacturing process (pre- and post-collapse states in the medium). This was an important intermediary step to validate our process for characterizing laser-generated, nonlinear acoustic wave propagation in 3D microscale granular media, while we were advancing our 3D microscale granular crystal self-assembly manufacturing capabilities. Figure 10 shows an overview of the experiment. Figure 11 shows the difference in pulse propagation in a collapsed microscale granular medium as a result of increased static loading. Figure 12 shows the differences between the pre- and post-collapse states as a function of applied static load and acoustic wave amplitude.

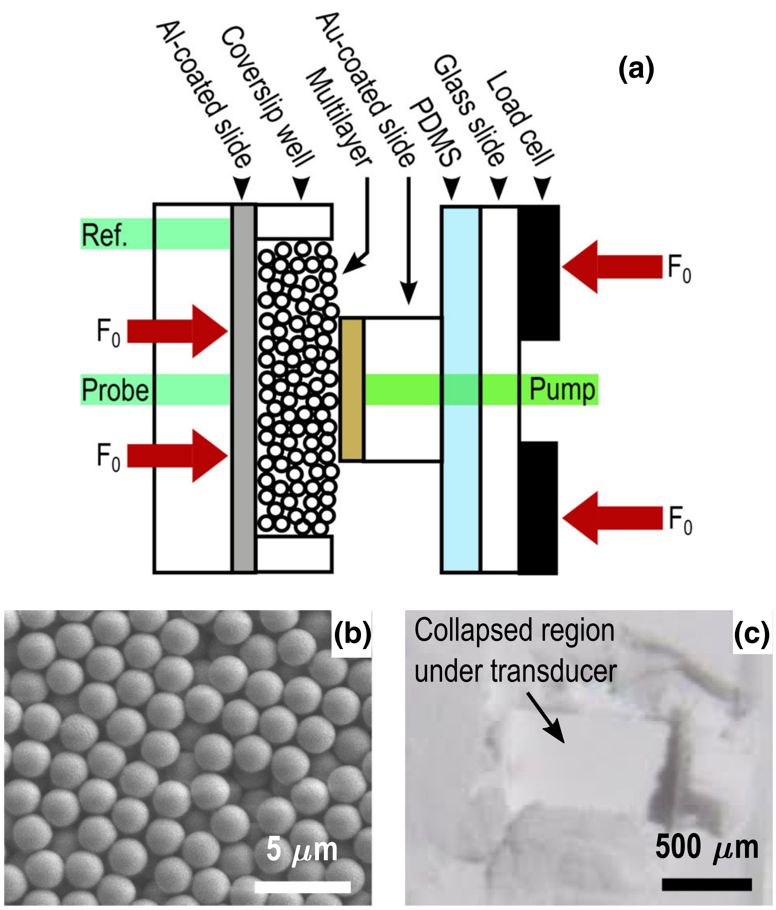

Figure 10: Overview of the experiment. (a) Schematic of the compression setup. (b) SEM image of the as-deposited multilayer surface, prior to modification with the razor blade and application of compression. (c) Photograph of a post-collapse multilayer, taken at a 45 degree angle.

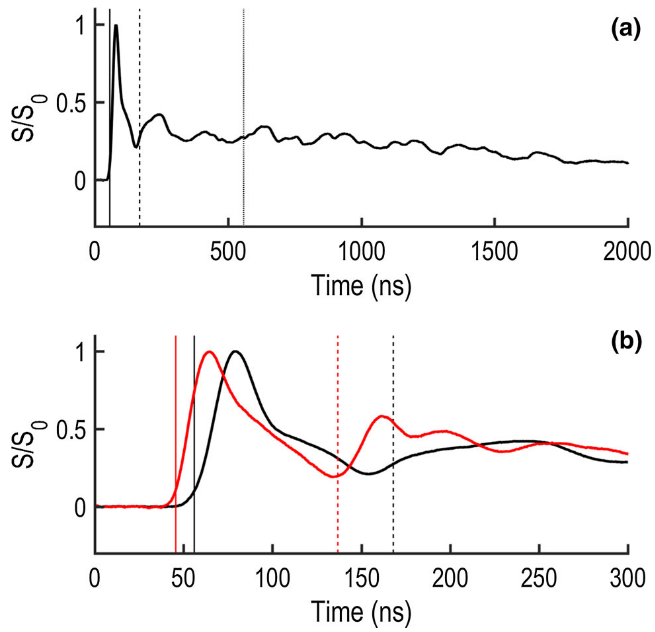

Figure 11: (a,b) Representative measured signals for the post-collapse case using the low amplitude excitation. Black and red curves correspond to static loads of F_R = 5.3 and F_R = 36, where F_R denotes the ratio of applied static load to adhesive force. Vertical solid and dashed lines denote the arrival times of the 1L and 3L pulses, respectively, for curves of the same color (where L denotes the length of the sample). The vertical dotted line is the time of first pulse arrival, plus the estimated round trip time for acoustic pulses traveling in the glass substrates. (a) Extended time window for the signal measured at F_R = 5.3. (b) Shortened time window, comparing the signals measured at static loads of F_R = 5.3 and F_R = 36.

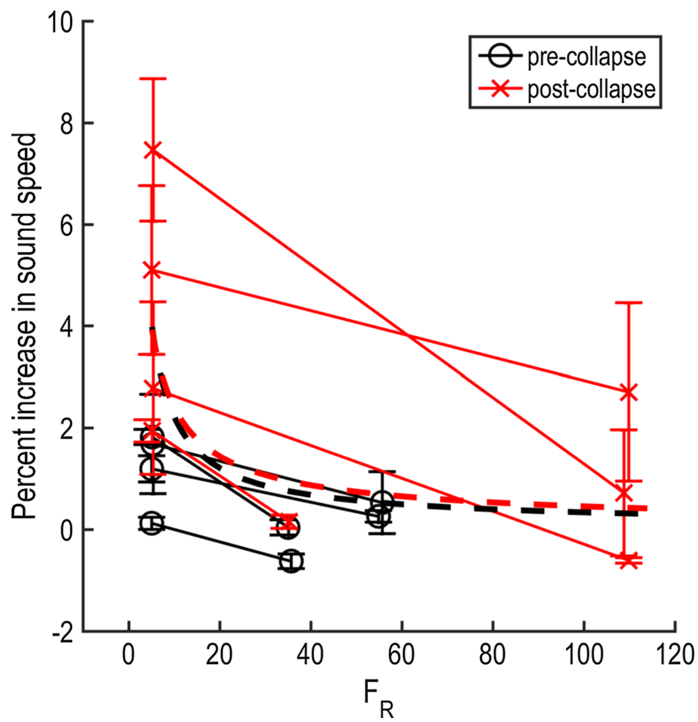

Figure 12: Percent increase in sound speed of high amplitude excitation, relative to low amplitude excitation, as a function of static load. The black circles represent the pre-collapse case and the red x's

represent the post-collapse case. Data obtained from the same location and state (pre- or post-collapse) are connected by solid lines. The error bar height corresponds to the difference between sound speeds being calculated using thresholds of $S/S_0 = 0.1$ and $S/S_0 = 0.3$. The average increase in sound speed at F_{min} is 1.2 ± 0.8% and 4.3 ± 2.5% for the pre- and post-collapse cases, respectively, where the error is equal to the standard deviation of all four experiments. Black and red dashed lines represent simulation results for the pre- and post-collapse cases, respectively.

8. Abi Ghanem, M., Khanolkar, A., Helwig, M., Wallen, S. P., Hiraiwa, M., Vogel, N., and Boechler, N., "*Longitudinal Eigenvibration of Multilayer Colloidal Crystals and the Effect of Nanoscale Contact Bridges*", **under review**, posted on arXiv: https://arxiv.org/abs/1810.03771 (2018)

In this work, we studied longitudinal eigenvibrations in multilayer microscale granular crystals, generated by laser ultrasonic excitation. We found that solid bridges of nanometric thickness drastically alter the stiffness of the contacts, and their presence is found to be dependent on the self-assembly process wherein they were deposited. Measurements of the eigenmode quality factors suggest that energy leakage into the substrate plays a role for low frequency modes but is overcome by disorder- or material-induced losses at higher frequencies. This was a critical step towards characterizing highly nonlinear wave propagation in 3D microscale granular crystals, by using the same planned technique to first characterize few-layer 3D microscale granular crystals at low acoustic excitation amplitude. Figure 13 shows an overview of the study. Figure 14 shows acoustic signals measured in our system, and our discrete element model used to describe the results. Table 1 shows the differences in contact stiffnesses revealed by our acoustic measurements, between samples made using different self-assembly manufacturing techniques. Figure 15 shows the morphology of the contacts for differing self-assembly manufacturing methods.

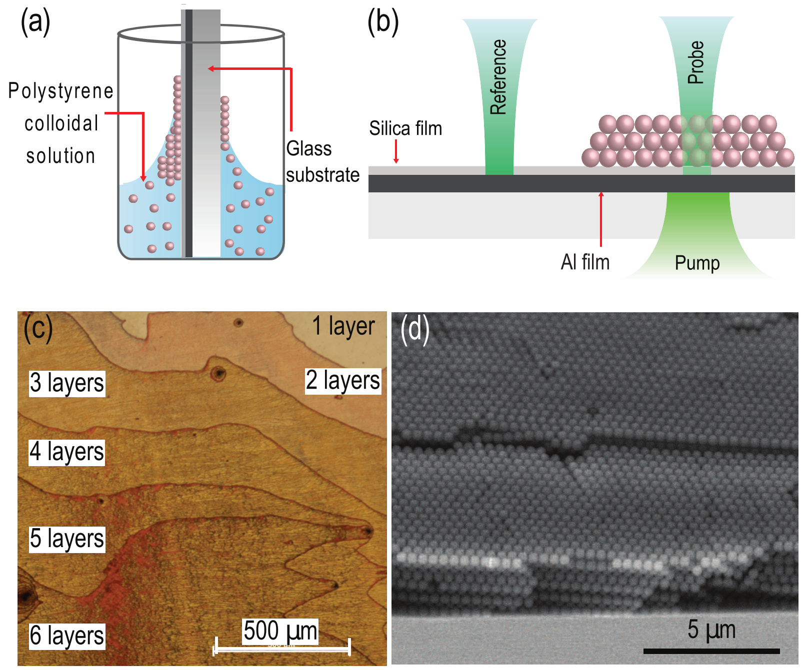

Figure 13: a) Schematic of the multilayer convective self-assembly technique. (b) Illustration of the laser ultrasonic technique used to excite and measure eigenmodes of the colloidal crystal. (c) Optical microscope image showing multiple regions of the colloidal crystal with different layer thicknesses. (d) Representative SEM image of the colloidal crystal.

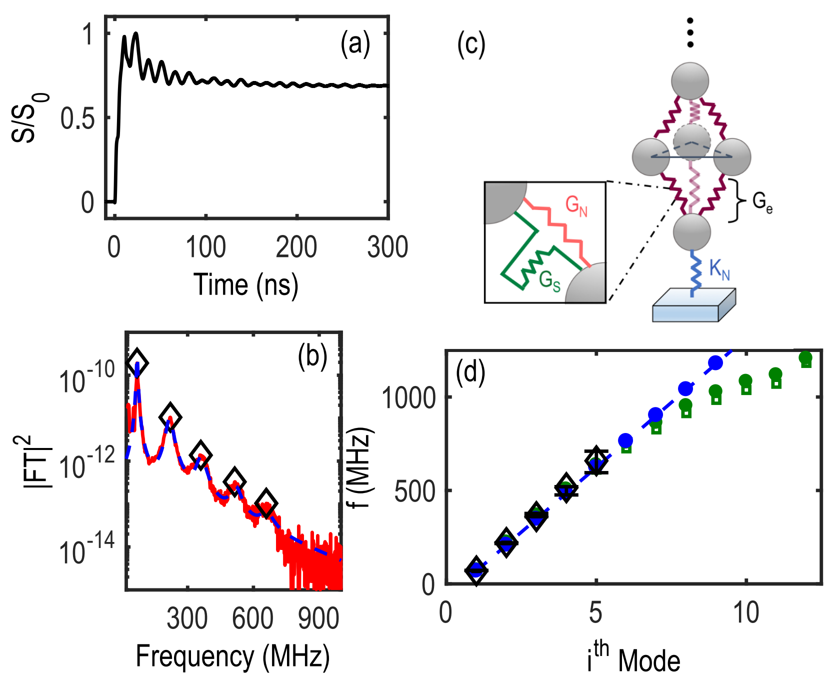

Figure 14: (a) Time domain signal corresponding to the out-of-plane eigenvibrations of a 12-layer-thick colloidal crystal. The signal amplitude S is normalized to its maximum amplitude S_0. (b) The solid red line

denotes the power spectrum of the time-derivative of the signal in (a), and the dashed blue line denotes the sum of five Lorentzians fitted to the measured spectrum. (c) Schematic of the quasi-one-dimensional coupled oscillator model. (d) Modal frequencies as a function of mode number. Black diamond markers are the modes identified in (b) denoted by the same marker type. The blue circle markers represent the calculated modal frequencies for a fixed-free continuum film adhered to a rigid substrate, where the first mode is matched to the measured fundamental mode. The blue dashed line is a visual guide to the blue circle markers, and represents a wave speed of 1060 m/s. The green markers represent the calculated modal frequencies of the coupled oscillator system using a particle- substrate stiffness obtained via a monolayer region of the same sample measured in (a,b) and an interlayer contact stiffness fitted to the fundamental measured mode (open square markers), and to all five measured modes (filled circle markers). The error bar half-widths in the measured spectral peaks denote the maximum shift in the position of the peaks when the power spectrum time window is adjusted by up to 4 ns.

Table 1: Measured and predicted (using the Derjaguin-Muller-Toporov, or "DMT" adhesive elastic contact model) particle-substrate and average interlayer contact stiffness. The DMT model assumes $w_{P\text{-}S}$ = 0.06 J/m^2 and w_{P-P} = 0.06 J/m^2, where w denotes the work of adhesion and subscripts p and s refer to particle and substrate, respectively.

	K_N (kN/m)	$G_{e,avg}$ (kN/m)
Sample 1	1.3	0.4
Sample 2	1.6	0.7
Air/water monolayer	0.4	-
DMT Model	0.1	0.1

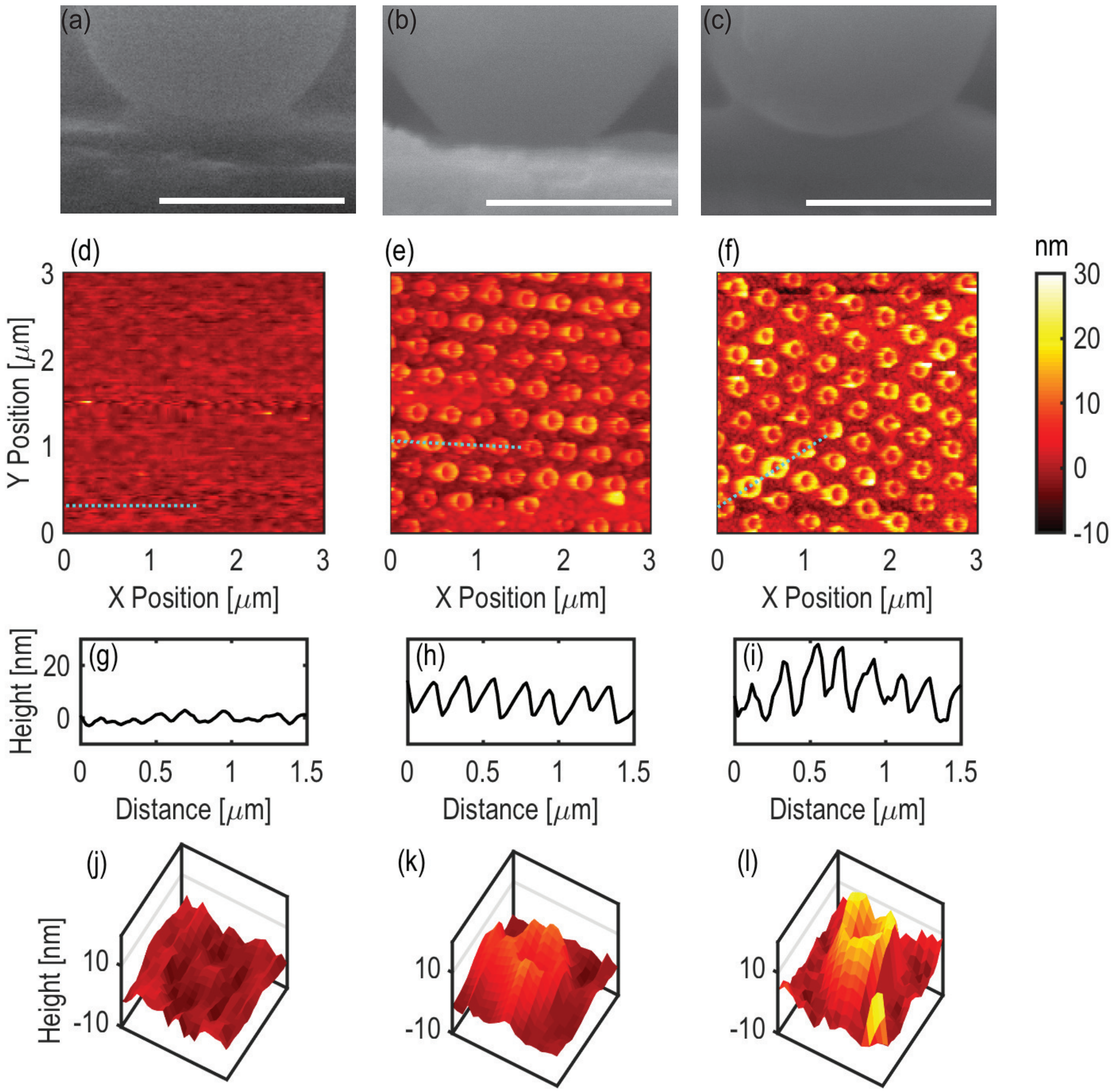

Figure 15: Scanning electron microscopy images of the monolayer regions in: (a) the air/water monolayer sample; (b) Sample 1; and (c) Sample 2. We note some minor lateral image distortion in the SEM image in panel (c). Scale bars represent 500 nm in all panels. (d) - (f) Tapping-mode Atomic Force Microscopy images of the substrate after removal of the spheres. (g) - (i) The surface topology of the substrate along the dashed line is shown in the corresponding panel directly above. (j) - (l) Isometric views of the AFM images of single 'well'-like features on a 0.4 μm x 0.4 μm area of the substrate. All panels in the same column correspond to the same sample.

9. **PhD Thesis:** Wallen, S., *Analytical and Computational Modeling of Mechanical Waves in Microscale Granular Crystals: Nonlinear and Rotational Dynamics*, University of Washington (2017)

In chapter 7 of Samuel Wallen's PhD thesis, our computational studies of energy partition in a 2D microscale granular crystal subject to an impulsive point load are described. This utilizes the computational model developed in Ref. [Wallen, S. P. et al., Wave Motion, 68, 22 (2017)], augmented in collaboration with Dan Negrut's research group to include particle detachment and re-attachment. The resulting dynamics show highly nonlinear, amplitude-dependent, energy partition dynamics that are unique from previous studies in non-adhesive, macroscale granular media. We are still currently working to explore these dynamics, and to assemble a journal publication on this topic. Figure 16 shows a schematic of the simulation setup. Figure 17 shows the definition of longitudinal, transverse, and rotational energy components. Figure 18 shows the low amplitude kinetic energy distribution, and Fig. 19 the high energy kinetic energy distribution. Figure 20 shows the amplitude dependence of the longitudinal particle velocity directly below the impactor sphere at the 30th layer, normalized to the initial particle velocity. Finally, Fig. 21 shows the amplitude dependence of each wave polarization along the surface of the granular crystal. In each case, we see discontinuities at sufficiently large particle velocities, which we attribute to particle detachment.

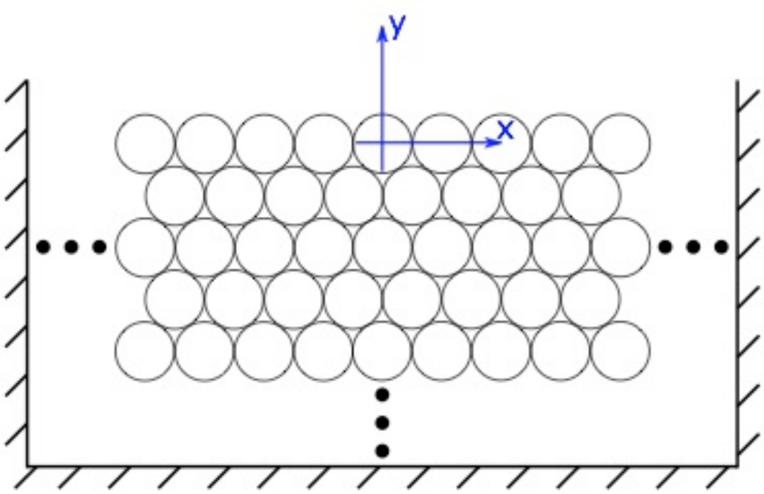

Figure 16: Schematic of the simulation setup for a 2D, HCP multilayer of microspheres.

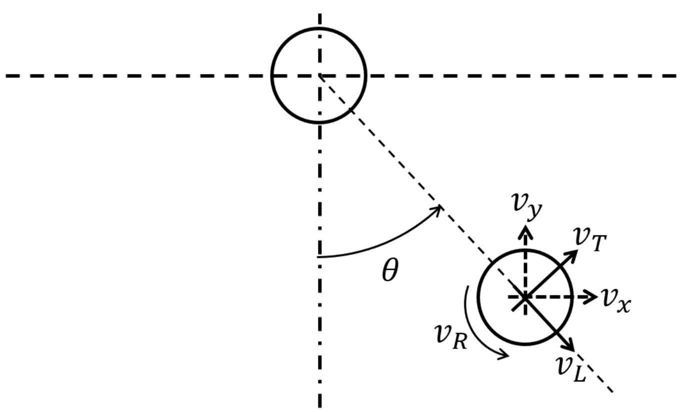

Figure 17: Diagram depicting the transformation from cartesian velocity components (simulation output) to longitudinal, transverse, and rotational velocity components.

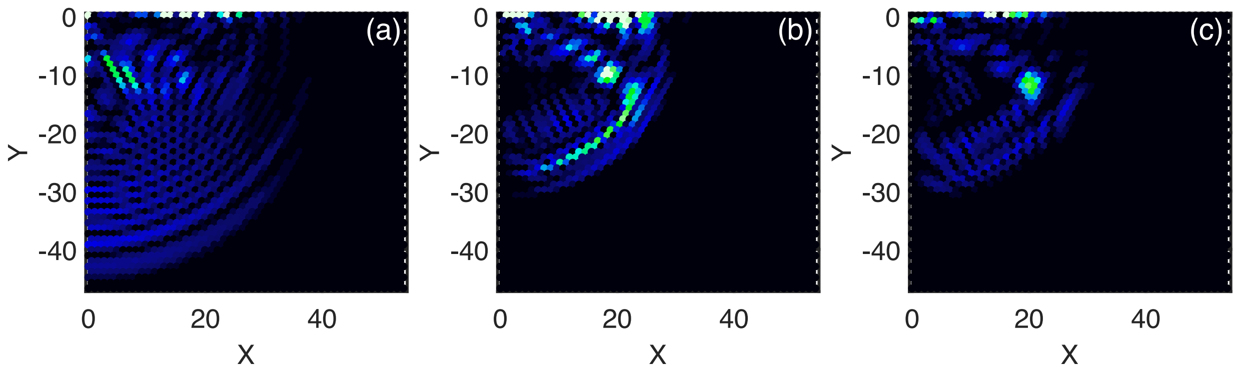

Figure 18: Spatial distributions of normalized kinetic energy for the case $v_0 = 1$, where v_0 is initial particle velocity. Panels (a), (b), and (c) correspond to longitudinal, transverse, and rotational parts of the kinetic energy.

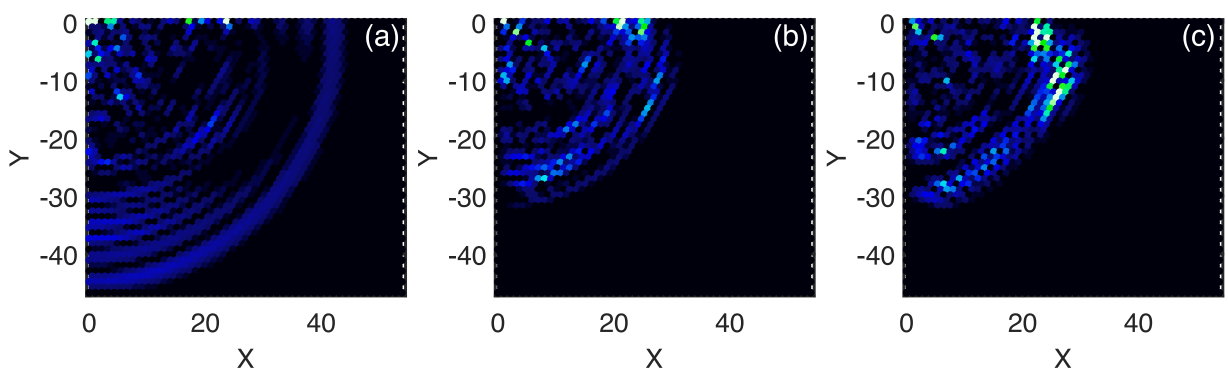

Figure 19: Spatial distributions of normalized kinetic energy for the case v0 = 10. Panels (a), (b), and (c) correspond to longitudinal, transverse, and rotational parts of the kinetic energy.

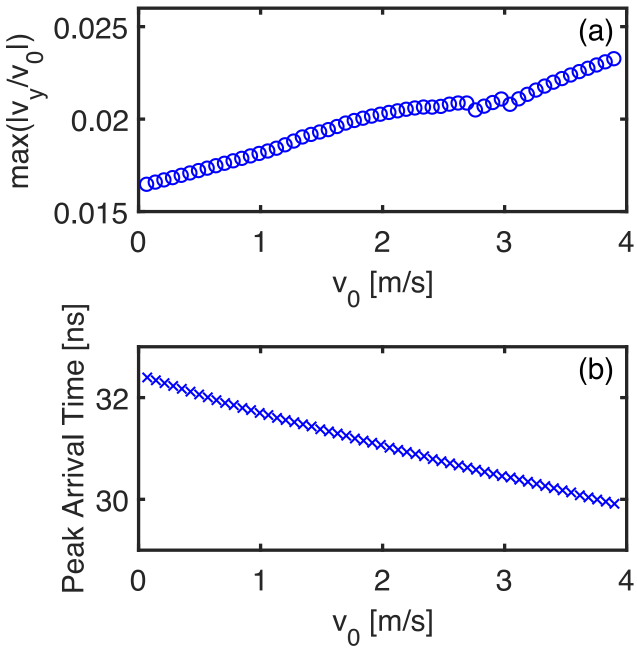

Figure 20: Amplitude dependence of (a) maximum particle velocity and (b) first peak arrival time for longitudinal waves along the vertical line below the excited sphere, at the 30th layer.

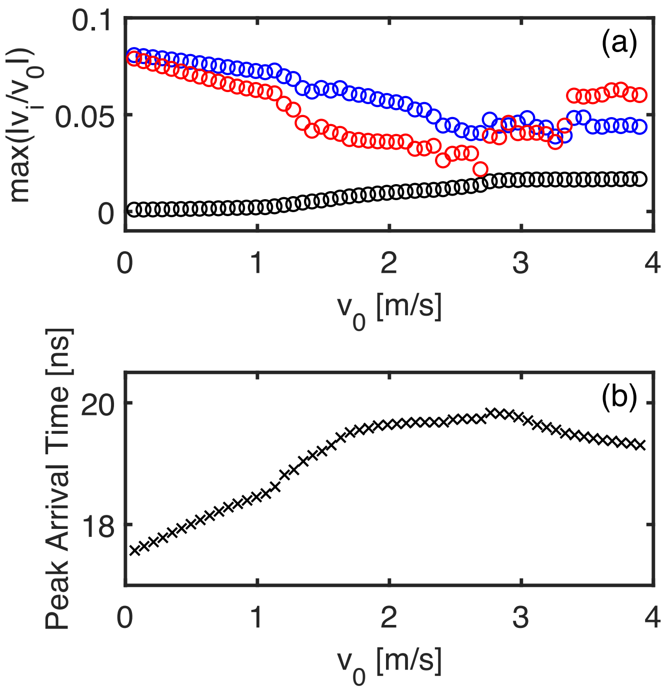

Figure 21: (a) Amplitude dependence of maximum particle velocity at the surface layer, at the 15th sphere. Black, blue, and red circles correspond to longitudinal, transverse, and rotational velocities. (b) Amplitude dependence of first peak arrival time for longitudinal velocity, for the same sphere as (a).

Unpublished results and future directions:

After encountering initial challenges, we succeeded in being able to manufacture "thick" 3D microscale granular crystals towards the later portion of the project, via vertical deposition convective self-assembly, as is shown in Fig. 13(a). An example of a manufactured 3D microscale granular crystal, composed of 390 nm diameter polystyrene spheres is shown in Fig. 22.

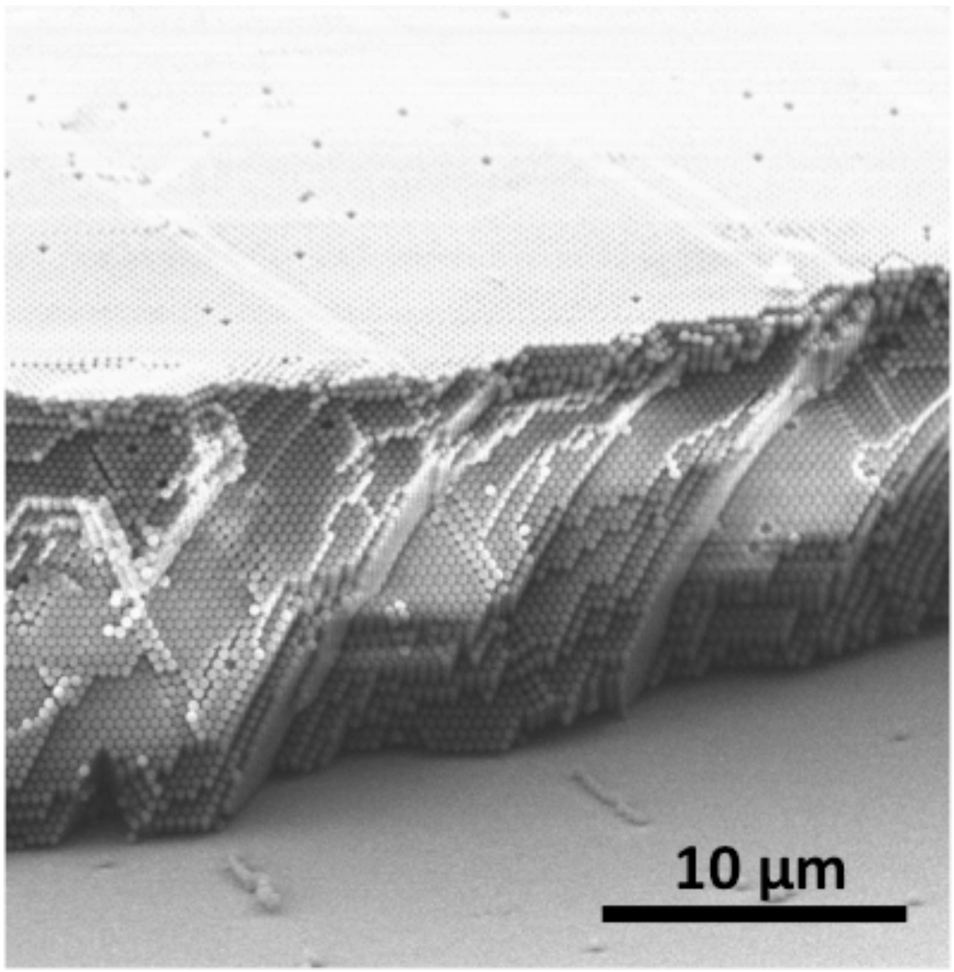

Figure 22: Scanning electron microscope image of 3D microscale granular crystal, composed of 390 nm diameter polystyrene spheres.

After this success, we achieved the following preliminary results.

1. **Highly nonlinear shock velocities in 3D microscale granular crystals**

We conducted experiments on polystyrene 3D microscale granular crystals, such as those shown in Fig. 22, using the setup shown in Fig. 23. A ~450 ns duration laser pulse excited the wave in the granular crystal, which was measured on the other side using a grating interferometer. Initial results showed an amplitude dependence of shock velocity upon shock amplitude, as shown in Fig. 24. We caution that these results should be considered as preliminary, as we are currently trying to confirm whether effects such as signal filtering, as may be due to photodiode bandwidth limitations, are contributing to the observed amplitude dependence. In future tests, we would like to try to confirm these effects with shorter pulse duration excitation (either due to a shorter laser pulse or a microprojectile impactor), higher bandwidth interferometry, and thicker microscale granular crystals. We are also interested in comparing the polystyrene results with 3D microscale granular crystals with silica particles of similar diameter.

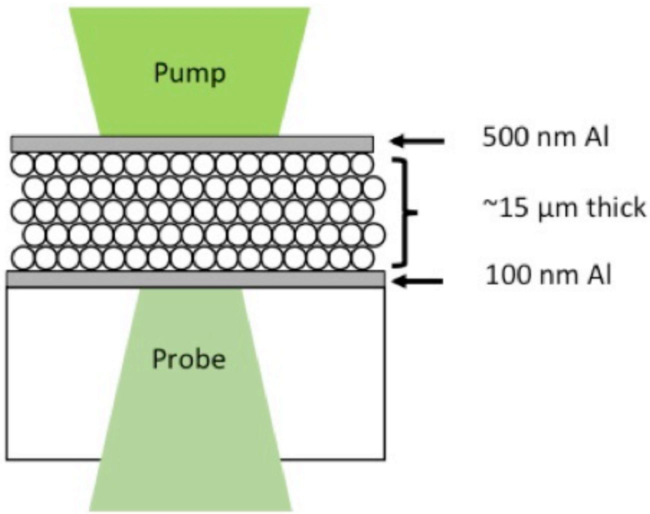

Figure 23: Schematic of experimental setup for studying amplitude dependent highly nonlinear wave speeds in 3D microscale granular crystals.

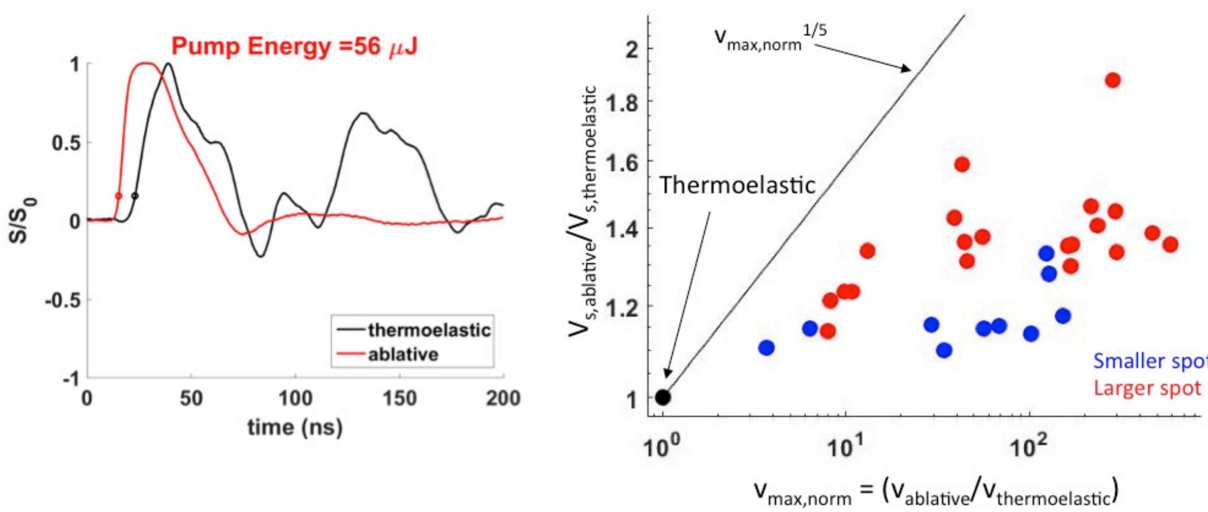

Figure 24: [Left] Time history pulse measured after traveling once through the microscale granular crystal with a low (thermoelastic) and high (ablative) amplitude excitation. [Right] Dependence of normalized wave speed on normalized particle velocity measured upon arrival of the wave.

2. Spallation and blast crater formation in 3D microscale granular crystals

In addition to studying amplitude-dependent, highly nonlinear wave, or shock, velocities in 3D microscale granular crystals, we also studied dynamic failure phenomena, including spallation and blast crater formation. Excitation was either applied at the substrate-microscale granular crystal interface, or, the microscale granular crystal was coated with a thin layer of aluminum, and the excitation was applied on the free surface, as is shown in Fig. 23. Several interesting phenomena were observed. For the first case, where excitation was applied at the substrate-microscale granular crystal interface, we routinely saw the spallation of entire large "grains" of self-assembled 3D microscale granular crystal, as is shown in Fig. 25.

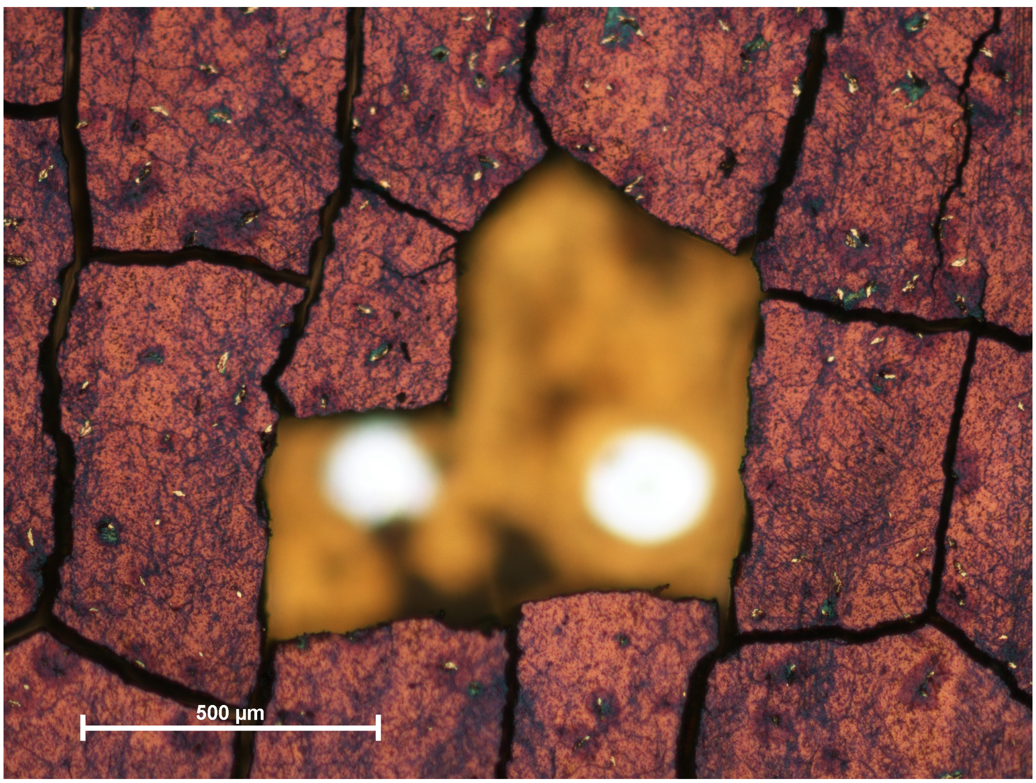

Figure 25: Microscope image of spalled region of 3D microscale granular crystal induced by laser-generated shock, where the laser excitation was applied at the substrate-microscale granular crystal interface.

In contrast to the phenomenon observed in Fig. 25, when the excitation was applied from the reverse direction (the second scenario previously mentioned), we observed both spallation and crater formation, which differed drastically for 3D microscale granular crystals composted of polystyrene vs. silica spheres. As can be seen in Fig. 26, which is a 3D microscale granular crystal composed of 390 nm diameter polystyrene spheres, the metal surface layer has seemed to peel back, and a melted crater formed into the microscale granular crystal. In contrast, Fig. 27 and Fig.

28, where experiments were performed on 3D microscale crystals composed of 500 nm diameter silica particles, we did not observe such melting. Instead, we saw either nearly complete ejection of the crystal within the excitation region (Fig. 27) or fragmentation and fracture of the microscale granular crystal into large "grains" (Fig. 28). We are currently planning (given sufficient available resources) to follow up on these early results to better understand the underlying physics governing the observed phenomena.

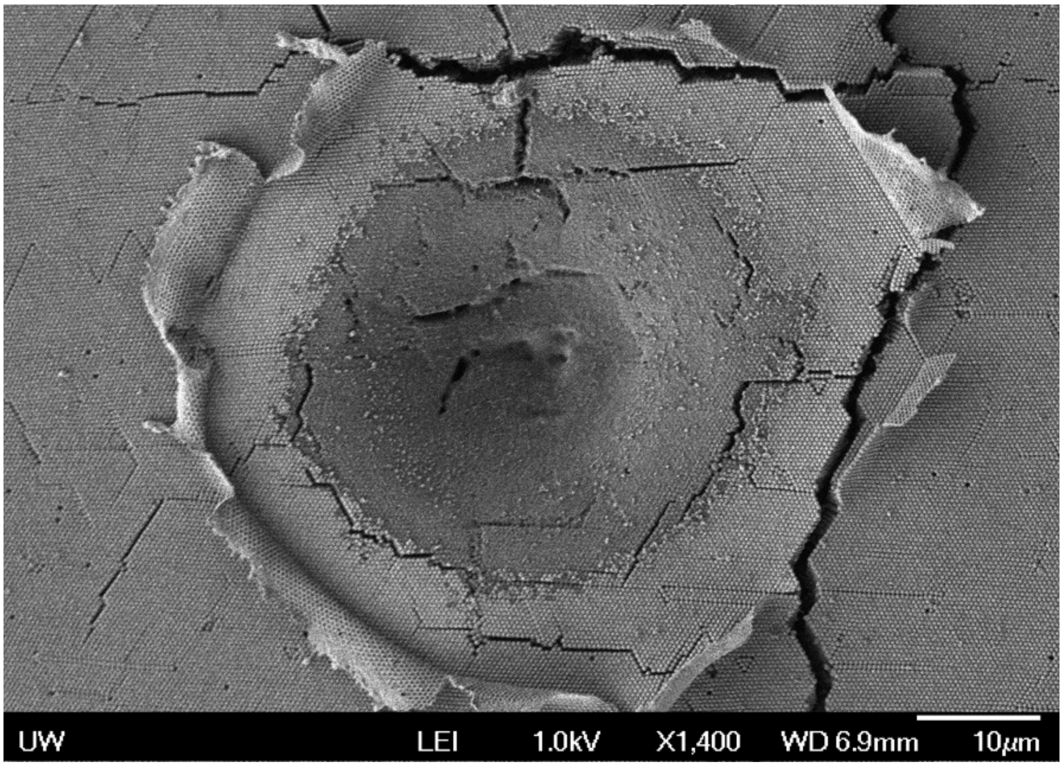

Figure 26: Scanning electron microscope image of melted-crater region, induced by laser-generated shock, created on the 3D microscale granular crystal composed of 390 nm diameter polystyrene spheres. In this case, the excitation was applied to the free metal-coated micrsocale granular crystal surface. The laser pulse had an energy of 50.7 μJ.

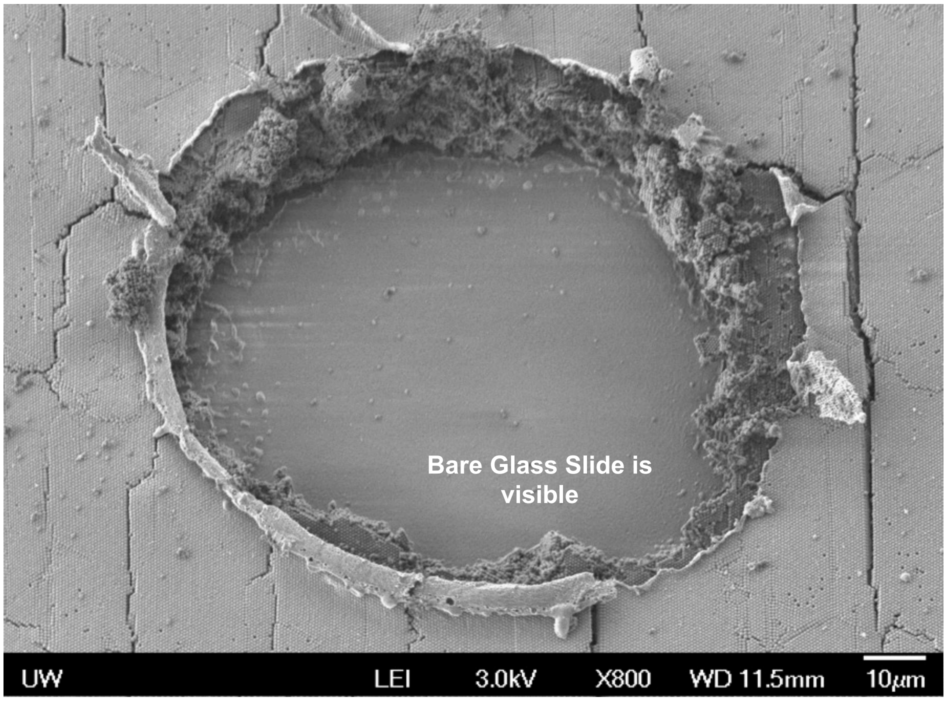

Figure 27: Scanning electron microscope image of complete spallation within the excitation region, in a 3D microscale granular crystal composed of 500 nm diameter silica spheres. In this case, the excitation was applied to the free metal-coated micrsocale granular crystal surface. The laser pulse had an energy of 57 μJ.

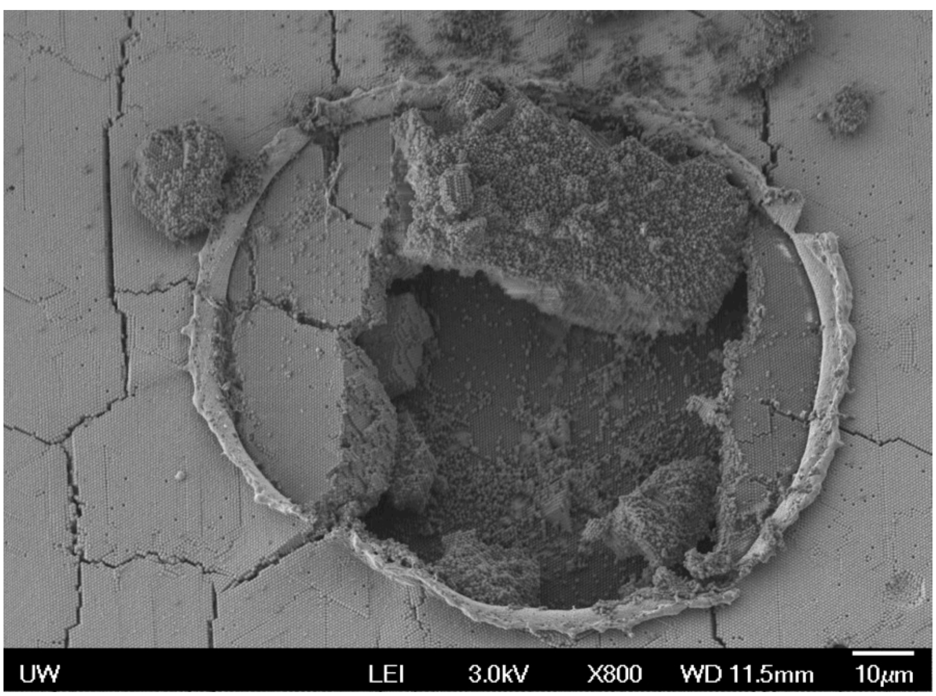

Figure 28: Scanning electron microscope image of partial spallation, and fragmentation into grains, within the excitation region in a 3D microscale granular crystal composed of 500 nm diameter silica spheres. In this case, the excitation was applied to the free metal-coated micrsocale granular crystal surface. The laser pulse had an energy of 57 μJ.