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The 2019 Nonlinear Mechanics and Dynamics Research Institute

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ABSTRACT

The 2019 Nonlinear Mechanics and Dynamics (NOMAD) Research Institute was successfully held from June 17 to August 1, 2019. NOMAD brings together participants with diverse technical backgrounds to work in small teams to cultivate new ideas and approaches in engineering mechanics and dynamics research. NOMAD provides an opportunity for researchers – especially early career researchers - to develop lasting collaborations that go beyond what can be established from the limited interactions at their institutions or at annual conferences. A total of 20 students came to Albuquerque, New Mexico to participate in the seven-week long program held at the Mechanical Engineering building on the University of New Mexico campus. The students collaborated on one of seven research projects that were developed by various mentors from Sandia National Laboratories, the University of New Mexico, and academic institutions. In addition to the research activities, the students attended weekly technical seminars, various tours, and socialized at various off-hour events including an Albuquerque Isotopes baseball game. At the end of the summer, the students gave a final technical presentation on their research findings. Many of the research discoveries made at NOMAD are published as proceedings at technical conferences and have direct alignment with the critical mission work performed at Sandia.

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John Mersch (SNL), Jeff Smith (SNL), Rob Kuether (SNL), Jonel Ortiz (SNL), Gustavo Castellucio (Cranfield), Keegan Moore (Nebraska), Rob Flicek (SNL), Kelsey Johnson (SNL), Karl Walczak (SNL), Cory Medina (SNL), Dane Quin (Akron), Ben Zastrow (SNL), Nathan Jackson (UNM), Peter Avitabile (Umass-Lowell), Pat Logan (Umass-Lowell), Dan Roettgen (SNL), Ben Pacini (SNL), Simone Manzato (SISW), Ed Habtour (SNL), Abdessattar Abdelkefi (NMSU), Mark Wilson (SNL), Scott Grutzik (SNL), Normand Modine (SNL), Yu-Lin Shen (UNM), Tariq Khraishi (UNM), Kyle Johnson (SNL), Neal Hubbard (SNL), Emily Miller (SNL), Edmundo Corona (SNL)

Seminar and Tutorial Speakers:

Matt Allen (UW-Madison), Bill Flynn (Siemens), Pete Avitabile (UMass Lowell), Keegan Moore (Nebraska), Dane Quin (Akron), Pat Logan (Umass-Lowell), Yu-Lin Shen (UNM), Jonel Ortiz (SNL), Cory Medina (SNL)

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ASC P&EM	Advanced Simulation and Computing
DE	Delivery Environments
ESS	Engineering Student Services (UNM)
FY	Fiscal Year
IMAC	International Modal Analysis Conference
ME	Mechanical Engineering
NEO	New Employee Training
NEPA	National Environmental Policy Act
NOMAD	Nonlinear Mechanics and Dynamics
Q&A	Questions and Answers
R&A	Review and Approval
SNL	Sandia National Laboratories
UNM	University of New Mexico
US	United States
USD	US Dollar

1. INTRODUCTION

The Nonlinear Mechanics and Dynamics (NOMAD) Research Institute united graduate-level and highly qualified undergraduate-level students from around the world to work on challenging research problems in engineering mechanics and dynamics. Students worked in teams of three under the guidance of mentors from Sandia National Laboratories, the University of New Mexico, and other universities from around the world to address research activities defined by the project leaders and NOMAD organizers. The Institute ran for seven weeks during the summer of 2019 at the Mechanical Engineering building on the University of New Mexico campus. Students attended weekly technical seminars and presented their research progress within their project teams on a weekly basis. At the end of the program, the project teams completed a proceeding document for a technical conference and presented their work at the final NOMAD seminar that was broadcast to Sandia and external collaborators.

Students who participated in the Institute developed as researchers by gaining technical knowledge in nonlinear mechanics and dynamics, while improving their written and oral communication skills. Sandia benefited from NOMAD through the development of collaborative relationships with the external engineering community and within Sandia. Engagement with technically skilled students enhanced the staff recruiting pipeline for Center 1500: Engineering Sciences, and beyond. The photograph in Figure 1 shows some of those who participated.

Figure 1. Some of the participants of the 2019 NOMAD Research Institute

The 2019 NOMAD Institute consisted of seven technical projects that engaged 20 students and 29 mentors from around the world. The program was supported by the Advanced Simulation and Computing (ASC) program and Delivery Environments (DE) program. In addition, the NOMAD organizing team was awarded CIF funding along with an additional support from Mike Pasik to fund a project. The total budget provided labor support for the program director, Rob Kuether, and the students, limited labor support for mentors, research and logistics contract to Tariq Khraishi at UNM, experimental equipment and supplies, group event expenses, and invited speaker costs. Commercial sponsors at Siemens LMS and Polytec provided experimental equipment and software to support the Institute work at no cost. The Structural Dynamics department, org. 1522, provided additional Sandia equipment for the NOMAD laboratory. This SAND report documents the programmatic details related to the 2019 NOMAD Research Institute.

2. PROGRAMMATIC DETAILS

2.1. Lessons Learned and Changes from 2018

Several lessons were learned from the previous NOMAD 2018 Institute. A summary of these lessons is provided below including the efforts made in 2019 to address them:

- Several of the students felt disconnected from Sandia having spent most of the summer at the University of New Mexico. The NOMAD organizers took this feedback into consideration and scheduled a full day tour of Sandia facilities and lab spaces. Additionally, the intern career fair was made available to the students, which was held on site at Sandia. Future institutes will further improve on this by asking management to give brief overviews of their departments.

- There were challenges associated with setting up SNL laptops during the first week, such as trouble logging into computers, administrative control and network access issues, and issues with program installation. This year, the NOMAD organizers worked closely with the CSU team and even had two computer support technicians on-site at UNM for the first Wednesday of the program. This significantly reduced the time to establish computer connections from three days down to one day.

- The students requested better access to printing resources, as the printers provided by the university presented some challenges. In NOMAD 2019, the organizers brought a printer into the office to allow students to print various documents directly from their SNL laptops.

- In 2018, the office space in room 320 was arranged such that the students felt crowded. This year, the NOMAD organizers attempted to put desks for students in the laboratory to manage the number of desks in the office space in 320. This was effective at reducing the office congestion, however new challenges arose with overcrowding in the laboratory. Future NOMAD plans need to appropriately balance this and potentially find additional lab space to provide safe and comfortable space for all.

- The 2019 NOMAD program reinstated a team building activity on the first day of the program, which allowed the students to interact and get to know one another. This helped build cross-team communications and establish connections that lasted the duration of the summer.

- ❖ Many of the project teams utilize Sandia's simulation tools such as Cubit and Sierra. In past years, the knowledge transfer of these program's capabilities was handled at the project level. This year, a one-hour tutorial was provided to all the students to give an overview of the mod/sim tools used at Sandia and within the NOMAD program. This helped cover many common topics that the students would need to understand for their project goals, alleviating some of the burden on the mentors.

2.2. Project Selection Process

A total of seven projects were selected for the 2019 NOMAD Research Institute. Several interested parties were contacted early in the Fall of 2018 to solicit ideas and organize mentor teams. The organizing team sought projects that satisfied the following requirements: 1.) Safety and Security, 2.) Quality, 3.) Impact, and 4.) Likelihood of Success. The mentors who participated in the 2019 Institute include:

- Abdu Abdelkefi, New Mexico State University
- Ben Pacini, Sandia National Laboratories
- Ben Zastrow, Sandia National Laboratories (ATA)
- Cory Medina, Sandia National Laboratories
- Dan Roettgen, Sandia National Laboratories
- Dane Quinn, University of Akron
- Ed Habtour, Sandia National Laboratories,
- Edmundo Corona, Sandia National Laboratories
- Emily Miller, Sandia National Laboratories
- Gustavo Castelluccio, Cranfield University
- Jeff Smith, Sandia National Laboratories
- John Mersch, Sandia National Laboratories
- Jonel Ortiz, Sandia National Laboratories
- Karl Walczak, Sandia National Laboratories
- Keegan Moore, University of Nebraska-Lincoln
- Kelsey Johnson, Sandia National Laboratories
- Kyle Johnson, Sandia National Laboratories
- Mark Wilson, Sandia National Laboratories
- Nathan Jackson, University of New Mexico
- Neal Hubbard, Sandia National Laboratories
- Normand Modine, Sandia National Laboratories
- Pat Logan, University of Massachusetts-Lowell
- Peter Avitabile, University of Massachusetts-Lowell
- Rob Flicek, Sandia National Laboratories
- Rob Kuether, Sandia National Laboratories
- Scott Grutzik, Sandia National Laboratories
- Simone Manzato, SISW
- Tariq Khraishi, University of New Mexico
- Yu-Lin Shen, University of New Mexico

A short description of the seven down-selected projects are given below:

- ❖ **Project 1: Mechanics of bolt loosening under dynamic loads**

Mentors:
John Mersch (SNL), Jeff Smith (SNL), Rob Kuether (SNL), Jonel Ortiz (SNL), Gustavo Castelluccio (Cranfield), Keegan Moore (UNL)

Bolt loosening occurs when a joint loses preload during exposure to dynamic loads such as mechanical shock or random vibration. A threaded fastener tends to loosen when the friction forces between the external and internal threads are overcome by external loads or actions acting on the bolted joint. Existing theories agree to this mechanism; however, several opposing theories exist as to what actions cause the reduction or loss of frictional forces. To better understand the mechanics of bolt loosening, the NOMAD team will be tasked with performing a combined experimental-computational study on a bolted structure. The computational portion of the study will include the development of a high-fidelity finite element model of a fastener to account for thread geometry and frictional contact interactions between the threads. This model will be exposed to various cyclic loads to quantify loss of preload force. These simulations will be complemented with an experimental study of the joint to further investigate the underlying mechanics of the structure and validate the analysis model. Fasteners instrumented with strain gages will be utilized to monitor and measure the loss of preload during harmonic excitation and relate this data to the corresponding model. The goal of the project is to gain a better understanding of the mechanics of bolt loosening and the mechanisms responsible for the loss of frictional restraints.

- ❖ **Project 2: Investigation of electrical contact chatter in pin-receptacle contacts**

Mentors:
Robert Flicek (SNL), Kelsey Johnson (SNL), Karl Walczak (SNL), Cory Medina (SNL), Dane Quinn (Akron), Ben Zastrow (ATA), Robert Kuether (SNL)

Electrical contact chatter refers to the loss of good electrical current flow through a closed circuit. This is generally defined as the electrical resistance exceeding a threshold for a specified time duration. Electrical contacts are often subject to random vibration environments during their service life (e.g. commercial aerospace components during flight), and design engineers must have confidence that the electrical contacts in their product will pass a good electrical signal in all anticipated environments. However, the fundamental physics governing chatter is still poorly understood, partly because it is inherently a multi-scale, multi-physics problem involving length scales from the component dimensions (order cm) down to surface texture (order nm), occurring on time scales on the order of ns, requiring consideration of disciplines such as contact mechanics, structural dynamics, tribology, lubrication, electrostatics, etc. The objective of this project is to develop a calibrated model of a simplified chatter tester, consisting of a single pin-receptacle contact pair. This may involve designing, building, and performing experiments with the chatter tester and obtaining surface displacement data using a Scanning Laser Doppler Vibrometer while simultaneously monitoring for chatter events and excitation. Numerical models will then be developed and calibrated, with the goal of understanding which parameters have the greatest influence on chatter performance.

❖ Project 3: Force reconstruction at mechanical interfaces

Mentors:
Peter Avitabile (UMass-Lowell), Dan Roettgen (SNL), Ben Pacini (SNL), Rob Kuether (SNL), Pat Logan (UMass-Lowell)

Previous work has shown that force reconstruction methods can predict an applied force's magnitude and location with a high degree of accuracy. An extension of these methods to characterize bolted connections is proposed. The effect of a joint on a structure with bolted connections could be conceptualized as a force applied to the connected linear components. Force reconstruction can be used to predict these forces and allow the effect of a joint on structure to be characterized without needing to assume a specific model for the joint's characteristics. To explore this application, two large beams will be assembled using a mechanical interface incorporating discrete contact elements with integrated force sensors. The NOMAD team will be tasked with accurately predicting the force the contact elements apply to the beams and confirming the results with the measured forces. The goal of the project is to explore the potential of characterizing a joint using force reconstruction and lay the groundwork for applying these methods to a more representative system.

❖ Project 4: Modeling and experimental validation of a pylon subassembly mockup with multiple nonlinearities

Mentors:
Simone Manzato (SISW), Rob Kuether (SNL), Dan Roettgen (SNL), Ed Habtour (SNL), Abdessattar Abdelkefi (NMSU)

The industrial approach to nonlinearities in structural dynamics is still very conservative, particularly from an experimental point of view. A demo aluminum aircraft used by Siemens PLM has been equipped with discrete nonlinear elements designed to replicate real-world engine pylon subassemblies to increase awareness on the effects of nonlinearities on design, and understand how these effects can be positively exploited, if properly understood. After some preliminary experiments aimed at understanding the coupled behavior of the aircraft-pylon mockup, it became clear that more in-depth numerical and experimental analysis are required on the pylon subassembly alone. The pylon element is expected to show three main sources of nonlinearities: (1) geometric nonlinearities of the connecting beam, (2) contact as the beam presses into the tapered block surface and (3) friction in the bolted connections. The goal of the project is to create a high-fidelity finite element model of the pylon subassembly to include all nonlinear physics and understand which nonlinear sources contribute most to the complex dynamic response. The model predictions will be validated with experimental data collected on a dedicated test fixture to analyze the nonlinear dynamic behavior of the pylon, leading to better understanding of the subassembly once it connects to the aircraft.

- ❖ **Project 5: Development of reactive potentials for molecular dynamic simulations**

Mentors:
Mark Wilson (SNL), Scott Grutzik (SNL), Normand Modine (SNL)

Reactive bond-order potentials are known to provide high accuracy for pair-interactions in atomistic molecular dynamics (MD) simulations. These potentials lack predefined bonds between atoms, and instead make estimates to interatomic bond-orders resulting in chemical bonds that can change at each simulation time step. This reversible bonding dynamics offers a capability to model chemical reactions in MD that is highly desirable for studying material performance and failure modes in nonequilibrium conditions (e.g. corrosive atmospheres or exposure to environmental species). When employing these types of potentials, one is limited to the available elemental constituents in a given potential, significantly reducing accessible material systems. Within the NOMAD project, the computational effort will seek to expand and develop novel material parameterizations for reactive potentials. The NOMAD team will work in a collaborative environment, tasked with design and implementation of a computational optimization method necessary for the parameterization. The team will build upon existing methods, adding complexity and detail.

- ❖ **Project 6: Indentation of heterogeneous materials: Factors affecting the indentation results and a comparison to bulk material testing**

Mentors:
Tariq Khraishi (UNM), Yu-Lin Shen (UNM), Kyle Johnson (SNL), Scott Grutzik (SNL)

Instrumented indentation has seen widespread applications for characterizing mechanical properties of materials. The technique involves the measurement of applied load and penetration depth, when the indenter is pressed against the test material. Analysis of indentation data has largely been based on theories which deal with homogeneous materials with a unique form of mechanical response (such as elastic-plastic). On the other hand, indentation behavior of heterogeneous materials, with indentation penetration well into the composite microscopic features, is much less understood. This project aims at studying the correlation between the indentation-derived material properties (e.g., elastic modulus and hardness) with the overall (macroscopic) mechanical properties, for materials containing microscopic constituents with distinctly different mechanical features. Examples of such materials include hard particles embedded within a ductile matrix, porous materials, and alternating hard-soft multilayer thin films. Finite element models incorporating sufficient details of microstructural heterogeneity will be constructed, and the models will be subjected to indentation loading as well as overall compressive loading. Simulation results from the two forms of loading will be compared, and deformation features at the micro-constituent level will be examined. The numerical findings will also be contrasted with available experimental data.

❖ Project 7: Validation of puncture simulations with various probe geometries

Mentors:
Neal Hubbard (SNL), Emily Miller (SNL), Edmundo Corona (SNL), Yu-Lin Shen (UNM)

Ductile fracture is a complex phenomenon that continues to attract substantial attention from researchers in solid mechanics. Sharp objects in a production environment can puncture fragile components made from ductile metals. Nonlinear dynamic simulations are utilized to help engineers plan processes such that these components do not fail under these loading environments. Previous work has produced experimental and finite element modeling results, but these efforts have not been coordinated and have been simplistic with respect to probe geometry. A previous NOMAD project from 2018 identified the constitutive and failure models that will be used with the material of interest. The team in 2019 will continue their work by correlating finite element modeling results to experimental data in a coherent way while exploring whether probe geometry has a significant effect on the energy required to penetrate the target. The team will first incorporate the experimental and modeling results from previous efforts to fill in any technical gaps. They will then use the experimental results to validate and refine their modeling and calibration procedure, for example, by adding geometric complexity to the probe models. The goal of the project will be to conclusively determine the significance of probe geometry, which has only been implied in prior work, to inform future experimental validation efforts.

2.3. Student Participant Selection Process

The NOMAD committee began recruiting students once the projects were down-selected so the students could be placed based on their research interests and skillset. The goal was to recruit three students per project, resulting in a target number of 21 participants. Two types of positions were available to the prospective students: no-fee agreement visitors and summer internships. The visitors were not hired on-roll at Sandia and allowed us to recruit students funded under certain fellowships (e.g. NSF). The summer internships were handled through the Student Intern Program (SIP) at Sandia.

Recruiting efforts relied heavily on distribution material sent to external university collaborators. A flyer crafted by Stephanie Blackwell in Creative Services served as our main distribution; the flyer is shown in Appendix A. Information on the flyer included dates, benefits, targeted disciplines, website and short project descriptions. All project mentors were asked to distribute the flyer to any university contacts who may have interested students. The summer internship positions were posted to the external Sandia website; the job posting is shown in Appendix B. With these recruiting efforts, over 150 students applied to the NOMAD program and 20 students were selected to participate in the 2019 Institute:

- Adam Bouma, New Mexico State University
- Benedict Pineyro, Embry-Riddle
- Brett Tucker, University of Alabama
- Brianna Johnson, Texas A&M
- Caleb Foster, Mississippi State University
- Chris Schumann, University of Wisconsin
- Christopher Johnson, University of Illinois at Urbana-Champaign
- Christopher Salazar, University of Rhode Island
- Connor Ligeikis, University of Connecticut
- Debby Fowler, University of Massachusetts @ Lowell
- Devyn Rice, New Mexico State University
- Fadi Rafeedi, University of California @ Los Angeles
- Helen Cleaves, North Carolina State
- Justin Shim, Michigan State University
- Matthew Cleal, University of New Mexico
- Max Miller, Rensselaer Polytechnical Institute
- Noah Sonne, University of Colorado @ Boulder
- Samuel Parker, University of Texas @ Austin
- Taylor Mason, Alabama University
- Thomas Adams, University of New Mexico

2.4. Facilities

The 2019 Institute was held at the ME building on the north campus of UNM. This off-site location provided lab and office space readily accessible by the students and housed all the amenities needed for the technical projects. UNM facilities provided office space for the students in room 320; the desk layout is shown in Figure 2. Adjacent to the student offices, the students were provided access to the computer labs with a guest Lobo ID card. UNM's Engineering Student Services (ESS) helped provide administrative support by collecting all necessary information and setting up guest student accounts. The students had access to a variety of UNM facilities, computer access and other amenities.

In addition to the office space, a personal office was provided for Rob Kuether on the third floor in room 323. A laboratory on the first floor provided sufficient space to set up the experimental equipment needed for Projects 1-4. A NEPA was in-place from the previous year to cover the ME building in 2019; these need to be re-submitted every three years. Each team utilized either an isolation table or a frame structure to set up their test hardware, fixturing, data acquisition and laptop computers. Additional rooms throughout the ME building were able to be reserved to hold weekly meetings, seminars, tutorials and other informal gatherings. The photograph in Figure 3 shows the students gathering in the auditorium for a project meeting.

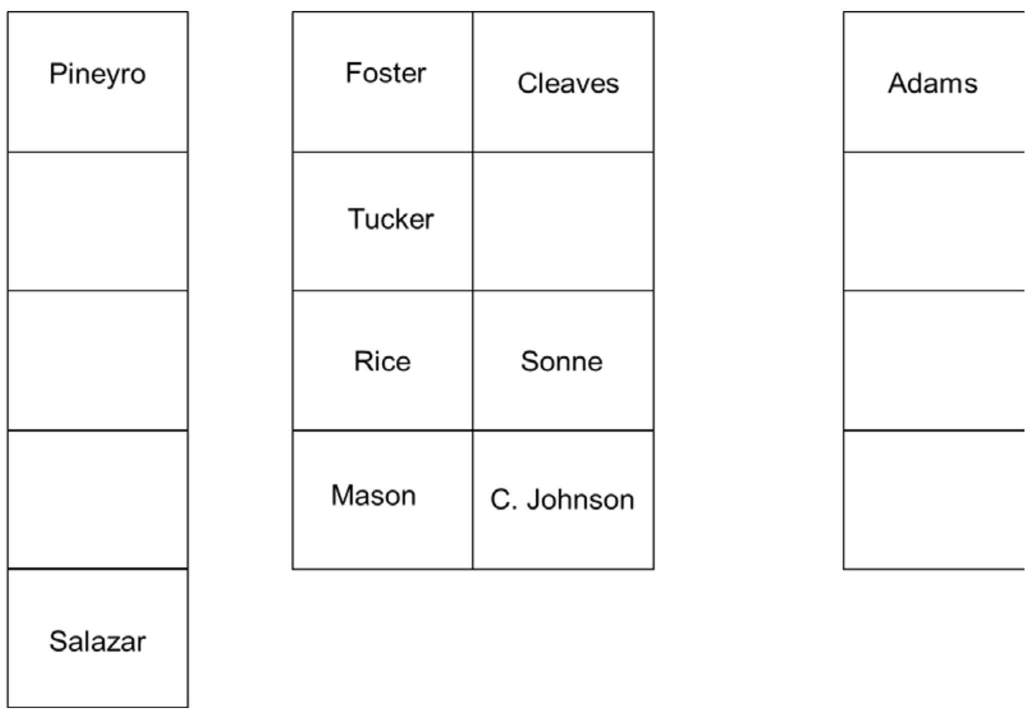

Figure 2. Office assignments for room 320 in the ME building

The auditorium on the main floor was reserved for the initial kickoff meeting, as well as the final student seminar. UNM provided daily parking passes for visitor use and weekly passes for Rob Kuether, who was on site for the duration of the program. These passes provided a number of parking options, including street parking on Redondo Dr. During the summer session, many of the students were absent from the university and there was enough parking during working hours. The ME building space did not present any notable challenges to the students or the organizers. Many of the visiting students stayed at the Casas del Rio dormitories on the north end of campus. The dorms provided a nice living space for the students, and had a lot of amenities including shared kitchens, laundry facilities, computer and printer access, common areas with cable television, and arcade/game room. A free UNM shuttle was available to the students to transport between the dorms and ME building during their stay, however many chose to take the 10-minute walk.

Figure 3. Auditorium in ME building

2.5. Calendar of Events

A summary of the events planned for the 2019 NOMAD Research Institute is given in Table 1. The following subsections provide further detail of the Seminars and Tutorials, Tours and Extracurricular Activities, and Final Student Presentations.

Table 1. Event calendar for NOMAD 2019

Monday, 6/17:	NEO Training for New Hires
Tuesday, 6/18:	Official Start of NOMAD 2019 Kickoff Presentations, Team Building and Training Welcome Dinner at Sadie's of New Mexico
Wednesday, 6/19:	Sierra/CUBIT Tutorial by Cory Medina and Jonel Ortiz
Thursday, 6/20:	Seminar by Matt Allen
Wednesday, 6/26:	Siemens/LMS Tutorial by Bill Flynn
Thursday, 6/27:	Seminar by Keegan Moore
Friday, 6/28:	Albuquerque Isotopes Baseball Game
Wednesday, 7/3:	Tour of the Museum of Nuclear Science and History
Monday, 7/8:	Presentation by Pat Logan
Wednesday, 7/10:	Seminar by Peter Avitabile
Thursday, 7/11:	Intern Career Fair at SNL
Tuesday, 7/16:	Seminar by D. Dane Quinn
Thursday, 7/25:	Final Student Presentations
Monday, 7/29:	Tours of Sandia National Labs
Tuesday, 7/30	Seminar by Yu-Lin Shen NOMAD Farewell Dinner at La Salita
Wednesday, 7/31:	Lunch Hosted by UNM for NOMAD Participants
Thursday, 8/1:	Last Day of NOMAD 2019

2.5.1. Seminars and Tutorials

A bulleted list of the technical seminars and tutorials given throughout the summer are given below. The objective was to supplement the research activities with educational lectures to expose the students to a vast array of topics they may encounter when working at a national laboratory. A brief description is provided beneath the tutorial titles, while the abstracts and speaker biographies are given for the technical seminars.

- **Sierra/CUBIT tutorial by Cory Medina and Jonel Ortiz**

The 1-hour tutorial covered the use of Sandia's finite element software packages that were used by most groups throughout the summer. Cory Medina and Jonel Ortiz are both staff members in the Component Science & Mechanics department, org. 1556 and provided the overview and short demonstration. In addition to the tutorial, they authored and distributed a document that served as a starter kit to learn SNL's mod/sim tools.

- **"Siemens/LMS Tutorial" by Bill Flynn**

Bill Flynn from Siemens/LMS visited NOMAD for a day to brief the experimental students on the data acquisition hardware and software they would be using to collect vibration data in the lab. He presented an overview of his company's capabilities and some of their newest products. Following his presentation, he provided direct feedback to each of the experimental setups and answered questions for the students. Bill has supported NOMAD for a number of years by donating data acquisition systems and temporary software tokens.

- **"Leveraging Quasi-Static Modal Analysis for Nonlinear Transient Dynamics of the Multi-Purpose Crew Vehicle" by Professor Matt Allen**

Nonlinear transient dynamic simulations are typically avoided in coupled loads analysis of launch vehicles because they would dramatically increase the complexity and computational cost relative to well-validated linear methods. In the case where a spacecraft exhibits significant nonlinearities during test, the typical approach is to correlate an effective linear model which matches the test article response at flight load levels. This work presents an alternative workflow based on the concept of quasi-static modal analysis. Assuming that the nonlinearities are hysteretic in nature and that mode shapes remain largely invariant with load level, a set of quasi-static structural analyses can be used to accurately estimate the changes in frequencies and effective damping ratios with increasing amplitude. Furthermore, a Bouc-Wen or other appropriate hysteretic representation can be used to efficiently simulate the transient response of a nonlinear modal or Hurty/Craig-Bampton model. This presentation first presents a brief review of research in the nonlinear dynamic response of structures with joints, and discusses modeling approaches including full-order nonlinear modeling in FE software, Quasi-Static Modal Analysis and reduced models with spiders and whole joint models such as the Iwan element. The methods are then demonstrated using loads that are representative of those applied to test hardware developed to support the Orion Multi-Purpose Crew Vehicle. Future applications could include support of nonlinear model correlation, uncertainty quantification in the presence of nonlinearity, and cross-checking of linear models tuned to represent flight level loads.

Matt Allen joined the faculty of the Engineering Mechanics program in the department of Engineering Physics at the University of Wisconsin-Madison in 2007. He was previously employed as a post-doctoral researcher at Sandia National Laboratories and received Doctoral and M. S. degrees from the Georgia Institute of Technology in 2005 and 2004 and a B.S. in Mechanical Engineering from Brigham Young University in 2001. His current interests include: nonlinear dynamic systems, experimental/analytical substructuring techniques, damping and nonlinearity due to bolted interfaces, system identification, biomechanical systems, … or in other words just about anything related to structural dynamics! He also enjoys downhill skiing, mountain biking, music, Spanish and playing card games with his kids.

- **"Reduced-order Modeling of Loosening in Bolted Joints Subjected to Axial Shock Excitation" by Assistant Professor Keegan Moore**

Maintaining preload in bolted joints is critical for safe and efficient operation of nearly all built-up structures. Dynamic loss of preload during operation occurs when sufficient shear force is applied to the joint such that slip is induced the threads. Such shear forces are often realized when the joint is subjected to sustained vibrations, resulting in loosening over relatively long periods of time, or extreme shock loading where loosening occurs over fractions of a second. Modeling of joint loosening often focuses on complex analytical approaches or high-fidelity simulations using finite element models. While such approaches may succeed for a single joint, they are unfeasible for use in simulations of entire built-up structures, which may possess dozens to thousands of joints. Thus, there is a need for reduced-order models (ROMs) that capture the dominant governing physics, but at drastically lower computational costs. This talk focuses on two approaches for reduced-order modeling of bolted joints with application to wave scattering across a threaded joint in a split-Hopkinson pressure bar subjected to extreme axial shock loading. The first approach models the joint using an adjusted Iwan element, identifies the unknown parameters using only the primary wave transmission and reflections. The resulting model is shown to reproduce the short-time response, but not the long-time response during and after loosening. The second approach introduces a new ROM for loosening in bolted joints subjected to axial shock excitation. The model introduces a mathematical relationship between the stiffness and torque of the joint and treats the torque as a dynamic internal variable governed by a first-order, ordinary differential equation. The resulting model is shown to capture the dominant effects of loosening in the joint and reproduce the long-time response.

Keegan J. Moore is an Assistant Professor in the Department of Mechanical and Materials Engineering at the University of Nebraska-Lincoln. He received his Ph.D. from the University of Illinois in 2018 and his B.Sc. from the University of Akron in 2014. He is an expert in theoretical and experimental linear and nonlinear dynamics and vibrations, and his work spans analytical, computational and experimental applications of nonlinear modal analysis. His current research focuses on data-driven methods for nonlinear system identification, reduced-order modeling and model updating of strongly nonlinear dynamical systems.

- **"Nonlinear Contact Force Reconstruction Using an SVD/Modal Filtering Approach" by Pat Logan PhD Candidate**

Inverse processes are often necessary to assess operating loads, especially when the loads are difficult to measure directly. Reconstruction is generally performed from vibration response data and some form of system model. Where some mismatch in dynamic behavior exists between the model and the real system, the estimated loads may be distorted. However, if the changes in system behavior are of interest, then those changes may be characterized through force reconstruction as

equivalent loads acting in conjunction with the original external inputs. These system changes may be linear in nature, but the concept may be extended to nonlinear behavior, including intermittent contact between components.
A modal based methodology for localization and reconstruction of inputs at potentially unmeasured locations is applied to the characterization of local system changes through their equivalent loading. Experimental studies are presented using a multi-plate structure subject to impact loading and an unmodeled contact condition.

Patrick Logan is a PhD student at the University of Massachusetts Lowell. Patrick has been a member of the Structural Dynamics and Acoustic Systems Laboratory since 2014, and is anticipating completion and defense of his dissertation, Force Reconstruction Beyond Measured Points, by the end of 2019.

- **"Highly Reduced Order Analytical Models Incorporating Measured Experimental Data for Full-Field Dynamic Response/Strain for Linear and Non-Linear Systems" by Professor Emeritus Peter Avitabile**

Dynamic response due to operating and occasional loads is an important consideration in the design of many structural systems. Obsessively large finite element models dominate the engineering community but often times are too cumbersome due to their computational needs; in addition, incorporation of measured data at limited points in an effective and meaningful manner pose difficulties.
Over the past decade, several new approaches have been developed that allow for limited sets of measured data, in conjunction with a finite element model, to be used for prediction of full-field linear response. The limited sets of measurements are used with a unique expansion algorithm to obtain this full field information. The technique is extended to linear components interconnected with nonlinear connection elements to also predict full-field dynamic response and dynamic strain.

The techniques presented are currently being extended for force estimation and damage detection applications and other applications.

B.S.M.E., Manhattan College, M.S.M.E., University of Rhode Island, D. Eng., University of Massachusetts Lowell, Professional Engineer, Rhode Island, Professor Emeritus, Mechanical Engineering, University of Massachusetts Lowell, Co-Director, Structural Dynamics and Acoustic Systems Laboratory, Director, Modal Analysis and Controls Laboratory, President Society for Experimental Mechanics 2016, Associate Editor – Handbook of Experimental Structural Mechanics

The Structural Dynamics and Acoustic Systems Laboratory (SDASL) focuses on research related to analytical and experimental problems in the areas of structural and acoustic systems. The main thrust of the SDASL is to develop, employ and improve techniques to solve these problems using analytical approaches that are verified through experimental techniques.

Over 4 decades experience in design, analysis, finite element modeling and experimental modal and structural dynamic testing. Main area of research is structural dynamics specializing in the areas of modeling, testing and correlation of analytical and experimental models and integration of analytical and experimental techniques. Research, testing and consulting performed for automotive, aerospace, defense and computer/consumer related areas. Written over 200 technical papers and given numerous seminars in the areas of experimental modal analysis, structural dynamics, vibration fixture design, and modeling and correlation.

- **"When the answer is almost right: An introduction to perturbation methods" by Professor D. Dane Quinn**

We like simple equations; linear equations are simple; we like linear equations. More specifically, we can often solve linear equations to obtain a closed form solution that can be used for prediction and design. Unfortunately, most systems in science and engineering are not linear and their models have no closed form solution. As a result, such nonlinear models are often difficult to use for design. However, models of physical systems are often "close" to linear; the model for the physical system looks like a linear system but with some extra nonlinear terms that are small, and it's these small nonlinearities that destroy our perfect linear world.

Perturbation methods describe a collection of approaches to approximate the solution to nonlinear equations that are almost linear, referred to as weakly nonlinear. These techniques make use of the known solution for the related linear problem, which is then modified to develop an approximate solution to the original nonlinear problem. This talk will introduce a variety of such techniques including regular and singular perturbation methods, and will highlight both how they are developed and when they can be applied.

D. Dane Quinn was awarded the B.M.E. degree from Georgia Tech in 1991 and, in 1995, a Ph.D. from Cornell University in the Department of Theoretical and Applied Mechanics. He is currently a Professor on the faculty of The University of Akron in the Department of Mechanical Engineering. and also serves as the Associate Dean for Undergraduate Research in the Williams Honors College. His research interests lie in the area of applied dynamical systems and mechanics, but when not thinking about nonlinear dynamics, he runs, plays soccer, and is the lead cowbell player in an Akron-area band.

- **"Indentation Behavior of Metal-Ceramic Multilayer Thin Films: Modeling vs. Experiment" by Professor Yu-Lin Shen**

Thin films consisting of alternating metal and ceramic layers are an exciting subset of materials with many promising attributes. This presentation highlights our recent studies on mechanical characterization of such coatings using nanoindentation. We focus on aluminum (Al)/silicon carbide (SiC) nanolayers, which serves as a model system for investigating the constraining effect due to the highly mismatched mechanical properties of the constituents. How this structural heterogeneity responds to nanoindentation is a current a subject of active research. The development of complex deformation patterns underneath the indentation, dictated by the structural heterogeneity, can lead to various forms of local damage. Our studies focus on the employment of numerical finite element modeling to corroborate with experimental observations as well as to extract meaningful constitutive properties. Special attention is given to the analyses of (i) plastic deformation in the metal layers, (ii) cyclic indentation response and composite modulus measurement, (iii) indentation-induced delamination, and (iv) indentation-induced shear band formation.

Professor Yu-Lin Shen received his Ph.D. in engineering from Brown University in 1994, and M.S. and B.S. in materials science and engineering from National Tsing Hua University in Taiwan. He was a post-doctoral research associate at Massachusetts Institute of Technology before joining University of New Mexico (UNM) in 1996. He is currently Professor and Chair in the Department of Mechanical Engineering at UNM. Professor Shen has been active in research and teaching in the areas of mechanical behavior of materials and solid mechanics. He is particularly well versed in applying modeling techniques to address micro-mechanical problems related to thin films, microelectronic devices and packages, and composite materials. He has published about 200 research papers, mostly in the form of journal articles. His book titled "Constrained Deformation of Materials" was published by Springer in 2010. In 2005 Professor Shen was elected Fellow of the American Society of Mechanical Engineers (ASME).

2.5.2. *Tours and Extracurricular Activities*

Throughout the summer, several extracurricular activities were planned to entertain the students and expose them to a few of the local attractions in Albuquerque, including a tour of the New Mexico Museum of Natural History & Science to expose the students to some of the rich history of New Mexico. A description of each event is provided below.

- **Welcome Dinner at Sadie's of New Mexico**

The kick-off dinner was organized to welcome the incoming students to New Mexico and provide a chance to get to know everyone in a social setting. There were also a number of professors visiting during this first week who were able to join in. The Sadie's of New Mexico location was chosen due to their ability to host large groups, and to introduce the students to the New Mexican cuisine unique to the region. The visiting students enjoyed tasting New Mexican dishes and left them curious about other food and restaurants around town.

- **National Museum of Nuclear Science & History Tour by Andy Rogulich**

In the third week, the students were brought to the National Museum of Nuclear Science and History, commonly referred to as the Nuclear Museum. This museum is a Smithsonian affiliate and is housed on Kirtland Air Force Base property, operated in part by Sandia. The tour was led by Andy Rogulich, a museum docent, who is retired from Sandia. The tour consisted of a historic overview of how the US began their atomic research, how WWII impacted our work to create an atomic bomb, and a tour of all of the museum exhibits related to nuclear weapon history. The tour covered 80 years of history in an hour and a half. The museum requested the tour groups include no more than 20 attendees with 10 – 15 attendees being the ideal group size. Admission is $12 per person, but the museum gives a discount for large Sandia groups ($8 per person). The tour lasted around 90 minutes, ending with a visit to the outdoor exhibition. The museum is open to the public, so there were no special considerations for accessing this tour.

- **Isotopes Baseball Game**

An evening at an Albuquerque Isotope's baseball game provided an additional opportunity to enjoy some time together and have some fun. The NOMAD organizers purchased a group of tickets along the first base line in the lower deck. The attendees enjoyed "ballpark" refreshments and snacks while watching the Isotopes play. This particular game was chosen since there were fireworks following the game. NOMAD was recognized on the scoreboard during the game, as shown in Figure 4 below. Regardless of whether the attendees liked baseball or not, a good time was had by all.

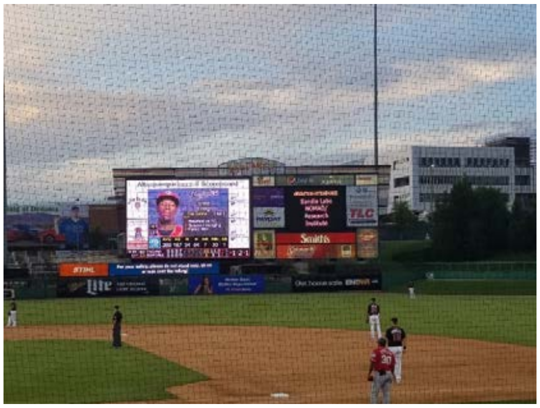

Figure 4. NOMAD group recognition at the baseball game

- ❖ **Intern Career Fair at Sandia National Labs**

Student Programs hosted their fifth annual onsite Intern Career Fair. This event is intended for students to discuss career opportunities at Sandia with recruiters and managers representing various divisions at Sandia. The Intern Career Fair is designed to increase interns' knowledge of the variety of exciting work performed at Sandia as well as encourage them to seek further employment with Sandia. The career fair booths were divided into the following disciplines:

  - Business/Other Mission Support
  - Computer Science/Cyber
  - Electrical/Computer Engineering
  - Materials Science & Engineering
  - Mechanical Engineering
  - Other Science & Engineering

- ❖ **Tours at Sandia National Labs (Full Day)**
  - **Technology Training and Demonstration Area**

Sandia's Technology Training and Demonstration Area (TTD) showcases technologies that can be cooperatively applied to a range of monitoring applications across the globe:

  - ➢ Nonproliferation
  - ➢ Counterterrorism
  - ➢ International security (including border security)
  - ➢ Arms control

The TTD is regularly employed to brief US government officials, academic colleagues, and industry partners. It also serves as a training and demonstration facility that hosts various courses and workshops, as well as a space for testing certain technologies in an open environment.

For maximum transparency, all of the technologies on display in the TTD are unclassified and exportable. Technologies in the facility were developed by industry; internally; or as part of National Nuclear Security Administration (NNSA), Department of Defense (DoD), and Department of Energy (DOE)-funded projects.

  - **National Security Technology Gallery**

The National Security Technology Gallery tour is a high-level overview of Sandia capabilities featuring current technologies. Particular emphasis is placed on Sandia's ability to draw on a vast Nuclear Weapons technology base that has enabled us to support the broader national security communities. Sandia's system approach to solving problems and our skill in applying "science with the mission in mind" are highlighted. Hardware, software, video clips and hands-on demonstration items are used to bring the technology to life. Historical items provide context for current and forward looking solutions to the nation's most difficult security challenges. We also showcase examples of how Sandia partners with business, industry, and universities to transfer our innovative R&D into the marketplace. The gallery provides value by educating sponsors, customers, visitors, recruits and members of the workforce about the scope of Sandia activities.

  - **Thunderbird Café for Lunch**

- **High Performance Computing Systems**

Corporate Computing Facilities/880 Annex - Primary Sandia National Laboratories data center that houses unclassified and classified enterprise computing, networking and telecommunications equipment. This facility also houses the unclassified and classified high performance compute clusters and mission co-located computing, networking and storage equipment.

- **Hypersonic Wind Tunnel**

The Aerosciences Test Capabilities facility, located in Tech Area 1, houses a Hypersonic Wind Tunnel, which is able to produce Mach 5, 8, or 14 flow past a model, and a Trisonic Wind Tunnel capable of producing flow velocities from Mach 0.5 to Mach 3. The facility supports Sandia research on fundamental aerospace physics, including characterization of vehicles and testing of flight components, and provides data to develop and validate computational models.

- **860 Lab**

The components and systems designed and built at Sandia National Laboratories will see a variety of normal, hostile, and abnormal environments throughout the duration of their lifetime; as much as 30 years. The testing done in building 860 aims to replicate as many of these environments as possible. This allows scientists and engineers to ensure their components are built to last the expected lifetime, no matter what they are exposed to. If any failure modes are found, the part can be re-designed to prevent these occurrences from happening during service life.

- **Farewell Dinner at La Salita**

A farewell get together at La Salita was a chance for the NOMAD group to reminisce about the seven weeks and wrap up the Institute. The students were able to get their last "green chili fix" and share some of their thoughts and experiences about the Institute. The dinner was held on the last Tuesday night of the program.

- **Farewell Lunch Hosted by UNM**

A delicious lunch was provided by UNM to show their appreciation for the participants of NOMAD. This was a great opportunity for UNM staff and the Dean of Mechanical Engineering, Christo Christodoulou, to visit with the students about the program and say their farewells.

2.5.3. Final Student Presentations

To close out the NOMAD Research Institute, the students were asked to present their research at a final technical seminar. The event was held in the main auditorium of the Mechanical Engineering building. Each group was allotted twenty minutes for presentation and Q&A, typical of what is offered at a technical conference. The students were asked to submit their final slide materials to Rob Kuether by Wednesday July 24th in order to allow sufficient time for R&A to approve the material for unlimited, unclassified release by Thursday, July 25th. On the day of the seminar, many visitors from Sandia and UNM were in attendance to watch the students present their summer work. The talks were also broadcast externally using Skype for Business. A cookie and coffee break was hosted by Sandia at the mid-point of the session. Each of the project's final presentations will be uploaded to the external NOMAD website to showcase the projects to prospective students and mentors.

Figure 5. Project #3 presenting their research at the final technical seminar

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3. FEEDBACK

3.1. Participant Feedback

Following the Institute, the participants were asked to complete a survey consisting of approximately 13 questions. Below is a compilation of their answers paraphrased for succinctness:

1. Was the institute worthwhile for you? Why or why not?

All participants responded that it was worthwhile for them. It gave many of them opportunities to work outside areas of their normal work/things they had never done before. They learned valuable skills, gained knowledge of Sandia and workflow at a National Lab, received hands-on experience and built relationships with a lot of new people.

"Yes, it was a wonderful opportunity, I learned a lot. Working for a National Lab has been a dream and I was not let down."

2. From a technical standpoint, what could have been better (e.g. papers provided earlier)?

Better idea of what the project will be, access to experimental results, papers and previous research. Provide information on what systems and programs will be used, i.e. Paraview, LMS, etc. Test the projects prior and provide pre-institute homework, reading, specific tasks and problems to work on.

3. From a programmatic standpoint, what could have been better (e.g. fewer presentations)?

Weekly seminars were good, once a week was good. Suggestions: have them be more diverse, more fundamental in nature, less high-level. Program was organized, nice if it was longer. Tours at Sandia over 2 days. Team building within teams. More opportunities to learn about work at Sandia, having people present on what they/their departments do would be nice.

4. From a facilities standpoint, what could have been better (e.g. better access to …)?

Most students said more space: lab space, more space upstairs and access to more conference rooms/classrooms. Some mentioned table for experiments and to expedite equipment coming from Sandia.

5. What could the mentors have done better (e.g. more pre-work)?

The students thought the mentors "were great", "phenomenal" and "extremely knowledgeable". Collectively, the students would like more interaction with the Mentors; not only their project mentors, but those of other teams. They would like them more "physically" present. They suggested better planning: more cohesive ideas collectively by the mentors on the projects, to provide more pre-institute homework and be clearer on the direction of the project.

6. What would have improved team dynamics?

Most of the students stated that their team got along great. Suggestions were: more pre-institute meetings, having a student that is very well versed on the subject matter, assessing and assigning roles within the teams at the beginning.

7. What could have been better about the duration, timing, and schedule for the Institute?

All, but 2, of the students said it should be longer. Most said longer by one week.

8. From your experiences this year, what is the ideal sized project team for the Institute?

All, but 2, said 3 was good.

9. What was the highlight of the institute for you?

Many said the Sandia on-site tours, meeting others and making friends. They enjoyed presentation day, exposure to Sandia, conducting interesting research and getting results in the end.

10. If you could, would you participate in the institute next summer if time/money permits?

Most said "of course"/"absolutely" and a couple said they would like to, but will probably find an internship more aligned with there field.

11. How much has the institute contributed to your understanding of the research that's done at other institutions and improved what you (will) do in your research?

Most stated it has contributed to their knowledge greatly (one said, "drastically"). It has broadened understanding of other's perspectives, understanding of the work done at a national lab and a the "bigger picture". A couple of students stated that it has changed their path, giving them a different direction to go in. *"I am going to shift my research to tackle more important issues in engineering."*

12. Do you have any additional comments?

It would have been nice to learn Python. Rob would make a great professor! NOMAD was an awesome experience, thanks so much. No SurfacePros next year and having mentors more physically present would be nice.

13. Please circle the value of the following activities (5 being very worthwhile/useful, 1 being very unnecessary/unhelpful):

<u>Seminars:</u>
Matt Allen's seminar **Leveraging Quasi-Static Modal Analysis for Nonlinear Transient Dynamics of the Multi-Purpose Crew Vehicle**

5 – Very Useful	4	3 – Neutral	2	1 – Not Useful	Did Not Attend
3	**7**	**7**			

Kegan Moore's seminar **Reduced-order Modeling of Loosening in Bolted Joints Subjected to Axial Shock Excitation**

5 – Very Useful	4	3 – Neutral	2	1 – Not Useful	Did Not Attend
3	9	5			1

Patrick Logan's seminar **Nonlinear Contact Force Reconstruction Using an SVD/Modal Filtering Approach**

5 – Very Useful	4	3 – Neutral	2	1 – Not Useful	Did Not Attend
3	7	2	3	2	1

Pete Avitabile's seminar **Highly Reduced Order Analytical Models Incorporating Measured Experimental Data for Full-Field Dynamic Response/Strain for Linear and Non-Linear Systems**

5 – Very Useful	4	3 – Neutral	2	1 – Not Useful	Did Not Attend
6	4	3			4

Dane Quinn's seminar **When the answer is almost right: An introduction to perturbation methods**

5 – Very Useful	4	3 – Neutral	2	1 – Not Useful	Did Not Attend
6	3	8			1

Yu-Lin Shen's seminar **Indentation Behavior of Metal-Ceramic Multilayer Thin Films: Modeling vs. Experiment**

5 – Very Useful	4	3 – Neutral	2	1 – Not Useful	Did Not Attend
1	8	4	1		2

<u>Tutorials:</u>

Cory Medina and Jonel Ortiz's **Sierra/CUBIT Tutorial**

5 – Very Useful	4	3 – Neutral	2	1 – Not Useful	Did Not Attend
5	4	3	2	1	1

Bill Flynn's **Siemens/LMS Tutorial**

5 – Very Useful	4	3 – Neutral	2	1 – Not Useful	Did Not Attend
3	3	2	2		7

<u>Activities:</u>

Welcome Dinner at **Sadie's**

5 – Very Nice	4	3 – Neutral	2	1 – Not Nice	Did Not Attend
14	2				1

Isotopes Baseball Game

5 – Very Nice	4	3 – Neutral	2	1 – Not Nice	Did Not Attend
9	1	1			5

Tour of the **Museum of Nuclear Science and History**

5 – Very Nice	4	3 – Neutral	2	1 – Not Nice	Did Not Attend
10	3				4

Intern Career Fair at SNL

5 – Very Nice	4	3 – Neutral	2	1 – Not Nice	Did Not Attend
3				1	12

Tours of **Sandia National Labs**

5 – Very Nice	4	3 – Neutral	2	1 – Not Nice	Did Not Attend
14	2				

3.2. Mentor Feedback

Following the Institute, the mentors were asked to complete a survey (5 provided feedback). Below is a compilation of their answers:

1. Was the institute worthwhile for you? Why or why not?

The mentors all said that this was worthwhile for them. They enjoy interacting with the students, conducting research through them and bringing new ideas to SNL. They enjoy building relationships with UNM professors, attracting potential employees near the conclusion of graduate school, and providing an opportunity for leadership. One student was converted to year-round status and is now working with SNL.

2. From a technical standpoint, what could have been better (e.g. papers provided earlier)?

The mentors on some of the projects could have done more background work for their projects so that the experiments were better scoped. Seven weeks is a short duration to make progress on a project. Papers should have been provided earlier, hardware should have arrived for pre-testing sooner and the mentors need to be more present.

3. From a programmatic standpoint, what could have been better (e.g. fewer presentations)?

Test set-up issues are meant to be solved by the students but at the same time, some pre-NOMAD work is very valuable to make sure that the work we are expecting the students to do is tractable given their timeframe. Having student presentations in the last week of the project is best. One seminar per week is not too much to ask from students, although it puts more load on the organizers to come up with them.

4. From a facilities standpoint, what could have been better (e.g. better access to …)?

The lab the tests are performed in is way too small and could lead to a tripping hazard. Sometimes the UNM internet connection was slow. It was difficult to monitor jobs on the HPC clusters over a slow network.

5. What could the mentors have done better (e.g. more pre-work)?

More pre-work and better scoping of experimental projects. Some mentors were not available enough. For experimental projects, the mentors need to be available to go to UNM (frequently throughout the week) in order to help their students; help via skype is most often not sufficient. Additionally, showing up in person shows that you support the students and that they are a priority. Breaking up the project into smaller achievable goals would help. The limitation on use of SNL software did not enable two mentors to help out and thus things relied on the SNL mentors to be on top of things.

6. What would have improved team dynamics?

The teams all got along very well. I'm not sure there is a way to improve team dynamics. It would help to have access to more rooms in the mechanical engineering building. The best meeting space was in the atrium. I think the teams will be able to work better if they can spread out a little. More team building. More relevant experience by the students chosen.

7. What could have been better about the duration, timing, and schedule for the Institute?

I think all of these aspects about the institute are good as is. I could certainly plan bigger projects if the institute lasted longer, but that is not necessary. We keep cost down and allow for more teams by keeping the duration short. It makes the interns focus on obtaining solutions and explaining them; there is not time to try a lot of creative ideas, only those that solve the problems. Institute could be 1-2 weeks longer, additionally if the students could come a week earlier or stay at the end the papers could be worked on from SNL.

8. From your experiences this year, what is the ideal sized project team for the Institute?

Three is a good number.

9. What was the highlight of the institute for you?

There were a lot of little highlights throughout which are usually arise out of working with a team on a problem and struggling through it with them and finally figuring out the problem in the end. I really liked seeing the interns succeed in overcoming obstacles. They realized that the problems were challenging and gained confidence that they could find solutions. This batch of students was one of the best yet. Collaboration with 1556 and converting one of the students to year-round intern status.

10. If you could, would you participate in the institute next summer if time/money permits?

The mentors would like to participate again.

11. Do you have any additional comments?

Thanks for putting this together Rob and Brooke! I look forward to it each year! Let me know how I can help! The institute was a great success this year. The interns learned about numerical methods of solving mechanics of materials problems, and I learned new ways to approach our typical problems. The team I worked with was friendly and very capable. I enjoyed my time with the students. They made progress on a project that I needed. SNL now has another strong candidate for future endeavors. NOMAD was a success in my book.

For those of you returning from a previous year, we have a few additional questions:

14. What did this year's Institute do better than your previous experience?

This years' students were much more impressive than last years. I was impressed with how they were all able to work through their problems and come to solutions. The students were very impressive. I liked having a team of 3 interns *vs.* 2 last year. It helps to have an additional collaborator, and it gives the interns a sense of strength in numbers. More organized in events ahead of time compared to last years. More experiments was good, as some students are not good numerically or theoretically.

15. What did this year's Institute do worse than your previous experience?

The (seeming) lack of pre-work and scope put forth by some of the mentors on some of the experimental projects. This led to a lot of last minute equipment transfer between Sandia and UNM which hampers the students' progress and reduces the satisfaction of their experience. Two of the mentors said, "I can't think of anything". Due to application, the projects were more difficult to scope, scoping should be a big focus for future mentors.

3.3. Lessons Learned during 2019

Based on the feedback from the students and mentors, and general observations during the 2019 program, the NOMAD organizing team was able to identify several lessons learned. A summary of these are provided below:

- Several of the experimental projects in 2019 faced challenges with having access to the correct equipment to perform the necessary measurements. The mentor teams need to appropriately size test equipment (e.g. shakers, sensors, etc..) well before the NOMAD Institute to allow enough time for acquisition. Each project team should have an experimentalist to help with preplanning and will be expected to deliver hardware and fixtures to the NOMAD organizers well before the program start. Another consideration would be to bring in one student from each experimental team two to three weeks in advance to learn the experimental setup before starting NOMAD.
- The NOMAD organizing team observed variable commitment from the mentors across the project teams. Several mentors were well engaged with the students; however, some were involved in name only. The NOMAD organizing team needs to communicate the expectations and time commitments of the mentors prior to the start of the Institute. In addition, the NOMAD organizers will establish a schedule of deadlines for the project teams to submit their project plans, test hardware, and other items needed prior to the start of the program.
- In addition to mentor commitment, better preplanning should be expected from the mentor groups to make the project consistent in scope and direction prior to the start. The NOMAD organizers need to communicate the expectations of the project planning document, including pre-institute homework to get the students familiar with the new topics. This project document and homework needs to be released to the students with sufficient time allotted to discuss via teleconference.

- ❖ Lab space was a significant challenge in 2019. The space was organized such that half the students both had experiments and workspaces all within the lab. It was noted that the lab was overcrowded at times. In future programs, this needs to be addressed. One possible mitigation is to obtain additional lab space for the student to establish their experiments. Another option is to reduce the number of experiments in the NOMAD program.
- ❖ Pre-institute training was requested by several of the students to learn more about the software (e.g. Paraview, Cubit, etc.) and experimental methods. The NOMAD organizing team should consider organizing "common" training material to distribute to the students depending on whether they will be working on experiments or simulations, or both.
- ❖ Even with more engagement with Sandia through the on-site tours and the career fair, several students were not aware of the various roles of the departments in Engineering Sciences. Efforts will be made in future years to request short overviews of departments from the management team.
- ❖ It would be beneficial to have the students give an informal seminar mid-way through the Institute to help them prepare for their final presentations. This would give the teams incentive to define their objectives and outcomes earlier in the summer and give them another opportunity to practice their communication skills.
- ❖ The NOMAD organizers will continue to improve and streamline the pre-institute activities to ensure the students have computer and network access as quickly as possible. The team will work to assign all trainings prior to the start of the Institute, as well as authorize all the necessary accounts. The CSU team will be asked to install all necessary programs on the student laptops to relieve that burden from the students.

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4. FINAL REMARKS

Overall, the 2019 NOMAD Research Institute was successful and provided a meaningful experience for the students and mentors alike. The organizing team received positive feedback from both parties, most of which stated that they would be willing to participate in future programs. The research completed during NOMAD was published both in seminar presentations as well as some conference proceedings. As results of their efforts, the 2019 NOMAD Institute produced five proceedings and presentations at international conferences. Four of the seven projects published proceedings at the 2020 SEM IMAC, while one of the other projects is waiting to decide on the appropriate venue for their research. A summary of the documentation produced by each project team is provided in Appendices C-I. Planning is underway for the 2020 NOMAD Research Institute with the intention to make improvements based on the feedback from 2019. As we move forward, we will continue to strive to provide the best experience for the students and engage staff and external collaborators to perform meaningful research in the interest of the Engineering Sciences Center at Sandia National Laboratories.

Figure 6. Rob Kuether and Brooke Allensworth celebrating another successful year

APPENDIX A. STUDENT RECRUITMENT FLYER

NOMAD RESEARCH INSTITUTE

CUTTING EDGE RESEARCH. COLLABORATION. NETWORKING. SOUTHWEST CULTURE.

The Nonlinear Mechanics and Dynamics (NOMAD) Research Institute seeks to tackle research challenges in the field of nonlinear mechanics and dynamics by forming diverse teams of B.S., M.S., and Ph.D. students, as well as post-doctoral and early-career researchers. The program is sponsored by Sandia National Laboratories and the University of New Mexico.

The Program.

- Held from **June 17, 2019** to **August 1, 2019** at the University of New Mexico Campus in Albuquerque, NM
- You are matched with research projects based on **your research interests and skills**
- **Internships available** to U.S. citizens (see job posting ID 665596 for grad)

The Benefit.

- Meaningful work in your area of interest to improve understanding of **cutting edge research and development**
- Collaborate with researchers from around the world under the mentorship of the **professional community**
- **Short-term position** to accomodate the graduate research commitments of students
- An opportunity to **present and publish** novel research in nonlinear mechanics and dynamics

The Engineering Disciplines.

- Mechanical
- Civil
- Aerospace
- Engineering Mechanics
- Applied Mathematics
- Materials

The Contacts.

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Visit NOMAD online at sandia.gov by visiting http://tinyurl.com/gw8r5wf

Sandia National Laboratories · UNM · N-O-MAD · U.S. Department of Energy · NNSA

2019 NOMAD PROJECT LIST

Mechanics of bolt loosening under dynamic loads

Bolt loosening occurs when a joint loses preload during exposure to dynamic loads such as mechanical shock or random vibration. The goal of this project is to gain a better understanding of the mechanics of bolt loosening and the mechanisms responsible for the loss of frictional restraints by simulating high-fidelity finite element models and validating the predictions with experimental measurements.

Investigation of electrical contact chatter in pin-receptacle contacts

Electrical contact chatter refers to the loss of good electrical current flow through a closed circuit, which may occur when electrical contacts are subject to random vibration environments. This project team will develop models and perform experiments on a simplified chatter tester, consisting of a single pin-receptacle contact pair, to understand which parameters have the greatest influence on chatter performance.

Force reconstruction at mechanical interfaces

Force reconstruction methods in structural dynamics can predict the magnitude and location of an externally applied force with a high degree of accuracy. In this project, the team will explore the potential of characterizing the forces in a joint using these methods by developing models and performing experiments on hardware designed to explicitly measure the joint forces for validation purposes.

Modeling and experimental validation of a pylon subassembly mockup with multiple nonlinearities

A demo aluminum aircraft has been equipped with discrete nonlinear elements designed to replicate real-world engine pylon subassemblies. The NOMAD team will generate high-fidelity model predictions of the pylon subassembly and validate the results with experimental data collected on a dedicated test fixture to understand which nonlinear sources contribute most to the complex dynamic response of the aircraft assembly.

Development of reactive potentials for molecular dynamic simulations

Reactive bond-order potentials are known to provide high accuracy for pair-interactions in atomistic molecular dynamics simulations. The computational effort during NOMAD will seek to expand and develop novel material parameterizations for reactive potentials by designing and implementing a computational optimization method necessary for the parameterization. The team will build upon existing methods, adding complexity and detail.

Indentation of heterogeneous materials: Factors affecting the indentation results and a comparison to bulk material testing

Indentation behavior of heterogeneous materials, with indentation penetration well into the composite microscopic features, is not well understood. This project aims at studying the correlation between the indentation-derived material properties (e.g., elastic modulus and hardness) with the overall (macroscopic) mechanical properties, for materials containing microscopic constituents with distinctly different mechanical features.

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SAND2019-0609 HR. SB

APPENDIX B. STUDENT INTERN JOB POSTINGS

Intern – Nonlinear Mechanics and Dynamics (NOMAD) RD Undergrad Summer

Sandia National Laboratories

What Your Job Will Be Like

The Nonlinear Mechanics and Dynamics (NOMAD) Research Institute is a seven-week long program held at the University of New Mexico (UNM) that brings together researchers from around the world to work on challenging research problems in engineering sciences. The Component Science and Mechanics Department is seeking motivated and productive student interns to contribute to a number of the summer research projects. The internship will provide you with opportunities to work in diverse research teams, to take part in a research project that will be published as a conference paper, and to engage with professionals working within their research fields.

Examples of past summer projects include:

- Constructing Optimal Surrogate Models for Bolted Fasteners in Multiaxial Loading (computational).
- Influences of Modal Coupling on Experimentally Extracted Nonlinear Modal Models (experimental with computational).
- A Priori Methods to Assess the Strength of Nonlinearities for Design Applications (experimental with computational).
- Fatigue Properties of Additively Manufactured Hiperco (computational).
- Material Failure Model and Properties for Puncture Simulations (computational).
- Predictive Structural Dynamics Modeling of Bolted Interfaces (computational with experimental).

Visit our website for more details related to these past projects:
http://www.sandia.gov/careers/students_postdocs/internships/institutes/nomad.html

Qualifications We Require

You bring the confidence and skills to be eligible for the job by meeting these minimum requirements:

- Currently attending and enrolled full time (or scheduled to graduate in the spring) in an accredited undergraduate program
- Pursuing a science, engineering, or math major
- Minimum cumulative GPA of 3.3/4.0
- Ability to work up to 40 hours per week during the summer
- You are available to participate in the Institute from June 17, 2019 - August 1, 2019

Qualifications We Desire

- Experience (or academic focus) in structural dynamics, mechanical vibrations, modal analysis, solid mechanics, or failure analysis is desired
- Undergraduate research that aligns with state-of-the-art research in nonlinear mechanics or dynamics
- Work independently, with the ability to integrate effectively into a dynamic multidisciplinary teaming environment.
- You should demonstrate strong social, organization, and communication skills (both oral and written)

Are you ready to expand your horizons? NOMAD offers teamwork and networking experience, the opportunity to apply skills from academia to other areas, provides valuable resources, a broader knowledge about work being done across the country and is an outstanding learning experience.

Sandia is committed to meeting the letter and spirit of the equal employment opportunity laws and applying good faith efforts to achieve a balanced workforce, including women, minorities and persons with disabilities at all levels and in all segments of the work force.

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Location:
Albuquerque, NM

Equal opportunity employer/Disability/Vet/GLBT

Intern – Nonlinear Mechanics and Dynamics (NOMAD) RD Graduate Summer

Sandia National Laboratories

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Examples of past summer projects include:

- Constructing Optimal Surrogate Models for Bolted Fasteners in Multiaxial Loading (computational).
- Influences of Modal Coupling on Experimentally Extracted Nonlinear Modal Models (experimental with computational).
- A Priori Methods to Assess the Strength of Nonlinearities for Design Applications (experimental with computational).
- Fatigue Properties of Additively Manufactured Hiperco (computational).
- Material Failure Model and Properties for Puncture Simulations (computational).
- Predictive Structural Dynamics Modeling of Bolted Interfaces (computational with experimental).

Visit our website for more details related to these past projects:

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Qualifications We Require

You bring the confidence and skills to be eligible for the job by meeting these minimum requirements:

- Earned bachelor's degree
- Currently attending and enrolled full time (or scheduled to graduate in the spring) in an accredited science, engineering, or math graduate program
- Minimum cumulative GPA of 3.7/4.0
- Ability to work up to 40 hours per week during the summer
- Candidate must be working towards a Ph.D or master's degree in mechanical engineering, civil engineering, aerospace engineering, materials science, engineering mechanics, applied mathematics or other applicable branches of science or engineering
- Candidate must be available to participate in the Institute from June 17, 2019 to August 1, 2019

Qualifications We Desire

- Experience (or academic focus) in structural dynamics, mechanical vibrations, modal analysis, solid mechanics, or failure analysis is desired
- Graduate research that aligns with state-of-the-art research in nonlinear mechanics or dynamics
- Candidate should be able to work independently, with the ability to integrate effectively into a dynamic multidisciplinary teaming environment
- This individual should demonstrate strong interpersonal, organization, and communication skills (both oral and written)

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*These benefits vary by job classification

Location: Albuquerque, NM

Equal opportunity employer/Disability/Vet/GLBT

APPENDIX C. PROJECT #1 DOCUMENTATION

Details of the research from Project #1 were documented as an IMAC proceeding published as:

M. Miller, C. Johnson, N. Sonne, et al., "Bolt Preload Loss due to Modal Excitation of a C-Beam Structure," in *38th International Modal Analysis Conference (IMAC XXXVIII)*, Houston, TX, February 2020.

The SAND #'s for all documentation produced from this project are listed below:

- NOMAD Final Seminar – SAND2019-8709 PE
- IMAC Conference Proceeding – SAND2019-12525 C

IMAC Abstract:

Bolted joints often risk failure due to the loss of fastener preload when subjected to dynamic, multiaxial loads. This process is a complex problem that depends on multiple attributes such as loading direction, rate, contact within the threads and the interface, material properties, and many others. Current literature suggests that oscillatory shearing loads appear to be most detrimental to the loss of preload in threaded fasteners. To investigate the effect of less idealized loading conditions, an experimental setup employing a bolted c-beam structure is used to study loss of preload from various initial preloads during harmonic excitation near specific resonant frequencies of the structure. The preload force is measured using bolts equipped with internal strain gauges and the structure is excited at specific modes via sine dwell excitation with an electrodynamic shaker. The experiments were designed to measure loss of preload as a function of excitation duration and strength. A finite element model incorporating a fully-threaded joint is developed in parallel to investigate the effectiveness of each at measuring and predicting bolt loosening.

APPENDIX D. PROJECT #2 DOCUMENTATION

Details of the research from Project #2 were documented as an IMAC presentation published as:

B. Johnson, C. Schumann, F. Rafeedi, et al., "Investigation of Electrical Contact Chatter in Pin-Receptacle Contacts," in *38th International Modal Analysis Conference (IMAC XXXVIII)*, Houston, TX, February 2020.

The SAND #'s for all documentation produced from this project are listed below:

- NOMAD Final Seminar and IMAC presentation– SAND2019-8709 PE

IMAC Abstract:

Electrical contact chatter is defined as the electrical resistance exceeding a threshold for a specified time duration, often occurring during random vibration events. The fundamental physics governing chatter is poorly understood due to the multi-scale, multi-physics nature of the problem. This makes any numerical analysis of this problem very challenging because it is difficult to include all potentially relevant physics in a single simulation. The objective of this paper is to investigate this problem using a simplified test setup consisting of a pin held in a stationary and relatively massive fixture, while the receptacle is placed on a large mass and allowed to move with respect to the pin. The pin and the receptacle are connected through a circuit that measures the resistance at the contact. The contact forces between the pin and the receptacle are calculated numerically using the finite element model calibrated to experimental modal data. An explicit dynamics transient simulation is subjected to the same random vibration environment as in the experimental tests to capture contact interaction and will be correlated to the electric resistance measurement between the pin and receptacle. From the experimental and numerical analysis, the parameters that have the greatest influence on chatter performance are determined and used to predict design changes to improve chatter performance.

APPENDIX E. PROJECT #3 DOCUMENTATION

Details of the research from Project #3 were documented as an IMAC proceeding published as:

D. Fowler, S. Parker, M. Cleal, et al., "Force Reconstruction at Mechanical Interfaces," in *38th International Modal Analysis Conference (IMAC XXXVIII)*, Houston, TX, February 2020.

The SAND #'s for all documentation produced from this project are listed below:

- NOMAD Final Seminar – SAND2019-8709 PE
- IMAC Conference Proceeding – SAND2019-11669 C

IMAC Abstract:

Traditional approaches to analyzing nonlinear systems often involve assuming a specific model form and model order for the nonlinearity. These nonlinearities in a system could instead be modeled as a nonlinear force applied to an underlying linear system. Force reconstruction methods can be used to recreate this nonlinear force from measured data, allowing the system change to be quantified. A modal based force reconstruction technique has proven capable of recreating force inputs at unmeasured locations and has been successfully applied to nonlinear intermittent contact forces in previous studies. To extend these findings, a two-beam system was designed such that intermittent contact occurs near the joint locations and the impact forces are measured using integrated force gages. Acceleration responses are obtained from a sparse measurement grid which does not include the contact locations. The responses are used in the force reconstruction process to form estimates of the nonlinear contact forces, which are then compared to the measured force values to validate the accuracy of the results.

APPENDIX F. PROJECT #4 DOCUMENTATION

Details of the research from Project #4 were documented as an IMAC proceeding published as:

C. Ligeikis, A. Bouma, J. Shim, et al., "Modeling and Experimental Validation of a Pylon Subassembly Mockup with Multiple Nonlinearities," in *38th International Modal Analysis Conference (IMAC XXXVIII)*, Houston, TX, February 2020.

The SAND #'s for all documentation produced from this project are listed below:

- NOMAD Final Seminar – SAND2019-8709 PE
- IMAC Conference Proceeding – SAND2019-12265 C

IMAC Abstract:

The industrial approach to nonlinearities in structural dynamics is still very conservative, particularly from an experimental point of view. A demo aluminum aircraft has been equipped with discrete nonlinear elements designed to replicate real-world engine pylon subassemblies to increase awareness on the effects of nonlinearities in design, and understand how these effects can be positively exploited, if properly understood. After some preliminary experiments aimed at understanding the coupled behavior of the aircraft-pylon mockup, it became clear that more in-depth numerical and experimental analyses are required on the pylon subassembly alone. For this paper, experimental data is collected to analyze the nonlinear dynamic behavior of the pylon, leading to better understanding of the subassembly once it connects to the aircraft. The pylon element has three main sources of nonlinearities: (1) geometric nonlinearities of the connecting beam, (2) contact as the beam presses into the tapered block surface and (3) friction in the bolted connections. Backbone curves are generated, which map the evolution of natural frequency and damping ratio with excitation amplitude. Using the experimental data, a low-order nonlinear model is identified to replicate the backbone characteristics and response of the pylon.

APPENDIX G. PROJECT #5 DOCUMENTATION

Details of the research from Project #5 were documented in the NOMAD Final Seminar as:

T. Adams, H. Cleaves, "Development of Reactive Potentials for Molecular Dynamic Simulations," in *2019 NOMAD Final Seminar Series*, Albuquerque, NM, July 2019.

The SAND # for documentation produced from this project is listed below:

- NOMAD Final Seminar – SAND2019-8709 PE

APPENDIX H. PROJECT #6 DOCUMENTATION

Details of the research from Project #6 were documented in the NOMAD Final Seminar as:

C. Foster, B. Pineyro, B. Tucker, "Indentation of Porous Materials: Factors Affecting the Indentation Results and a Comparison to Bulk Material Testing," in *2019 NOMAD Final Seminar Series*, Albuquerque, NM, July 2019.

The SAND # for documentation produced from this project is listed below:

- NOMAD Final Seminar – SAND2019-8709 PE

APPENDIX I. PROJECT #7 DOCUMENTATION

Details of the research from Project #7 were documented in the NOMAD Final Seminar as:

C.J.T. Mason, D.D. Rice, C.J. Salazar, "Validation of Puncture Simulations with Various Probe Geometries," in *2019 NOMAD Final Seminar Series*, Albuquerque, NM, July 2019.

The SAND # for documentation produced from this project is listed below:

- NOMAD Final Seminar – SAND2019-8709 PE

The students also prepared a conference paper and will be submitting this to an appropriate conference in the future.

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