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The 2018 Nonlinear Mechanics and Dynamics Research Institute

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Prepared by
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Abstract

The 2018 Nonlinear Mechanics and Dynamics (NOMAD) Research Institute was successfully held from June 18 to August 2, 2018. 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 17 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 six research projects that were developed by various mentors from Sandia National Laboratories, 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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Project Mentors:
John Mersch (SNL), Jeff Smith (SNL), Gustavo Castelluccio (Cranfield), John Emery (SNL), Peter Grimmer (SNL), Dan Roettgen (SNL), Ben Pacini (SNL), Matt Allen (UW-Madison), Matt Brake (Rice), Rob Flicek (SNL), Christoph Schwingshackl (Imperial), Eric Dodgen (NSC), D. Dane Quinn (Akron), Kyle Johnson (SNL), Tariq Khraishi (UNM), Adam Brink (SNL), Scott Grutzik (SNL), Neal Hubbard (SNL), Walter Gerstle (UNM), Paolo Tiso (ETH Zurich)

Seminar and Tutorial Speakers:
Matt Allen (UW-Madison), Brian Lester (SNL), Bill Flynn (Siemens), Matt Brake (Rice), Tariq Khraishi (UNM), Pete Avitabile (UMass Lowell), Walter Gerstle (UNM), Ben Davis (UGA)

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NOMENCLATURE

Abbreviation	Definition
AM	Additive Manufacturing
ESS	Engineering Student Services
FY	Fiscal Year
IMAC	International Modal Analysis Conference
ME	Mechanical Engineering
MPC	Multi-Point Constraints
MTTC	Manufacturing Training and Technology Center
NEO	New Employee Training
NEPA	National Environmental Policy Act
NOMAD	Nonlinear Mechanics and Dynamics
Q&A	Questions and Answers
R&A	Review and Approval
SHM	Structural Health Monitoring
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 2018 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, each project team 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 2018 NOMAD Research Institute.

The 2018 NOMAD Institute consisted of six technical projects that engaged 17 students and 21 mentors from around the world. The program was supported by the Advanced Simulation and Computing (ASC) program at a level of $200K and Delivery Environments (DE) program at a level of $100K. In addition to this funding, the NOMAD organizing team was awarded $100K of CIF funding along with an additional $50K of weapon response funding from Mike Pasik. The total $450K 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 provided experimental equipment and software to support the Institute work at no cost. Department 1522 provided additional Sandia equipment for the laboratories and 1545 provided Sierra licenses for NOMAD trainer computers. This SAND report documents the programmatic details related to the 2018 NOMAD Research Institute.

2. PROGRAMMATIC DETAILS

2.1. Lessons Learned and Changes from 2017

A summary of the lessons learned during the 2017 NOMAD Research Institute are provided below:

- ❖ The organizers need to improve marketing of Skype access for the technical seminars and final student presentations.
- ❖ Most of the students felt they were not engaged with the other project teams during the summer. The NOMAD organizers need to consider cross-project activities to share on-going research efforts with all participants. One idea is to hold a brief stand-up meeting once or twice a week for the students to discuss their progress and challenges.
- ❖ The students have requested having a white board in their offices, along with access to printers. Both of these should be addressed in the upcoming year.
- ❖ The project mentors should continue to improve on the pre-institute homework in order to better prepare the students for their actual work. Assigning a long list of papers to read is not sufficient to prepare the students, and it is unlikely that they will actually read all the references. Specific homework problems need to be developed to prepare the students with the skills needed to contribute to their research on the first day.
- ❖ A Sierra tutorial should be provided to those intending to use the code.
- ❖ Many students suggested holding the Institute for a longer period, as six weeks was not enough time to finish the research and publish the results.
- ❖ There was a clear distinction between the students hired as interns, and those who were visitors. It seems that the visitors viewed the interns as “privileged” since they had access to all of Sandia’s computing resources. In future years, the NOMAD organizing team needs to work towards a recruiting framework that provides consistent access and benefits to all students.
- ❖ During the summer, the NOMAD Connect site ran out of space and it took almost a week to get more for the students to upload and share their files. The NOMAD organizing team needs to consider archiving past years on a separate hard drive.
- ❖ On-site visits from mentors were extremely beneficial for the students and we need to continue to advocate that on-site mentors make frequent visits to UNM.
- ❖ An up-to-date calendar of events should be maintained on the Connect website.

There were a number of changes that occurred between the 2017 and 2018 Institute, most notably the collaborations established with the Mechanical Engineering department at the

University of New Mexico. Tariq Khraishi at UNM helped organize the program by providing logistic support related to the use of facilities on UNM's campus, as well as helped mentor one of the project teams. During FY18, Diane Peebles moved into a new management position in the New Mexico Partnerships department, and Jeff Smith served as acting manager during the spring/summer. Diane maintained her advisory support through the remainder of the fiscal year to ensure a smooth transition. As part of these transitions, there were a number of changes and lessons learned from FY17 that were achieved during the planning stages in FY18. These include:

- ❖ Based on student feedback and a sufficient budget, the institute was extended from six to seven weeks for 2018. Additionally, the organizers offered students an additional week if their schedules permitted to work on their conference papers.

- ❖ Many of the projects were organized in such a way that leveraged both computational and experimental mechanics and dynamics. Often the two are intermixed and each project reflected this in their objectives. This aligns well with our shared funding support from ASC and DE.

- ❖ A renewed partnership was formed with UNM's ME department with the collaboration with Prof. Tariq Khraishi. Tariq helped secure space for the NOMAD program, and lead the efforts in UNM's administrative support. The university was able to help secure a block of rooms in their dormitories for NOMAD use.

- ❖ The Institute was held at the Mechanical Engineering building on UNM's north campus. This was a new facility for the us, and provided sufficient office and lab space for the students and mentors. Additionally, the building offered other amenities to allow us to hold technical seminars and other meetings throughout the summer.

- ❖ Dan Roettgen in 1522 helped lead the lab support by providing experimental equipment needed for the UNM laboratory. He served as the main POC for the NOMAD team and ensured there were no conflicts with equipment scheduling

- ❖ Based on historical data, the number of projects was held to six in order to provide the students with the best possible experience. Budget is one factor that limits the size of the program, but another major factor is the ability to find mentors willing to engage with students. Each mentor puts forth noteworthy time commitments to ensure the students feel engaged with the project team.

- ❖ Weekly seminars from various professors were organized to occur each week to supplement the student's educational experience during the summer. Topics spanned disciplines across dynamics and mechanics.

- ❖ This year only two of 17 students were foreign nationals in an effort improve SNL's strategic recruiting pipeline of highly qualified candidates in technical fields often difficult to recruit in. Trainer laptops with Sierra finite element codes were provided to the visiting students.

- ❖ We continued to receive positive feedback from the students regarding the organized activities planned by the NOMAD coordinators and made an effort to continue this effort.

2.2. Project Selection Process

A total of six projects were selected for the 2018 NOMAD Research Institute. A call for projects was distributed on October 30, 2017 to a variety of internal and external prospective mentors to solicit project ideas and teams. The organizing team received a total of twelve project ideas from the community and the down-selection process evaluated each based on 1.) Safety and Security, 2.) Quality, 3.) Impact, and 4.) Likelihood of Success. The mentors chosen to participate in the 2018 Institute include:

- John Mersch, Sandia National Laboratories
- Jeff Smith, Sandia National Laboratories
- Gustavo Castelluccio, Cranfield University
- John Emery, Sandia National Laboratories
- Peter Grimmer, Sandia National Laboratories
- Dan Roettgen, Sandia National Laboratories
- Ben Pacini, Sandia National Laboratories
- Matt Allen, University of Wisconsin-Madison
- Rob Kuether, Sandia National Laboratories
- Matthew Brake, Rice University
- Rob Flicek, Sandia National Laboratories
- Christoph Schwingshackl, Imperial College
- Eric Dodgen, NSC
- Dane Quinn, University of Akron
- Kyle Johnson, Sandia National Laboratories
- Tariq Khraishi, University of New Mexico
- Adam Brink, Sandia National Laboratories
- Scott Grutzik, Sandia National Laboratories
- Neal Hubbard, Sandia National Laboratories
- Walter Gerstle, University of New Mexico
- Paolo Tiso, ETH Zurich

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

- ❖ **Project 1: Constructing Optimal Surrogate Models for Bolted Fasteners in Multiaxial Loading**

Joining technology (welds, bolted joints) are usually among the weakest link in structures that control failure due to the localization of stresses and strains. The disparate length scales spanned by the component or system model down to the fine, yet important, geometric details of a joint make full scale computational calculations inconvenient and too demanding. Hence, there is a need to investigate surrogate models that simplify the geometry of the joints (such as plugs instead of threads) or reproduce an equivalent constitutive surrogate (such as spot weld).

Constitutive models are typically calibrated to match experimental data from ideal materials specimens and joints. Even when joints may suffer multiaxial loads during service, experimental data are often limited to pure shear and pure tension at a few loading rates. These data convolve a number of physical phenomena that obscures validation and limit the predictive power of models. One challenge is to develop predictive surrogate models that synthesize the available data in approaches that predict the response of joints for regimes beyond the validation data.

At NOMAD we will focus on answering two main questions:

1. What are the best strategies to simplify the geometry of threaded fasteners under multiaxial loading.
2. What are the most practical material constitutive models capable of reproducing multiaxial failure.

Regarding geometric fidelity, Castelluccio and Brake (C&S 2017) suggested that plug models are preferable to 2.5D models for representing tension data and they explored sensitivities of model response to various surrogates *in tensile loading configurations*. What model sensitivities exist to shear and/or multi-axial loading responses? Can we draw similar conclusions under general multiaxial loading?

In terms of the material constitutive model, it is usually assumed that one material model and one parameterization governs the entire geometric surrogate (plug). If this assumption is relaxed, can we create more robust surrogate models? Can we refine local materials parameters to result in a more robust behavior, *i.e.*, predictive of shear and tension at various rates? What happens if the constitutive representation include rate-dependence and damage?

Finally, what is the optimal fidelity form combining geometric and constitutive models? How does it compares to experimental data and, most importantly, does it match the results for the right reasons?

- **Project 2: Influences of Modal Coupling on Experimentally Extracted Nonlinear Modal Models**

Research has shown that structures can be modeled as a combination of weakly nonlinear uncoupled quasi-modal models. These modal models can take many forms such as a basic cubic stiffness and damping force, or a modal Iwan model. A few assumptions are required to complete this analysis: 1) the mode shapes of the structure are not amplitude dependent, and 2) the modes of the structure do not couple or interact in the amplitude range of interest. Recently, a hypothesis was proposed that when multiple modes are excited that exercise the same nonlinear joint, the modes of a structure begin to couple and exchange energy. This project would test this hypothesis on a physical system using a series of narrow-band and broad-band excitation techniques.

First, the structure will be investigated with hammer impact tests to gather ring-down data and determine the amplitude dependent stiffness and damping due to broadband impact excitation. Next, shaker testing will be implemented to investigate both narrow and broadband excitation.

This will be completed through a series of burst-random and windowed-sinusoid tests. The amplitude dependent stiffness and damping from these three methods will be compared to see if the excitation of multiple modes in broadband excitation changes the nonlinearity observed in the structure's modes. The experimental members of the team are to develop and compare the nonlinear modal models for each nonlinear mode for the various excitation techniques. As a stretch goal, the team will implement a proposed method to capture the modal coupling physics to produce a single nonlinear modal model that accurately predicts all loading cases for an amplitude range of interest.

In parallel, a finite element model of the physical test structure from above will be updated using physical nonlinear elements at specific joints of interest. Recent studies have shown that using a quasi-static approach allows for a nonlinear finite element model to be updated rapidly utilizing test data for a single mode at a time. Note, this approach does not use coupled modes to update the model. This finite element model can be loaded in the same fashion as the experiment to see if similar nonlinear trends are observed between the experiment and numerical model. In addition, the modeling members of the team can create separate nonlinear finite element models which are individually updated using experimental data from each of the experimental excitation techniques. Observing the changes in physical parameters should provide more insight into the modal coupling phenomena. If successful, this project will show how different excitation techniques can influence nonlinear model parameters as a result of modal coupling.

- **Project 3: A Priori Methods to Assess the Strength of Nonlinearities for Design Applications**

Jointed interfaces affect the dynamics of a structure in two ways: the reduction of natural frequency and increase in energy dissipation as the response amplitude of the structure is increased. Because these changes violate the principles of linear modal analysis, this necessitates expensive qualification experiments to assess the dynamics of a structure across a broad range of possible excitations. Further, any model calibrated from a subset of the necessary experiments is unable to predict the response outside of the excitation regimes measured. Historically, the state-of-the-art techniques can predict the stiffness of a jointed system to within 25% and the dissipation to within two orders of magnitude. Therefore, if design tools existed to assess the nonlinearity of a jointed interface and redesign it during the initial design phase, this would lead to significant savings in qualification testing and improved performance in terms of dynamic properties and failure rates.

The quantification of nonlinearities in assembled systems is an open research question in nonlinear dynamics. From the analysis of a series of benchmark systems, four new observations have been made:

1. Interfaces in which there is a high, uniform contact pressure yield system dynamics that *appear* linear.
2. Portions of interfaces that have a moderate contact pressure, which have previously been assumed to be time invariant during dynamic excitation, exhibit significant fluctuations during dynamic loading.
3. Portions of interfaces that have low contact pressure are the source of energy dissipation within a jointed structure.

4. Modifications to the support structure around an interface affect how the interface is loaded and thus the *perceived* strength of nonlinearity.

From these observations, a new hypothesis for an *a priori* method for predicting the strength of a nonlinearity in an interface is proposed: *The strength of a nonlinearity in a jointed system can be predicted by quantifying the magnitude and uniformity of contact pressure within an interface and by assessing the modal excitation of an interface.* That is, a two-step procedure could be explored:

- First, a nonlinear contact simulation is used to assess the magnitude and uniformity of contact pressure in an interface.
- Second, modal analysis of a linearized system is used to quantify the likely modal excitation of the interface.

If successful, this new metric will have significant ramifications for the design of jointed structures.

❖ Project 4: Fatigue Properties of Additively Manufactured Hiperco

As technology and processes improve, additively manufactured (AM) components are becoming more prevalent in industrial and consumer applications. Material flaws in the form of voids and/or micro-cracks are inherent to the AM process to the detriment of the component's mechanical strength properties. Mechanical fatigue failure is the failure of a component under a cyclic load, typically under the material's yield strength. AM parts, though often possessing a higher yield strength, typically demonstrate reduced fatigue life. This project will focus on the effect that these inherent flaws have on the expected component fatigue life.

Hiperco (Fe-Co-2V) is a soft ferromagnetic material that is commonly used in electrical components. Hiperco possesses excellent magnetic properties, the material has low strength, poor ductility, and low workability due to a B_2 microstructure, which inhibits dislocation motion. Recently there has been interest in producing Hiperco through AM in the hope of improving mechanical properties. However, the fatigue properties of Hiperco are unknown for AM or conventional processing. A major objective of this research, which will benefit both Sandia and the scientific community, includes characterizing the fatigue properties of wrought and AM Hiperco. Microscopy will also be performed on starting material and fracture surfaces to identify microstructure characteristics and defects.

The steps of fatigue failure include creation of micro-cracks, coalescence of these cracks into larger defects, stable crack growth and finally complete fracture. Using the finite element software Abaqus in conjunction with crack growth prediction software FRANC3D, this research will correlate expected and observed flaw size in Hiperco with observed fatigue life.

The expected outcome of this NOMAD research project will be:

1. A correlation of flaw size to fatigue life degradation in AM processed Hiperco.
2. A statistical description of coupon failure based on expected and observed flaws in AM processed Hiperco coupons.

3. A complete data analysis of the physical fatigue testing for the AM and conventionally machined Hiperco coupons.
4. A numerical model simulating a fatigue test using an observed flaw size and morphology.
5. A journal paper detailing the experimental and numerical portions of this research.

❖ Project 5: Material Failure Model and Properties for Puncture Simulations

Ductile materials fail through mechanisms of void nucleation and crack growth. A typical tensile failure begins with reversible elastic deformation, proceeds through permanent plastic deformation, and ends with rupture. Dislocations in the grains of a metal do not slip in the elastic range but begin moving in the plastic range; as the dislocations interact with grain boundaries and each other, they cause increasing resistance to plastic deformation. The applied load and the true stress rise together during work hardening. When the dislocations have no room to move, voids open up in the material. As these voids coalesce into cracks, the true stress rises rapidly and the sustained load decreases. Rupture occurs when the cracks propagate through the part and the load is reduced to zero.

Sharp tools in a production environment can puncture fragile components. This project will analyze a slender probe as it penetrates a ductile material. Finite element models of probe penetration problems need material models that are accurate through the full range of strain. Elastic properties are frequently derived and are available for most metals with a strong statistical basis. Stress-strain curves including the plastic range are limited and usually stop at the ultimate strength, where void nucleation occurs.

Tests have been performed on coupons of 7075-T651 plate with three probes. The geometry of the coupon and probes will be provided, as well as appropriate initial and boundary conditions. The mean kinetic energy required for each of the probes to penetrate the coupon was measured and will also be provided. The objective of this project is to demonstrate three advanced failure models for 7075-T651 plate and derive the requisite parameters for each model. The material properties and failure parameters may be obtained from published sources and through optimization. Numerous failure models have been demonstrated in published literature; those that perform best will be suggested as candidates. A finite element mesh will be produced with sufficient resolution that element size does not interfere with parameter optimization. A preprocessor and an explicit dynamic analysis program will be available to the team. Three (3) failure models will be applied to the model; for each failure model, the analysis will be performed with each of the three (3) probe geometries that were used in the tests. The simulation results will be summarized in a manner that shows how well the finite element solution agrees with the test results. The parameters of the models may be optimized to a reasonable extent to improve the agreement.

The team will deliver (1) a finite element model containing the mesh, boundary conditions, and material properties for each of the failure models; (2) a report describing the mesh, material properties, failure models, and results of the finite element analyses; and (3) a short presentation with the same information as the report.

- **Project 6: Predictive Structural Dynamics Modeling of Bolted Interfaces**

Most assemblies of systems and components involve fastening to join individual substructures, most common of which are bolted joints. These fasteners apply a preload force to the mating subcomponents and press the interfacing surfaces together. The normal contact and tangential frictional forces carried through these joints are responsible for the transfer of loads between the assembled substructures. Often, these bolted joints are designed such that the mating surfaces do not produce macro-slip relative to one another during operation (i.e. via large preload bolt tensions), although micro-slip can occur at moderate excitation levels due to slipping within low pressure regions of the contact zone. At low response amplitudes, micro-slip effects may be negligible and the joint can be approximated as linear by assuming the material in contact remains in contact.

The objective of this project is to explore the predictability of structural dynamic finite element analysis to accurately predict the modes of a jointed structure with preloaded, bolted interfaces. The results from a 2017 NOMAD project revealed that an accurate finite element model of a bolted beam assembly could be generated by first preloading the nonlinear finite element model with nonlinear contact at the interfaces, and linearizing the model by calibrating the contact areas assumed to be tied together using multi-point constraints (MPCs). The finite element models used within this work assumed the mechanical interfaces were nominally flat, however optical measurements revealed that there is slight curvature to the interfaces. These curvatures are measured to be on the order of 30 to 100 micrometers, which are of similar length scales of the gap sizes predicted by the nonlinear preload analysis. This project will explore a modeling workflow that perturbs the node locations on the interface mesh to capture the true curvature of the hardware, and study the sensitivities of the interface on the linearized modal analysis. A high fidelity model and reduced order model approach will be developed to evaluate the feasibility and accuracy of these techniques.

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 18 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 foreign nationals who were already funded by their home institution. NOMAD budget allocated funds to pay for their housing and reimbursed their meal expenses with a $50/day per diem. A total of fourteen internships were made available during FY18 and the remainder were either brought in as visitors or leveraged interns from other departments at SNL.

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 400 students applied to the NOMAD program and 17 students were selected to participate in the 2018 Institute:

- Ernesto Camarena, Purdue University
- Anthony Quintana, New Mexico State University
- Victoria Yim, University of California Berkeley
- Benjamin Moldenhauer, University of Wisconsin-Madison
- Aabhas Singh, University of Wisconsin-Madison
- Philip Thoenen, University of Southern California
- Craig Broadman, Rice University
- She'ifa Punla-Green, Rensselaer Polytechnic Institute
- Edward Rojas, New Mexico State University
- Jacob Biddlecom, Clemson University
- Matthew Mills, University of California Davis
- Benedict Pineyro, Embry-Riddle Aeronautical University
- Nathan Bieberdorf, Georgia Institute of Technology
- Zachary Towner, Georgia Institute of Technology
- Matthew Fronk, Georgia Institute of Technology
- Gabriela Guerra, New Mexico State University
- Matthew Southwick, University of Pittsburgh

2.4. Facilities

The 2018 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 foreign and US 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, including gym and computer access.

In addition to the office space, a personal office was provided for Rob Kuether on the fourth floor. A laboratory on the first floor provided sufficient space to set up the experimental equipment needed for Projects 2, 3 and 6. In previous years, a NEPA was generated for the MTTC building (2016) and was modified to cover the ME building in 2018. Each team utilized either an isolation table or a frame structure to set up their hardware, fixturing, data acquisition and laptop computers. The photograph in Figure 3 shows the configuration of the lab space during NOMAD. Additional rooms throughout the ME building were able to be reserved to hold weekly meetings, seminars, tutorials and other informal gatherings.

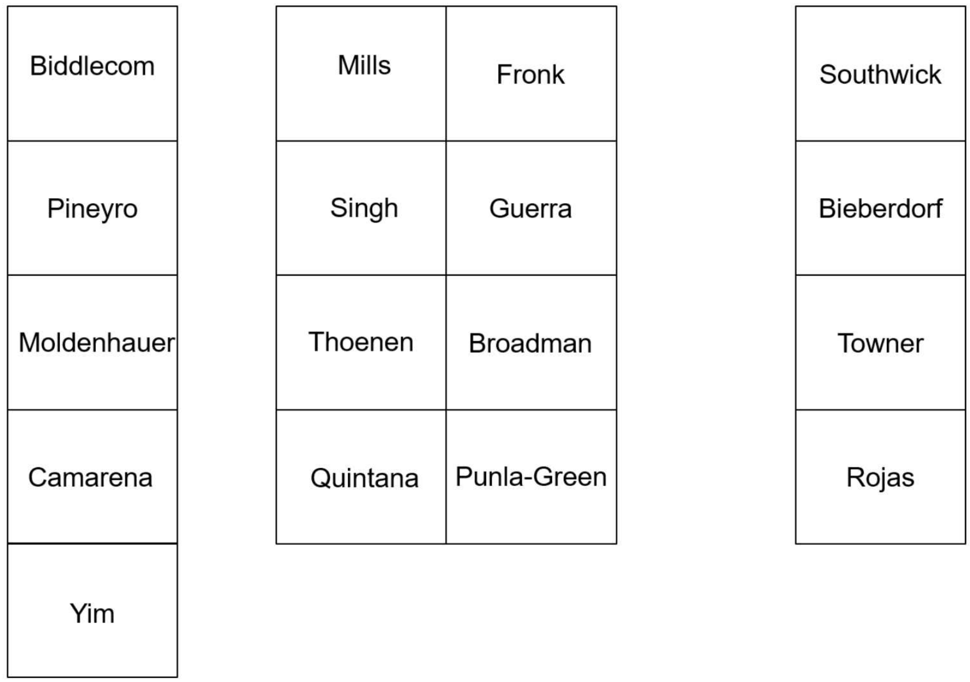

Figure 2. Office assignments for room 320 in the ME building.

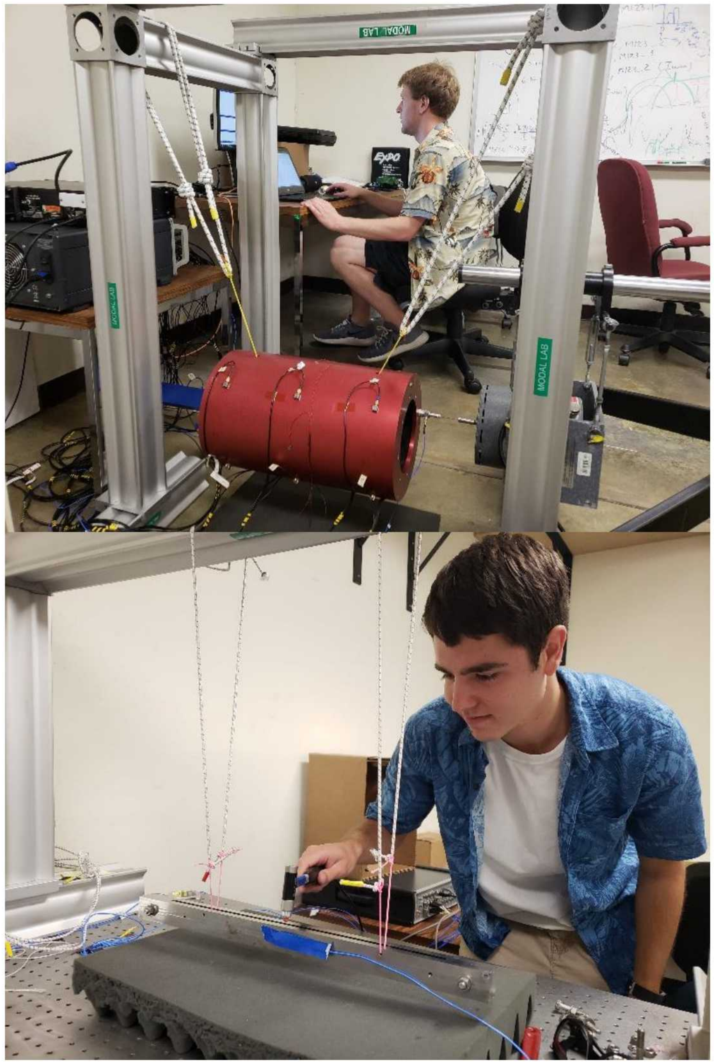

Figure 3. Lab space used in ME building.

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 Rodondo Dr. During the summer session, many of the students were absent from the university and there was sufficient 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.

2.5. Calendar of Events

A summary of the events planned for the 2018 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 2018.

Monday, 6/18:	NEO Training for New Hires
Tuesday, 6/19:	Official Start of NOMAD 2018 Kickoff Presentations and Training
Wednesday, 6/20:	Welcome Dinner at Sadie's of New Mexico
Thursday, 6/21:	Seminar by Matt Allen
Friday, 6/22:	Constitutive Modeling Tutorial by Brian Lester
Tuesday, 6/26:	Siemens/LMS Tutorial by Bill Flynn
Wednesday, 6/27:	Seminar by Matt Brake
Tuesday, 7/3:	Da Vinci Exhibit Tour
Thursday, 7/5:	Seminar by Tariq Khraishi
Saturday, 7/7:	Isotopes Baseball Game
Monday, 7/9:	Seminar by Zhu Mao
Tuesday, 7/10:	Nuclear Science & History Museum Tour by Andy Rogulich
Wednesday, 7/11:	Seminar by Peter Avitabile
Wednesday, 7/18:	Seminar by Walter Gerstle
Thursday, 7/26:	Seminar by Ben Davis
Tuesday, 7/31:	Final Student Presentations Farewell Dinner at El Pinto
Thursday, 8/2:	Last Day of NOMAD 2018

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.

❖ **"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 companies 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.

❖ **"Constitutive Modeling Tutorial" by Brian Lester**

Brian Lester, an R&D Mechanical Engineer in the Solid Mechanics department, gave the students a 2-hour tutorial related to material constitutive modeling. Throughout his talk, he presented some of the fundamental aspects associated with material modeling, whether it be elastic, plastic, viscoelastic, etc.. He concluded his presentation by presenting some of the current state-of-the-art research in constitutive modeling. Brian supported NOMAD in the past by serving as a mentor to one of the technical projects.

❖ **"Overview of Modeling and Test Methods for Nonlinearity due to Friction at Interfaces" by Professor Matt Allen**

One of the greatest challenges in structural dynamics in our day is to predict the stiffness, damping and nonlinearity in a structure caused by the interfaces between its parts. Over the past few decades, finite element modeling of structures has improved dramatically, to the point that we can create a predictive model of a structure, but this is only true if the structure is constructed from one solid piece of a well characterized material. Realistic structures are assembled from many parts and uncertainties in the damping and stiffness of the joints are the major source of modeling uncertainty. Furthermore, joints are the most common source of nonlinearity in automotive and aerospace structures. Current methods are not adequate to predict joint behavior, so industry relies on testing to determine the damping in the built up system, validate models for the stiffnesses of the joints and to detect any nonlinearities. This can only be done once the first prototype has been built, at which point design changes may be very expensive.

This talk will present an overview of modeling methods for assembled structures with nonlinearities at the interfaces. The most basic is the ubiquitous "whole-joint" approach, where clusters of nodes are spidered to a single interface node. The models connecting the interface nodes can then be linear or nonlinear, such as Segalman's four parameter Iwan model. In the latter case it is important to understand how the nonlinearity affects each mode of the structure in the dynamic response. A framework is presented in which a nonlinear quasi-static loading can be used to infer the effective natural frequency and damping of a mode, as a function of response amplitude, due to the net effect of all of the nonlinear interfaces. A corresponding experimental system identification framework is briefly reviewed, based on the Hilbert transform, which allows one to measure these same characteristics for structures with weak nonlinearities, such as typically occur due to micro-slip in bolted interfaces. These techniques are combined to show how a nonlinear Hurty/Craig-Bampton model for an structure can be updated to reproduce the nonlinearity measured in each mode of the assembled structure.

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.

- **"Tribomechadynamics: The Emergence of a New Field at the Confluence of Tribology, Contact Mechanics, and Structural Dynamics" by Professor Matthew Brake**

Tribology, contact mechanics, and structural dynamics are three sub-disciplines of mechanical engineering that are each concerned with the study of interfaces in mechanical systems. Despite this, these three sub-disciplines have remained separate due to length scale considerations, solution techniques, and response metrics. As a result, common problems solved within one of these sub-disciplines rarely affects research within the other sub-disciplines. To address this, the field of Tribomechadynamics was founded to bridge the scales from the nano- and micro-structural characterizations of tribology to the macroscale modeling of structural dynamics. The goal of this new field is three fold: to develop predictive models of jointed structures that can be used to affect the design phase of a product, to predict the degradation of an interface over time due to wear/fretting, and to enable the optimization of jointed structures to reduce weight, be wear resistant, or have advantageous properties. This talk presents the emerging field of Tribomechadynamics in the context of both the applications that it addresses (such as aeroturbines) and the basic research being used to advance our physical understanding of assembled systems. Through a series of experimental studies, Tribomechadynamics has been able to elucidate the sources of variability typically observed in jointed systems, allowing for repeatable measurements and validated numerical models. This talk concludes with open research questions and areas for future investigations in this nascent field.

Prof. Brake started at Rice University in 2016 after working at Sandia National Laboratories for nine years. Prior to Sandia, Prof. Brake graduated from Carnegie Mellon University in 2007. Prof. Brake has been elected to several leadership positions, including as the chair of the ASME Research Committee on the Mechanics of Jointed Structures, the vice-chair of the Nonlinear Dynamics Technical Division of SEM, and as the secretary of the ASME Technical Committee on Vibration and Sound. He is a recipient of the 2012 Presidential Early Career Award for Scientists and Engineers and he recently won the 2018 C.D. Mote Jr Early Career Award. Much of Prof. Brake's career has focused on developing large scale collaborations and supporting graduate student education. To this end, he founded and directed both the Nonlinear Dynamics of Coupled Structures and Interfaces (ND-CSI) Summer Program at Rice University and the Nonlinear Mechanics and Dynamics (NOMAD) Institute at Sandia National Laboratories. His primary research interests are in interfacial mechanics, tribology, model reduction theory, uncertainty propagation, and nonlinear dynamics.

- **"Dislocations and Plasticity: A Primer" by Professor Tariq Khraishi**

This presentation governs the essential essence of dislocations in crystals, in particular metallic crystals. It covers their creation, their effect on the crystals and their relationship to crystal plasticity, as well as to overall specimen plasticity. Some of the potential and promise of understanding dislocations in crystals, along with their interactions and movement, will be shown.

Tariq Khraishi is originally from Jordan. He finished his B.S. (in 1994) and M.S. (in 1996) in Mechanical Engineering from the University of Idaho in Moscow, Idaho. His M.S. research focused on computational fluid dynamics studies of blood flow in a human abdominal aortic aneurysm. He then moved West seven miles across the Idaho-Washington state border to join a PhD program in Mechanical Engineering at Washington State University in Pullman, Washington. His PhD work, completed summer 2000, focused on dislocation theory and modeling (namely 3D dislocation dynamics). His general area of expertise is in solid mechanics and computational materials science with particular emphasis on understanding structure-property relationships. Some of his areas of expertise relate to nanocomposites, biomechanics, eigenstrain theory and computations, finite-element modeling of solids and fluids, metamaterials, epitaxial growth of materials, and irradiated metals.

His work as a professor has been supported by NSF, DoD, NASA, two national laboratories (LLNL and SNL), and companies. He is well-published with over 100 refereed publications, many in top journals like Nature. He is/was on the editorial board for several journals including being the Founding Editor for the International Journal of Theoretical and Applied Multiscale Mechanics. He has won many awards for research and teaching. He has advised dozens of PhD and MS students. He is currently a Professor of Mechanical Engineering at the University of New Mexico.

- **"Structural Dynamics Identification via Computer Vision and Data Analytics in Structural Health Monitoring" by Professor Zhu Mao**

Among the current efforts to improve structural safety and reliability, Structural Health Monitoring (SHM) plays a very important role, in which real-time data are acquired and analyzed for the ultimate goal of status awareness, condition-based maintenance and retrofit, operational risk minimization, and human life safety. Yet any such condition assessment is inevitably constrained by the observability of the sensing hardware and corrupted by various kinds of uncertainties, which degrades the SHM decision-making capability dramatically, leading to unidentifiable system dynamics, as well as both false damage alarms and missed detections or classifications. In this presentation, the research activities at UMass Lowell related to non-contact full-field system testing and identification will be introduced. Specifically the enhanced modal identification and damage detection on wind turbine blades, by means of video motion magnification and other computer vision techniques, will be presented. The second half the presentation concerns the uncertainty quantification, and its applications to the SHM decisions. Probabilistic uncertainty quantification models which characterize the actual distributions of selected SHM features as random variables will be briefed. Structural damage is detected via outlier analysis based on the established probabilistic model, given the quantified significance level of decision threshold. Receiver operating characteristics will be compared among different scenarios to have an optimal trade-off between sensitivity and specificity. Bayesian decision theory is then adopted to classify the type of damages in a recursive manner, and posterior probability facilitates the selection of the correct model.

Zhu Mao received his Ph.D. in 2012 from the University of California San Diego, and now holds the Assistant Professor position in the Department of Mechanical Engineering at the University *of Massachusetts Lowell. His research interests include dynamics and vibration, structural health monitoring, signal processing, statistical modeling and risk analysis, uncertainty quantification and prognosis.*

Dr. Mao has published over 50 papers on top tier journals and internationally-recognized conference proceedings. He serves as the reviewers for 28 international journals and is currently the Vice Chair of the Technical Division of Model Validation and Uncertainty Quantification at the Society for Experimental Mechanics. He is on the Program Committee and serves as the Session Chairs for the SPIE Smart Structures/NDE conference, International Modal Analysis Conference, International Conference on Digital Image Correlation and Noncontact Experimental Mechanics, and the World Conference on Structural Control and Monitoring. He has a wide collaboration with Los Alamos National Lab, Air Force Research Lab, Army Research Lab, etc. He is the winner of 2011 D. J. DeMichele Scholarship Award of SEM, the recipient of 2018 AFOSR Young Investigator Program award, and the SAGE Publishing Young Engineer Lecture award to be presented by SEM in 2019.

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

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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.

- **"The State-Based Peridynamic Lattice Model – An Alternative Approach to Solid Mechanics" by Professor Walter Gerstle**

Leonard Euler and Daniel Bernoulli developed a model for linear elastic bending of beams around 1750, shortly after Isaac Newton and Gottfried Leibnitz developed calculus in the mid 1600's. Without any concept of stress and strain, the Euler-Bernoulli model related bending moment to bending curvature. Only in the 1820's did Claude-Louis Navier and Augustin-Louis Cauchy develop a linear elastic model for the deformation of three-dimensional solid bodies. Cauchy conceived the concepts of stress and strain, both analytical calculus concepts, which have guided our thinking about solid mechanics ever since.

During the 1900's, scholars extended the linear elastic Navier-Cauchy model to include the concepts of plasticity, creep, fracture, and damage. Concurrently, mathematicians Clifford Truesdell and Walter Noll developed a model called "continuum mechanics", which generalized the concepts of stress and strain to allow for large deformations.

By developing the finite element method, John Argyris, Ray Clough, and Olgierd Zienkiewicz first implemented computational elasticity on digital computers in the 1950s. Since that time, scholars have extended the finite element method to simulate the nonlinear behavior of solids, but their methods fall short in modeling damage and fracture.

Therefore, in 2000 Stewart Silling developed the continuum peridynamic theory, which allows the deformation field to be discontinuous while assuming the material reference space is a continuum. Thus, engineers must first discretize continuum peridynamics to implement it on a digital computer.

The question arises: can we directly develop a discrete, rather than a continuum, model for the deformation of solid bodies that is immediately implementable on a digital computer? The state-based peridynamic lattice model, presented here, is such a model.

We describe the state-based peridynamic lattice model, present some simulation examples, and describe its benefits and shortcomings.

Have we committed a grave error by departing from an analytical (calculus) model for solid mechanics? Let us discuss this in the seminar!

Walter Gerstle is a professor of civil engineering at the University of New Mexico with an emphasis on structural engineering. He has been active in researching the computational modeling of concrete structures since 1980. Gerstle obtained his BS degree from the University of Colorado, and MS and PhD degrees from Cornell University. He is a licensed professional engineer.

- **"On the Edge: Stories of Stability Lost and Found in Structural Mechanics" by Professor Ben Davis**

Modern engineering structures need to be lightweight yet also able to withstand harsh loading environments. These competing requirements can manifest in structures that operate on the edge of stability. Here, we will discuss recent efforts to model and test two such structures.

First, we will consider the odd history of fluttering hydrofoils. In the early days of fluid-structure interaction research, there was considerable debate as to whether it is possible for a structure to flutter underwater. This debate was put to rest in 1965 when a test in a high-speed water tunnel demonstrated flutter of a sub-cavitating hydrofoil. However, the test article failed as a result of the instability, and no subsequent tests on fluttering hydrofoils have been conducted. Efforts to model the 1965 test were met with limited success, and to this day, there remains an unresolved question as to why classical aerodynamic models used with water as the fluid medium either considerably over-predict the flutter speed or fail to predict the flutter phenomenon altogether. Two explanations have been proposed for this, but neither has been conclusively confirmed. One explanation involves the viscous differences between air and water, whereas the other suggests the effects of chordwise bending become non-negligible in water. With a series of new water tunnel tests and modeling efforts, we now are attempting to resolve these long-standing questions by uncovering the key physical mechanisms responsible for underwater flutter.

Next, we will look at recent efforts to delay the onset of snap-through instability using piezoelectric materials. Post-buckled and curved structures experience dramatic snap-through instabilities when external loads from mechanical, fluid, or thermal environments result in a loss of local stability and a jump to a remote stable equilibrium. Fatigue caused by snap-through is a concern in many engineered systems because of the large stress reversals involved. Here, we consider the static actuation of flexible piezoelectric materials bonded to clamped-clamped post-buckled beams. This nonlinear electromechanical system is modeled using elastica theory with new extensions to account for the influence of piezoelectric actuation on the structure. Static equilibrium positions and their stability are computed across a large configuration space using numerical integration and a shooting method. Experimental results demonstrate that critical snap-through loads can be altered by factors ranging from 0.4 to 2.0, and numerical results indicate that even larger changes to snap-through loads are physically realizable.

Ben Davis joined the faculty of the College of Engineering at the University of Georgia as an Assistant Professor in the fall of 2014. He leads the Dynamic Devices and Solutions Lab, home to the only high-speed water tunnel in the Southeast, and the only such facility dedicated to fluid-structure interaction research. Previously, he worked for six years at NASA as a propulsion structural dynamics and acoustics analyst at the Marshall Space Flight Center. His professional and research expertise span the areas of structural vibration, acoustics, acoustic-structure interaction, nonlinear dynamics, fluid-structure interaction, and elastic stability. He holds a B.S.E. from Duke University, an M.S. from Georgia Tech, and a Ph.D. from Duke University, all in Mechanical Engineering.

2.5.2. Tours and Extracurricular Activities

Throughout the summer, a number of extracurricular activities were planned to entertain the students and expose them to a few of the local attractions in Albuquerque, including two guided museum tours. The first was a guided tour of the Da Vinci Exhibit at the New Mexico Museum of Natural History & Science and the other was at the National Museum of Nuclear Science & History 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.

- **New Mexico Museum of Natural History & Science**

During the third week of the NOMAD program, the students and organizers gathered at the New Mexico Museum of Natural History & Science to tour the traveling da Vinci Exhibit and supplement their educational experience in the NOMAD program. The works of da Vinci span various disciplines, including the design of various mechanical devices. The museum displayed many of his mechanical designs, including weaponry, flying machines, and attempted perpetual motion devices. The goal was to motivate the students by exposing them to the works of one of the world's greatest scientists who founded many of the concepts of our modern society. The group was split into two as the tour was led by two docents who were extremely knowledgeable of the exhibits. Each group spent one hour learning about the art exhibit while the other hour was spent with Da Vinci's scientific works. A photograph of the group is shown in Figure 4. Admission to the museum was $15 per person and the tour lasted about 2 hours. Following the tour, the students were given free passes to view one of the Planetarium screenings being shown that day. Since the museum is open to the public, there were no special foreign national considerations for this tour.

Figure 4. Group photograph of the Da Vinci Exhibit Tour.

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

In the week following the Natural History Museum visit, 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. Since the museum is open to the public, there were no special foreign national considerations for this tour.

- **Isotopes Baseball Game**

An evening at an Albuquerque Isotope's baseball game provided an additional opportunity to enjoy some time together socially and have some fun. The NOMAD organizers purchased a group of tickets along the third base line in the upper 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. Regardless of whether the attendees liked baseball or not, a good time was had by all.

- **Farewell Dinner at El Pinto**

A farewell get together at El Pinto was a chance for the NOMAD group to reminisce about the seven weeks and wrap up the Institute. Most of the students had not had the opportunity to make it out to El Pinto due to the distance from the UNM campus, so the group had organized carpools to drive out to the Northwest part of town. 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 following the final presentations.

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 25th in order to allow sufficient time for R&A to approve the material for unlimited, unclassified release by Tuesday, July 31st. On the day of the seminar, a number of 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 donut and coffee break was hosted by UNM at the mid-point of the session. Each of the project’s final presentations have been 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.

2.6. Lessons Learned during 2018

A summary of the lessons learned during the 2018 NOMAD Research Institute are provided below:

- ❖ Many of the students faced the same challenges during the first few days: trouble with logging onto their laptops, administrative controls, network access, and installing necessary programs. The organizers need to be better prepared to quickly resolve computer issues and should plan to give a short tutorial on using SNL computing resources such as Leostream, Sierra, Cubit, etc..

- ❖ 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 outcomes earlier in the summer, and give them another opportunity to practice their communication skills.

- ❖ Many of the students noted that they would like better access to the SNL site: ability to visit intern career fairs, seminars, tours, etc.. They also wanted to get a better appreciation of the organization of the departments and better understand what type of work is going on at the Labs.

- ❖ Next year, the organizers should consider better arrangements and organization of the offices and labs at UNM. The office space was crowded and half of the students ended up setting up their workspaces in the lab. We will make a more directed effort to make usable workspace next year. Additionally, we need to advertise the use of adjacent rooms (e.g. computer lab) for team meetings to ensure the other students are not interrupted throughout the day.

- ❖ A number of students commented on the disorganization of the mentors. Many of the mentors had conflicting ideas on which direction the project should take. We will need to communicate to the mentors that they should all agree to a project plan prior to the start of NOMAD to minimize confusion/conflict.

- ❖ The pre-institute homework is an essential part of the project to help the students be prepared on the first day and start making immediate contributions. More emphasis on the homework should be placed in the upcoming year.

- ❖ Next year, the director will make a more conscious effort to include team building activities during the first week, and promote better cross-team communication.

- ❖ This year most of the students had access to all of SNLs computing resources such as HPCs, Matlab, Sierra, Cubit, etc.. This was a significant improvement compared to years past, and allowed the students to learn how to perform computational analysis using state-of-the-art computing resources.

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 (with tick marks representing the number of participants with a similar answer).

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

- Yes, gained teamwork and networking experience.
- Yes, very worthwhile, learned a tremendous amount about modeling and fracture using FEA.
- Yes, good experimental experience.
- Absolutely, opportunity to apply skills from academia to an area I've not heard of.
- Yes, was nervous as an undergrad, have learned an amazing amount about solid mechanics and how to contribute to a team.
- Definitely, learned a lot of resources I could use back home.
- Absolutely, great opportunity to work/network with peers and professionals, gained invaluable knowledge, valuable as a researcher and individual.
- Yes, team research experience was amazing.
- Yes, unique and rewarding experience. Work environment motivates people to work happily, enthusiastically to find solutions. Thank you for the opportunity.
- Yes, I learned so much about modeling, troubleshooting and storing data. **– I**
- Yes, I had a fun time, learned a lot from the mentors, teammates and project itself.
- Yes, great learning experience. **– II**

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

- Smart card issues, and Surface Pro glitches.
- It would be nice if experimental data was complete at the start of the institute.
- More relevant seminars.
- N/A
- Access to the specific parameters from the experiments that were run prior to our arriving at NOMAD, rather than just the results/data.
- Pre-work provided earlier.
- More solid mechanics-based seminars. Greater interaction with the other teams.
- Maybe a joint start-up/tutorial of Leostream and how to maneuver the software of SNL, rather than leaving it to the mentor or whomever was around.
- Tutorials should be done in the first 2 weeks.
- Data provided sooner, we could have done more. **– I**
- Homework was useful, Abaqus license would have been nice.
- Larger archive of research papers.
- Uploaded Sierra Documentation and sample codes earlier.
- Overview of similar projects in the past, more milestone tasks during the summer.

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

- Availability to attend the intern career fair, etc. **– I**
- N/A **– II**
- Not sure.
- Program was well planned and laid out. Would have been interesting to collaborate with the other groups.
- Fewer presentations.
- Loved the overall program. Presentations from other managers at SNL would provide further knowledge of the work going on. Onboarding process could be sped up, mentors could be responsible for set of the laptops, which would provide director and OAA not to carry the burden.
- More hands-on presentations/seminars; seminar to go over computer program or analysis. **– I**
- Number was really good. **- I**
- Presentations were interesting, some more relevant than others. No issues, because Rob and Brook are the real MVPs.
- Tutorials were too long.
- Reduce events during the workday, as those days are less productive.

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

- Lack of "real" interaction with mentors and separation from opportunities at SNL.
- N/A **– I**
- More spacious experimental room.
- The lab could have been larger.
- More than sufficient.
- Run down facility and all teams in a less cramped space.
- Loved the UNM campus and ability to stay at Casas (but, was told rooms were furnished with linens and they were not.)
- Quiet spaces.
- FNs it would be helpful to have matlab, excel PP, word, etc. and access to the connect site.
- Everything went smoothly.
- Would have been nice having DAQs with higher sampling rates.
- Having separate spaces for the teams, without everyone talking at once. **– I**
- Larger work areas, work on base to get SNL experience.

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

- Daily skype meetings was a bit too much overseeing.
- Sierra was the biggest learning curve, pre-institute homework would be beneficial.
- Better communication about project goals in the beginning, more talking outside of the weekly meetings. **– I**
- N/A **– I**

- Mentors were very thorough, prior to the program having an understanding of the topics/project. Mentors went above and beyond, making sure we were supported every step of the way.
- Pre-work earlier, walk through code (QSMA) before NOMAD.
- Pre-work was good; but, mentors were not on the same page about half way through the project, and were giving conflicting direction.
- Instead of answering questions for us or talking over us, let us express our ideas or issues, as we know the intricacies and problems. Troubleshooting would have been better if mentor wasn't answering questions for me by the other mentor.
- Great job, very supportive.
- Mentors were awesome, clearly defined all expectations and there the whole way.
- Mentors were great. Ben Pacini was very accessible and always very helpful. Some mentors weren't involved as much, I would have appreciated their knowledge.
- Mentors could not consistently make our meetings, establishing a day that works at the beginning and emphasizing that participation in them is important would be good.
- Mentors could have a common understanding of the goals of the project before the first meeting.

6. What would have improved team dynamics?

- N/A **- IIII**
- More similar tasks.
- Our team got along very well.
- Better communication.
- Meeting members of the group prior to arriving in ABQ. Communication about strengths, weaknesses, expectations and skills prior to starting.
- Team building activities would be nice**. – I**
- Ours was good, diverse with different talents.
- Working together more, our team was split between lab and offices due to limited space in lab. **– I**
- Encourage students to meet every morning to discuss goals for the day and have more communications about progress and questions.

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

- It was just right. **– I**
- Longer would be better. If an extra week is available, more notice would be good.
- Longer would have been helpful. **– I**
- Start one week earlier. **- II**
- A few weeks longer, to expand more on findings, however, the pace/workload was manageable.
- Perfect duration, add interim presentations.
- Intense 7 weeks, extend 2 weeks to allow for more in-depth, meaningful paper.
- A week to finish up the paper, a week earlier. **- I**

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

- 3 **– IIIIIIIII**
- 2 or 3 is good. **– II**
- 2 was good, allowing constant contact, dividing work equally.

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

- "Foot in the door" and SNL teamwork experience.
- Fracture modeling and FEA. Mentor being an expert in the area was awesome.
- Getting actual reliable data on the last day.
- Collaborating with people from different fields.
- The project presentations at the end was rewarding and insightful. **- I**
- Experience and meeting new people**. – I**
- The highlight, hands down, was the people. Networking, I was able to grow and develop skillsets as a researcher and explore various aspects about working with a national laboratory.
- The independence of the research, but support of the mentors.
- Getting accepted as a FN, seminars, getting good results and final presentations.
- Using the HPCs.
- The progress we made in 7 short weeks.
- Collaborating on a challenging project, experienced mentors and fascinating seminars.
- The ability to show our project results experientially and numerically.

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

- No, pursuing research/work that are aligned with dissertation.
- Yes, I would love the opportunity. **– II**
- Probably not, let someone with less experience have the opportunity.
- Yes. **– IIIII**
- Anything for Rob.
- Absolutely, it was a phenomenal experience. Research is along the lines of my work and I look forward to the collaboration benefiting both parties.
- Yes, 100% without a doubt.
- No, but I'd like to see the final presentations.
- Maybe, depends on future path.

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?

- Other institutes, not a lot. HPC experience, more well-rounded at solid mechanics.
- Technical seminars were very interesting. My research not aligned with fatigue and fracture, but I've gained knowledge that will help in the future.
- Got good testing experience.

- Significantly. The modal analysis lectures involve similar analysis that I do.
- I learned about various fields within mechanics. The projects, lectures and final presentations opened my eyes to these topics, which I could potentially be interested in.
- A lot, given I am doing the same research at home.
- Broadened knowledge of work being done across the country, given me tools and resources that I will carry with me through my career.
- My interest in this research has been satisfied by the institute.
- My interest in research increased, and my perspective of research has become stronger, I am motivated to continue.
- Increased my understanding for research and for how others do things at other institutes. **– I**
- Research is similar, but NOMAD widened my scope, to see the bigger picture.
- It matches perfectly with my current research interests. **– I**
- Significantly, NOMAD further exposed me to varieties of research through seminars and provided a good experience solving a research problem with limited time.

12. Do you have any additional comments?

- My bicycle was stolen from UNM.
- Overall organization of the institute was excellent, administrative questions were always promptly answered.
- Thank you for the opportunity.
- N/A **– IIII**
- A tour of Albuquerque would be nice.
- Microsoft and Matlab for FNs, to be able to participate more with less restrictions. A memento would be nice, a pen, folder or t-shirt.
- The mentors really cared about us learning. They had BBQs and made me feel very welcomed.
- Thanks for a good summer. NOMAD Hawaiian shirts!

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

Seminars:

Matt Allen's seminar **Overview of Modeling and Test Methods for Nonlinearity due to Friction at Interfaces** (June 21, 2018)

5 – Very Useful	4	3 – Neutral	2	1 – Not Useful	Did Not Attend
7	**8**				

Matt Brake's seminar **Tribomechadynamics: The Emergence of a New Field at the Confluence of Tribology, Contact Mechanics, and Structural Dynamics** (June 27, 2018)

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

Tariq Kyraishi's seminar **Dislocations and Plasticity: A Primer** (July 5, 2018)

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

Zhu Mao's seminar **Structural Dynamics Identification via Computer Vision and Data Analytics in Structural Health Monitoring** (July 9, 2018)

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

Peter Avitabile's seminar **Highly Reduced Order Analytical Models Incorporating Measured Experimental Data for Full-Field Dynamic Response/Strain for Linear and Non-Linear Systems** (July 11, 2018)

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

Walter Gerstle's seminar **The State-Based Peridynamic Lattice Model – An Alternative Approach to Solid Mechanics** (July 18, 2018)

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

Ben Davis's seminar **On the Edge: Stories of Stability Lost and Found in Structural Mechanics** (July 26, 2018)

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

<u>Tutorials:</u>

Brian Lester's **Constitutive Modeling Tutorial** (June 22, 2018)

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

6 1 2 3 1 2

Bill Flynn's **Experimental Vibrations Tutorial**, Siemens LMS (June 26, 2018)

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

Activities:

Welcome Dinner at **Sadie's** (June 20, 2018)

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

Tour of **New Mexico Museum of Natural History and Science** (July 3, 2018)

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

Isotopes Baseball Game (July 7, 2018)

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

Tour of the **Museum of Nuclear Science and History** (July 10, 2018)

5 – Very Useful	4	3 – Neutral	2	1 – Not Useful	Did Not Attend
11	**2**				**2**

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?

- Access to SNL computing was great. Not having the mid-term presentation.
- Integrating experimental and numerical analysis in one project.

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

- Defining project goals ahead of time.

- Encourage communication between the different teams, last year I was more aware of what others were working on.

3.2. Mentor Feedback

Following the Institute, the mentors were asked to complete a survey. Below is a compilation of their answers:

1. Was the institute worthwhile for you? Why or why not?
    - Yes, I learned about combining constitutive models with various failure criteria and mesh dependency in fracture simulations.
    - Yes, our projects got very interesting results that will lead to future research and NOMAD projects.
    - Yes. It provided an opportunity to collaborate with researchers at SNL in addition to having preliminary work done on an interesting problem that I defined.
    - Yes, it was. As a new employee still learning the ropes of our codes and tools, teaching our team how to run things was helpful for me. Since the time was so constrained it forced me to quickly learn new things so that I could teach them, so we could get things off the ground. It was also a good opportunity to improve my leadership and project management skills.
    - Yes, I learned a lot about Sandia's finite element computing capabilities with Sierra. I enjoyed working with the students.
    - Yes. Our project provided results beneficial to Sandia, and I feel like it had a positive impact on our students. At the end of the project, all of them said they would consider working at Sandia, which I think is positive. I know 2 of our team members had not considered a "research" career before NOMAD and would consider it afterwards.

2. From a technical standpoint, what could have been better (e.g. papers provided earlier)?
    - The technical content was good. The students would have taken the topic deeper if time had permitted. The project was scoped well for the available time.
    - I'm not sure
    - Providing the contact information for the students earlier so that I can provide them with reading material and homework more than just a few weeks before the start of the institute.
    - I think the message that the homework was optional was taken too much to heart; our students clearly didn't do the homework assignment very in-depth, which set us back a bit and made our pre-institute conference calls kind of pointless. I get that technically maybe we aren't supposed to assign work before they're being paid, but maybe we should make the optional part more of a "fine print" thing and give the impression that it is an expectation.
    - I would have enjoyed more interaction with Sandia Technical Staff.
    - No recommendations here other than for myself. I would pick a less risky topic; the AM material we wanted to use did not end up working well, and this is my fault for not making sure it would work before using it as a project.

3. From a programmatic standpoint, what could have been better (e.g. fewer presentations)?
    - I would have liked having another Sandia mentor on the team and three students. My assistant Sandia mentor left Sandia about the time the institute started, so the students relied on me and a UNM professor for guidance.
    - I'm not sure. Having students as interns was a good move though because it was much easier to get a hold of them through Skype and data transfer via email
    - No comment.
    - I think that having the students give mid-point update presentations would have been helpful. I don't think that the extra time they spend on it is wasted, since it helps for the final presentations later. It gives the students an incentive to have their projects well-defined at an earlier point.
    - I gave a seminar in what was apparently a weekly series, but was not invited to attend any of the other seminars. I would have enjoyed attending the other seminars.
    - No recommendations here.

4. From a facilities standpoint, what could have been better (e.g. better access to …)?
    - It was great to let the students use the Sandia HPCC.
    - A better system for parking passes.
    - A few of the students seemed to indicate that they didn't have access to, or opportunity to go to Sandia. As the institute seems to be a recruiting tool, I worry that they didn't get the full SNL intern experience and missed out on seminars, tours, networking events, etc.
    - The facilities situation at the MTTC building was a lot better, it was nice to have separate offices (that weren't super crowded) for the teams.
    - I would have enjoyed access to Sandia computing facilities.
    - I would like to have given the students a tour of Sandia. I know they would have enjoyed visiting some of our facilities.

5. What could the mentors have done better (e.g. more pre-work)?
    - Meet with students more often
    - You'd have to ask the students
    - No comment.
    - I think having a mentor meeting where all the mentors get together and talk about the projects would be helpful. For example, the projects looking at material nonlinearities were all kind of using a lot of the same workflows, and maybe we could have saved some time and given them all the same example problems to get them started on running Sierra.
    - I appreciated the preparation and clear project presentation of the Sandia Co-mentor.
    - I thought our project went well. Maybe the students will offer some suggestions.

6. What would have improved team dynamics?
    - All the social interactions were very helpful. The team was very optimistic. No improvements were needed.
    - I'm not sure, I did not notice any friction amongst the students.
    - No comment.
    - I think our team sometimes was embarrassed or scared to ask when they were confused about something. We should have somehow made them feel safer to ask basic questions.

- More frequent interaction with students and Sandia Technical Staff.
- I really felt our team worked great together and don't think I would have changed anything. Several mentors had them over to our houses which I think was helpful in making them feel welcome.

7. What could have been better about the duration, timing, and schedule for the Institute?
   - It would be nice to extend the duration to 12 weeks.
   - I'm not sure
   - Earlier in the summer would be better to avoid conflicting too much with ND-CSI and other events.
   - If possible, it would be nice to form the teams earlier, so that we can meet with them and get them understanding the project better before they arrive.
   - A longer duration would be preferable.
   - I think an extra week or two would have been very beneficial to our group. I felt they had just reached the point where they were comfortable with our codes and were getting good results.

8. From your experiences this year, what is the ideal sized project team for the Institute?
   - Three students and three mentors
   - Three students.
   - Four students.
   - 2-3. I think with 3 people often one person ends up doing a lot less, and I don't know how much more productive teams of 3 are than 2. The group that had 2 seemed to get just as much done as the teams of 3.
   - Project team (2 mentors and 2 students) was about right.
   - I felt like 3 was a good number. It helped spread the workload among different strengths without them getting bored.

9. What was the highlight of the institute for you?
   - The students got excited about the technical challenge and the results they obtained.
   - Non-technical interactions with the students
   - Visiting and engaging the students. Not being responsible for organizing it (very happy to see Rob Kuether in that role now!)
   - The Greek meal after the final presentations.
   - Learning about Sandia's approach to computing was very interesting.
   - Their final presentation when they showed how much they had accomplished in such a short time. We had a great team. Another highlight was that several said they would like to work here someday and would like to come back next summer.

10. If you could, would you participate in the institute next summer if time/money permits?
    - Yes **- III**
    - It depends on my workload next FY. This did take up a ton of my time (>50%) during the institute. However, our students had less experience in FEA than we expected which meant they needed a lot of guidance.
    - Yes, I would like to continue.

11. Do you have any additional comments?
    - The institute was well planned and coordinated. Everyone I worked with had a fun and enlightening experience. The students made new friendships.
    - I think NOMAD is a great event and look forward to it each year. Having a select group of students come to Sandia ~3-4 weeks before NOMAD to do some prep work seemed to be very helpful to making the summer smooth (especially for experimental projects).
    - No
    - I think it might be a cool icebreaker activity to have every student give a 5-minute talk on their own research back home during the first week. We could tell them in advance that we will do that and ask them to prepare a couple slides (which they should already have…). It would break the ice and get them more comfortable speaking to each other.
    - Thank you for allowing me to participate in NOMAD.
    - Thank you to Brooke and Rob for all the hard work making NOMAD successful. This is no small task, and I believe even though this institute takes a lot of effort from all of us, it is making a positive difference in the students' career paths.

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

12. What did this year's Institute do better than your previous experience?
    - N/A
    - Easier access to lab (no swipe card necessary)
    - Having the Institute at the main campus of UNM seemed to be very beneficial. The students had much better access to the resources they needed, and it was a good space for them.
    - More diversity in the projects; last year it seemed like a lot of them were super similar.

13. What did this year's Institute do worse than your previous experience?
    - N/A
    - Nothing of note, it seems like NOMAD is a well-tuned event
    - A few of the students seemed to indicate that they didn't have access to, or opportunity to go to Sandia. As the institute seems to be a recruiting tool, I worry that they didn't get the full SNL intern experience and missed out on seminars, tours, networking events, etc.
    - The facility wasn't as good or convenient as the MTTC building.

4. FINAL REMARKS

Overall, the 2018 NOMAD Research Institute was successful and provided a meaningful experience for the students and mentors. 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 as the students finalized their documentation after returning to their home institutions. As a results of their efforts, the 2018 NOMAD Institute produced five proceedings and presentations at international conferences. Three of the six projects published proceedings at the 2019 SEM IMAC, one of the projects presented at the 2018 ASME IMECE, another at the 2019 AIAA SciTech conference, and one was published as a SAND report. A summary of the documentation produced by each project team is provided in Appendices C-H. Planning is underway for the 2019 NOMAD Research Institute. Many of the lessons learned from 2018 will be integrated into decision process for the upcoming program. As we move forward, we will continue to strive to provide the best experience for the students and engage staff in Engineering Sciences Center 1500.

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 M.S. and Ph.D. students, as well as post-doctoral and early-career researchers, from the U.S. and abroad. The program is sponsored by Sandia National Laboratories and the University of New Mexico.

The Program.

- Held from **June 18, 2018** to **August 2, 2018** 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 and foreign citizens attending U.S. institutions (see job posting ID 660515 for undergrad and 660517 for grad)
- Interested foreign citizens attending foreign universities should contact the NOMAD technical lead

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.

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

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2018-1282 HR. SB

2018 NOMAD PROJECT LIST

Constructing Optimal Surrogate Models for Bolted Fasteners in Multiaxial Loading.

This project will develop optimally calibrated, reduced-order models to simplify accurate predictions of the response of threaded fasteners under multiaxial loading while also exploring the most practical and appropriate constitutive material model to reproduce multiaxial failure.

Mentors: John Mersch (Sandia National Laboratories), Jeff Smith (Sandia National Laboratories), Gustavo Castelluccio (Cranfield University), John Emery (Sandia National Laboratories), and Peter Grimmer (Sandia National Laboratories).

Influences of Modal Coupling on Experimentally Extracted Nonlinear Modal Models.

This project will use a state-of-the-art system identification technique to populate nonlinear quasi-modal models of an experimental system with jointed interfaces using both narrow and broadband excitation techniques, and validate their models using excitations over an extensive range of amplitudes.

Mentors: Dan Roettgen (Sandia National Laboratories), Ben Pacini (Sandia National Laboratories), Matt Allen (University of Wisconsin-Madison), and Rob Kuether (Sandia National Laboratories).

A Priori Methods to Assess the Strength of Nonlinearities for Design Applications.

The goal of this project is to explore a metric for design to quantify the strength of a nonlinearity in bolted structures using the magnitude and uniformity of the contact pressure within an interface and assessing the loads applied to the interface during modal excitation.

Mentors: Matt Brake (Rice University), Adam Brink (Sandia National Laboratories), Ben Pacini (Sandia National Laboratories), Rob Flicek (Sandia National Laboratories), Christoph Schwingshackl (Imperial), Eric Dodgen (National Security Campus), and Dane Quinn (University of Akron).

Fatigue Properties of Additively Manufactured Hiperco.

In this study, the students will explore the effect of inherent flaws on the fatigue life of additively manufactured (AM) Hiperco material coupons in comparison to conventionally manufactured specimens and develop finite element models to predict crack growth as a correlation of the observed flaw size in AM materials.

Mentors: Kyle Johnson (Sandia National Laboratories), Tariq Khraishi (University of New Mexico), Adam Brink (Sandia National Laboratories), Scott Grutzik (Sandia National Laboratories), and Matt Brake (Rice University).

Material Failure Model and Properties for Puncture Simulations.

In this project, a team of students will use state-of-the-art material failure models to predict the kinetic energy required for a probe to penetrate a coupon of 7075-T651 aluminum and validate the predictions with existing experimental measurements.

Mentors: Neal Hubbard (Sandia National Laboratories), and Lin Zheng (Sandia National Laboratories).

Predictive Structural Dynamics Modeling of Bolted Interfaces.

This project will explore the predictability of a structural dynamics finite element model of a bolted structure with preloaded interfaces by perturbing the discretized mesh to capture the curvatures on the interface observed with optical measurements and validating the predictions with experimental modal analysis.

Mentors: Rob Kuether (Sandia National Laboratories), Paolo Tiso (ETH Zurich), Adam Brink (Sandia National Laboratories), and Dane Quinn (University of Akron).

Sandia National Laboratories

N-O-MAD

U.S. DEPARTMENT OF ENERGY

NNSA

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APPENDIX B: NOMAD GRADUATE STUDENT INTERN POSTING

Intern – Nonlinear Mechanics and Dynamics (NOMAD) RD Graduate 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 the 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 the student with opportunities to work in diverse research teams, to participate in a research project that will be published as a conference paper, and to engage with professionals working within their research fields.

The summer projects include:

- Constructing Optimal Surrogate Models for Bolted Fasteners in Multiaxial Loading. Utilize numerical studies to investigate the best strategies to simplify the geometry of threaded fasteners under multiaxial loading while also exploring the most practical and appropriate constitutive material model to reproduce multiaxial failure (computational).
- Influences of Modal Coupling on Experimentally Extracted Nonlinear Modal Models. Utilize a state of the art system identification technique to populate nonlinear modal models of an experimental system with jointed interfaces using both narrow and broadband excitation techniques, and validate their models using excitations over a broad range of amplitudes (experimental with computational).
- A Priori Methods to Assess the Strength of Nonlinearities for Design Applications. Explore a metric for design to quantify the strength of a nonlinearity in bolted structures using the magnitude and uniformity of the contact pressure within an interface and assessing the loads applied to the interface during modal excitation (experimental with computational).
- Fatigue Properties of Additively Manufactured Hiperco. Explore the effect of inherent flaws on the fatigue life of additively manufactured (AM) Hiperco material coupons in comparison to conventionally manufactured specimens and develop finite element models to predict crack growth as a correlation of the observed flaw size in AM materials (computational).
- Material Failure Model and Properties for Puncture Simulations. Utilize state-of-the-art material failure models to predict the kinetic energy required for a probe to penetrate a coupon of 7075-T651 aluminum and validate the predictions with existing experimental measurements (computational).
- Predictive Structural Dynamics Modeling of Bolted Interfaces. Explore the feasibility of developing a predictive structural dynamics finite element model of a bolted structure with preloaded interfaces by perturbing the discretized mesh to capture the curvatures on the interface observed with optical measurements and validating the predictions with experimental modal analysis (computational with experimental).

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 3.0/4.0
- Ability to work up to 40 hours per week during the summer
- Legally authorized to work in the United States of America – Sandia will not sponsor work authorization for this position.
- Candidate must be working towards a Ph.D or masters 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 18, 2018 to August 2, 2018

Qualifications We Desire

- Ability to be available for an extra week after NOMAD to work on documentation (June 18, 2018 - August 10, 2018)
- Experience (or academic focus) in structural dynamics, mechanical vibrations, or modal analysis, solid mechanics, or failure analysis is desired
- Graduate research that aligns with one of the six technical projects listed above is desired
- 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)

To Apply:
Visit:
sandia.gov/careers and search for job number **660517**

About Sandia:
Sandia National Laboratories is the nation's premier science and engineering lab for national security and technology innovation, with teams of specialists focused on cutting-edge work in a broad array of areas. Some of the main reasons we love our jobs:

- Challenging work with amazing impact that contributes to security, peace, and freedom worldwide
- Extraordinary co-workers
- Some of the best tools, equipment, and research facilities in the world
- Career advancement and enrichment opportunities
- Flexible schedules, generous vacations, strong medical and other benefits, competitive 401k, learning opportunities, relocation assistance and amenities aimed at creating a solid work/life balance*

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*These benefits vary by job classification

Location:
Albuquerque, NM

Equal opportunity employer/Disability/Vet/GLBT

SAND2018-1213 O

APPENDIX C: PROJECT #1 DOCUMENTATION

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

E. Camarena, A. Quintana, V. Yim, P. Grimmer, J. Mersch, J. Smith, J. Emery, G. Castelluccio, “Multiaxial Loading of Threaded Fasteners,” in *2019 AIAA SciTech Conference*, San Diego, CA, January 2019.

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

- NOMAD Final Seminar – SAND2018-8318 C
- SciTech Conference Proceeding – SAND2018-13573 C

SciTech Abstract:

The simulation of various structural systems often requires accounting for the fasteners holding the distinct parts together. When fasteners are not expected to yield, simple reduced representations like linear springs can be used. However, in analyses of abnormal environments where fastener failure must be accounted for, fasteners are often represented with more detail. One common approach is to mesh the head and the shank of the fastener as smooth cylinders, neglecting the threads (referred to as a plug model). The plug can elicit a nonlinear mechanical response by using an elasto-plastic material model, which can be calibrated to experimental load-displacement curves, typically in pure tension. Fasteners rarely fail exclusively in pure tension so the study presented here considers current plug modeling practice at multiaxial loadings. Comparisons of this plug model are made to experimental data as well as a higher fidelity model that includes the threads of the fastener. For both models, a multilinear elastic-plastic constitutive model is used, and two different failure models are explored to capture the ultimate failure of the fastener. The load-displacement curves of all three sets of data (the plug model, threaded model, and the experiments) are compared. The comparisons between simulations and experiments contribute to understanding the role of multiaxial loading on fastener response, and motivate future work on improving fastener models that can accurately capture multiaxial failure.

APPENDIX D: PROJECT #2 DOCUMENTATION

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

B.J. Moldenhauer, A. Singh, P. Thoenen, D.R. Roettgen, B.R. Pacini, R.J. Kuether, M.S. Allen, "Influences of modal coupling on experimentally extracted nonlinear modal models," in *37th International Modal Analysis Conference (IMAC XXXVII)*, Orlando, FL, January 2019.

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

- NOMAD Final Seminar – SAND2018-8336 C
- IMAC Conference Proceeding – SAND2018-12203 C

IMAC Abstract:

Research has shown that mechanical structures can be modeled as a combination of weakly nonlinear uncoupled modal models. These modal models can take many forms such as a basic cubic stiffness and damping force model, or a modal Iwan model. This method relies on two assumptions: 1) the mode shapes of the structure are not amplitude dependent, and 2) the modes of the structure do not couple or interact in the amplitude range of interest. Recently, a hypothesis was proposed that when multiple modes are excited that exercise the same nonlinear joint, the modes begin to couple. This hypothesis is tested on a physical system using a series of narrow-band excitation techniques via a modal shaker and broad-band excitation from a modal hammer. The resulting amplitude dependent stiffness and damping from the various excitation types are used to characterize the degree of modal coupling. Significant modal coupling is observed between three of the low order modes of a cylindrical structure with a beam connected to a plate on its end, which exhibits nonlinearity due to micro-slip in bolted joints.

APPENDIX E: PROJECT #3 DOCUMENTATION

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

E. Rojas, S. Punla-Green, C. Broadman, M.W.R. Brake, B.R. Pacini, R.C. Flicek, D.D. Quinn, C.W. Schwingshackl, E. Dodgen, "A Priori Methods to Assess the Strength of Nonlinearities for Design Applications," in *37th International Modal Analysis Conference (IMAC XXXVII)*, Orlando, FL, January 2019.

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

- NOMAD Final Seminar – SAND2018-8327 C
- IMAC Conference Proceeding – SAND2018-11460 A

IMAC Abstract:

One of the greatest challenges to the optimization of assembled systems is a lack of understanding of how jointed interfaces augment system dynamics. As a result, bolted systems are often over-engineered to a degree where excess mass and failure prevention mechanisms become costly. Thus, a design tool that can assess the nonlinearity of a joint prior to manufacturing and experimentation will lead to significant savings in qualification testing and improved performance in terms of dynamic properties and failure rates. Recent research has yielded four key observations regarding the behavior of nonlinear systems:

1. Interfaces with high, uniform contact pressure yield system dynamics that appear linear.
2. Portions of interfaces that have a moderate contact pressure, which have previously been assumed to be time invariant during dynamic excitation, exhibit significant fluctuations during dynamic loading.
3. Portions of interfaces with low contact pressure are the source of energy dissipation within a jointed structure.
4. Modifications to the far-field structure around an interface affect how the interface is loaded, and thus affect the perceived strength of nonlinearity.

Based on these observations, a new hypothesis for an *a priori* method for predicting the strength of a nonlinearity (SNL) in an interface was proposed: the SNL of a jointed system can be predicted by quantifying the magnitude and uniformity of contact pressure within an interface and by assessing the modal excitation of an interface. This work attempts to validate this hypothesis by defining a SNL metric based on the reduction of natural frequency and the increase in energy dissipation as the response amplitude of a structure is increased. This metric will be developed by correlating numerically extracted contact pressure and modal strain from a finite element model (FEM) to experimentally extracted amplitude dependent frequency and damping.

APPENDIX F: PROJECT #4 DOCUMENTATION

Details of the research from Project #4 were documented as an ASME IMECE conference presentation published as:

M. Mills, J. Biddlecom, B. Pineyro, T. Khraishi, K. Johnson, S. Grutzik, A. Brink, M. Brake, "Characterizing the Fatigue Behavior of Wrought Fe-Co-2V using Experimental, Computational, and Analytical Techniques," in *2018 ASME International Mechanical Engineering Congress & Exposition (IMECE)*, Pittsburgh, PA, November 2018.

The team is currently preparing a journal paper cited as:

M. Mills, J. Biddlecom, B. Pineyro, T. Khraishi, K. Johnson, S. Grutzik, A. Brink, M. Brake, "Characterizing the Fatigue Behavior of Wrought Fe-Co-2V using Experimental, Computational, and Analytical Techniques," to be submitted to *International Journal of Fatigue* (in preparation).

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

- NOMAD Final Seminar – SAND2018-8328 C
- IMAC Conference Presentation – SAND2018-8328 C

IMECE Abstract:

Fe-Co-2V is a soft, ferromagnetic material that is commonly used for electrical components that require strong magnetic properties. Applications include high-performance transducers, actuators, high field magnets, and solenoid valves. Despite the excellent magnetic properties of Fe-Co-2V, it often exhibits low strength, poor ductility, and low workability due to a phase transformation from disordered BCC to an order B2 microstructure. Current and emerging applications for Fe-Co-2V require a thorough understanding of its fatigue performance; however, limited fatigue data currently exists for Fe-Co intermetallic alloys. Therefore, this work characterizes the fatigue properties of wrought Fe-Co-2V through strain-controlled fatigue testing coupled with numerical and analytical modeling. Young's Modulus, ultimate strength, and yield stress were determined through monotonic tension tests. The fatigue behavior was characterized using fully reversed, strain-controlled fatigue testing for applied strain amplitudes ranging from 0.1% to 1.0%. Failure mechanisms were subsequently investigated through fractography with a scanning electron microscope. Inspection of the failure surfaces revealed that crack initiation occurred at defects at or near the specimen surface with propagation of less than approximately 200 microns before final brittle fracture. A combined numerical and analytical approach was taken for developing a predictive fatigue failure model. A microstructure-sensitive multistage fatigue (MSF) model was used to predict total cycles until failure and provided upper and lower bounds on fatigue life based on initial flaw size. Parameters obtained from micromechanical finite element simulations, such as maximum plastic shear strain range and crack tip opening displacements, were used as inputs to the MSF model.

APPENDIX G: PROJECT #5 DOCUMENTATION

Details of the research from Project #5 were documented as SAND report published as:

N. Bieberdorf, Z. Towner, N.B. Hubbard, W. Gerstle, "An Evaluation of Different Plasticity and Failure Laws in Simulating Puncture in 7075-T651 Aluminum," SAND2018-9205, Sandia National Laboratories, Albuquerque, NM, August 2018.

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

- NOMAD Final Seminar – SAND2018-8330 C
- SAND Report – SAND2018-9205

SAND Report Abstract:

In this work, various material models were studied for their ability to simulate puncture in a thin aluminum 7075-T651 plate due to low-velocity probe impact. Material models were generated by mixing and matching various work hardening laws with different failure criteria, and several hybrid material models were investigated. Finite element simulations of aluminum impact-response, based on each material model, were employed to predict the energy required for puncture and final plate tear-out geometry. Probes of different size and shape were used to impose various loading regimes, and numerical predictions were compared to experimental results from a previous study. It was found that no single combination of hardening and failure laws yielded universally accurate data, but that several material models could be used more reliably than others. Further, the importance of obtaining unique parameter-sets for work-hardening and failure criteria was illustrated.

APPENDIX H: PROJECT #6 DOCUMENTATION

Details of the research from Project #6 were documented as an IMAC proceeding published as:

M. Fronk, G. Guerra, M. Southwick, R.J. Kuether, A.R. Brink, P. Tiso, D.D. Quinn, "Predictive Modeling of Bolted Assemblies with Surface Irregularities," in *37th International Modal Analysis Conference (IMAC XXXVII)*, Orlando, FL, January 2019.

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

- NOMAD Final Seminar – SAND2018-8332 C
- IMAC Conference Proceeding – SAND2018-11908 C

IMAC Abstract:

Bolted interfaces are a major source of uncertainty in the dynamic behavior of built-up assemblies. Contact pressure distribution from a bolt's preload governs the stiffness of the interface. These quantities are sensitive to the true curvature, or flatness, of the surface geometries and thus limit the predictive capability of models based on nominal drawing tolerances. Fabricated components inevitably deviate from their idealized geometry; nominally flat surfaces, for example, exhibit measurable variation about the desired level plane. This study aims to develop a predictive, high-fidelity finite element model of a bolted beam assembly to determine the modal characteristics of the preloaded assembly designed with nominally flat surfaces. The surface geometries of the beam interface are measured with an optical interferometer to reveal the amount of deviation from the nominally flat surface. These measurements are used to perturb the interface nodes in the finite element mesh to account for the true interface geometry. A nonlinear quasi-static preload analysis determines the contact area when the bolts are preloaded, and the model is linearized about this equilibrium state to estimate the modal characteristics of the assembly. The linearization assumes that nodes/faces in contact do not move relative to each other and are enforced through multi-point constraints. The structure's natural frequencies and mode shapes predicted by the model are validated by experimental measurements of the actual structure.

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