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The 2017 Nonlinear Mechanics and Dynamics Research Institute

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Prepared by
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The 2017 Nonlinear Mechanics and Dynamics Research Institute

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Abstract

The 2017 Nonlinear Mechanics and Dynamics (NOMAD) Research Institute was successfully held from June 19 to July 28, 2017. NOMAD seeks to bring together participants with diverse technical backgrounds to work in small teams to utilize an interactive approach to cultivate new ideas and approaches in engineering. 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 from around the world came to Albuquerque, New Mexico to participate in the six-week long program held at 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, academia, and other government laboratories. In addition to the research activities, the students attended weekly technical seminars, toured the National Museum of Nuclear Science & History, 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 that was broadcast via Skype. 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.

ACKNOWLEDGMENTS

The authors would like to acknowledge a number of people and programs for their support of the 2017 Institute. First we would like to thank the WSEAT and ASC P&EM subprogram for their funding support to host the Institute. Next we would like to thank Jim Redmond and Dennis Croessmann for their leadership and guidance throughout the planning and execution process. We owe gratitude to all those listed below who helped contribute to the success of the program:

Sandia National Laboratories Staff and Management:
Michaela Negus, Craig Dickensheets, Scott Smith, Dan Rohe, Greg Tipton, Suzanne Cordova, Briana Sanchez, Kevin Tracey, Richard Drake, Samuel Browne, Terri Galpin

Student Participants:
Kyle Starkey (Purdue), Matthew Fronk (Georgia Tech), Kevin Eschen (Minnesota), Melicent Stossel (Washington), Alejandro Barrios (Georgia Tech), Peter Grimmer (UW-Madison), Wensi Wu (Cornell), Wes Scott (UW-Madison), Patrick Hughes (UCSD), Jonel Ortiz (TAMU), Giuliana Davis (UNM), Aabhas Singh (UW-Madison), Matteo Scapolan (Torino), Yuta Saito (UIUC), Deborah Fowler (UMass Lowell), Garrett Lopp (UCF), and Dhiraj Bansal (UC-Boulder)

Project Mentors:
Tim Walsh (SNL), Adam Brink (SNL), Matthew Brake (Rice), Wilkins Aquino (Duke), Gustavo Castelluccio (Cranfield), John Emery (SNL), Jeff Smith (SNL), John Mersch (SNL), Matt Allen (UW-Madison), Paolo Tiso (ETH Zurich), Paul Heyliger (CSU), Ward Johnson (NIST), Kevin Troyer (CSU), Dan Roettgen (SNL), Ben Pacini (SNL), Ryan Schultz (SNL), and Micah Shepherd (Penn St.)

Seminar and Tutorial Speakers:
Matt Allen (UW-Madison), Bill Flynn (Siemens), Matt King (Altair), David Najera (ATA Engineering), Fernando Moreu (UNM), Scott Grutzik (SNL), Pete Avitabile (UMass Lowell), D. Dane Quinn (Akron), and Kyle Johnson (SNL)

Finally, the authors would like to thank the corporate sponsors who offered their time and resources to the NOMAD Institute: Bill Flynn from Siemens/LMS, Matt King and John Brink from Altair, David Najera and Dan Kuriger from ATA Engineering.

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NOMENCLATURE

Abbreviation	Definition
AIMS	Albuquerque Institute of Math & Science
AM	Additive Manufacturing
ASC	Advanced Simulation & Computing
CAASE	Conference on Advancing Analysis and Simulation in Engineering
CB	Craig-Bampton
DOF	Degree-of-freedom
FRF	Frequency Response Function
FY	Fiscal Year
HCB	Hurty/Craig-Bampton
IMAC	International Modal Analysis Conference
IT	Information Technology
LEFM	Linear Elastic Fracture Mechanics
MRR	Maintenance, Repair and Replacement
MTTC	Manufacturing Training and Technology Center
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
WSEAT	Weapons Systems Engineering Assessment Technology
WSS	Wireless Smart Sensors

1. INTRODUCTION

The Nonlinear Mechanics and Dynamics (NOMAD) Research Institute unites graduate-level and highly qualified undergraduate-level students from around the world to work on challenging research problems in engineering sciences. Students work in teams of three under the guidance of mentors from Sandia National Laboratories, academia, industry, and other government laboratories from around the world to address research activities defined by the project leaders and NOMAD organizers. The Institute runs for six weeks during the summer at the University of New Mexico campus. Students attend weekly technical seminars and present their research within their project teams on a weekly basis. At the end of the program, project teams are expected to complete a proceeding document for a technical conference and present their work at the final NOMAD seminar that is 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 the Center 1500: Engineering Sciences, and beyond. The 2017 NOMAD Institute consisted of six technical projects that engaged 17 students and 18 mentors from around the world. The photograph in Figure 1 shows some of those who participated.

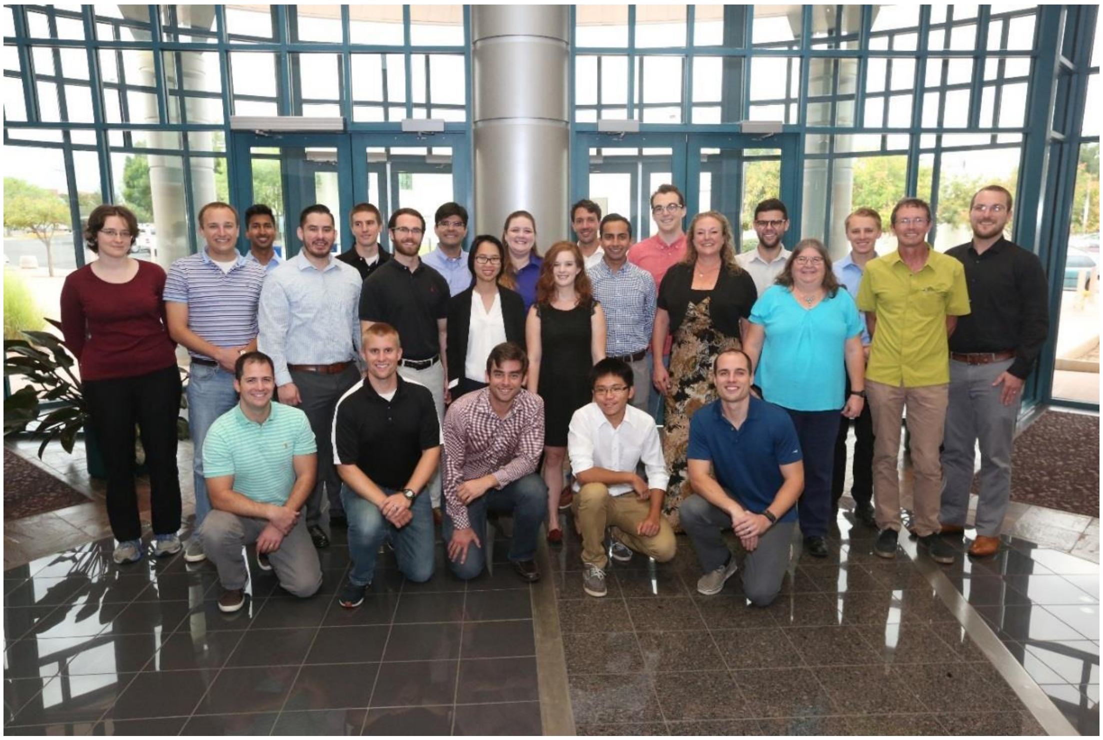

Figure 1. Some of the participants of the 2017 NOMAD Research Institute.

In 2017, NOMAD was supported by the Advanced Simulation and Computing (ASC) and Weapons Systems Engineering Assessment Technologies (WSEAT – now known as Delivery Environments, DE) at a level of $200K for the fiscal year (FY). This funding provided for space rental at UNM, invited speaker costs, logistical support for foreign national interactions, experimental equipment and supplies, limited support of the program coordinator, and limited support for student interns. It also includes some of the student costs, along with miscellaneous administrative needs (graphic arts, photography, network costs, etc.). Commercial sponsors provided equipment and software to support the Institute work at no cost to Sandia. Mentors paid for their time supporting NOMAD through their own individual direct programs (which are generally the beneficiary of the work), or by their home institutions if they were not Sandia employees. This SAND report documents the programmatic details related to the 2017 NOMAD Research Institute.

2. PROGRAMMATIC DETAILS

2.1. Lessons Learned and Changes from 2016

There were a number of changes that occurred between the 2016 and 2017 Institute, most notably in technical and administrative leadership positions. Starting in FY17, Rob Kuether and Brooke Allensworth took over the planning, organization and execution from previous leaders, Matt Brake and Michaela Negus. Diane Peebles, manager of department 1556, remained the only consistent team member through the transition. Matt and Michaela made themselves available to help the new leadership team and answer any questions. As part of this transition, there were a number of changes and lessons learned from 2016 that were achieved during the planning stages. These include:

- ❖ In order to appropriately reflect the shared funding support from ASC and WSEAT, it was decided to target an even share of computational and experimental projects during the project call.
- ❖ A theme of "Integration of Test and Analysis" was chosen to provide some guidance to the desired project focus during the project call.
- ❖ Past Institutes have focused heavily on projects related to joint mechanics research, and the new NOMAD planning committee had decided to broaden the scope of projects to more general topics in mechanics and dynamics.
- ❖ Other locations were explored to host NOMAD, mostly building sites in Research Park right outside of the Eubank gate. We were interested in holding the program at a location that would be more accessible to the Sandia mentors. Ultimately the program returned to the MTTC building at UNM for the third year in a row.
- ❖ It was decided to reduce the number of technical projects to six in order to allow us to focus on quality of experience for the students and mentors. Due to lack of support from the STAR program, the high school student project was not organized during FY17.
- ❖ The NOMAD planning team decided to reduce the number of mentors per project in order to seek more focused mentorship and reduce the amount of conflicting feedback. In past Institutes, projects with more than two or three mentors have been observed to have difficulty in deciding a path forward which diluted the end objective of the research.
- ❖ Past Institutes recruited 75% foreign participants and 25% US, however this years recruiting strategy was adjusted to 75% US students and only 25% foreign. This strategy aligns with NOMAD's long-term goals to provide a strategic recruiting pipeline of highly qualified candidates in fields that Sandia often finds difficult to recruit in.
- ❖ Suggestions to provide pre-Institute homework and suggested readings to the students prior to the start of NOMAD continued to receive positive feedback from mentors and students. Due to the short length of the program, the students who completed the homework were better prepared to start working on their research objectives on day one.

- ❖ Trainer laptops were purchased to provide student visitors with local versions of Sandia's in-house Sierra finite element analysis codes.

- ❖ We explored further sponsorship opportunities to provide more resources to the project teams. This year ATA Engineering offered licenses to their Attune and IMAT software.

- ❖ Weekly seminars from subject matter experts were organized to occur each Wednesday at 1PM. The talks supplemented the participant's educational experience during the summer.

- ❖ It was decided to no longer host tours on Kirtland Air Force Base due to extra effort needed to obtain base access for all students and coordinate escorts. This may be reconsidered in future Institutes.

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

- ❖ Hosting a poster session at the end of the institute had left the students dissatisfied about their final presentation material since the posters needed to be finalized three weeks after the start of NOMAD. The students felt they could not make sufficient progress to make posters that demonstrated their research and results. This year, a final seminar was organized during the last week of NOMAD to allow the students sufficient time to develop and present their research.

- ❖ All experimental and office equipment should be delivered the week before the start of the Institute to allow sufficient time to organize and accommodate delays.

- ❖ Visitors were provided reimbursement of their local travel and provided lodging at the UNM Casas del Rio dormitories.

2.2. Project Selection Process

A total of six projects were selected for the 2017 NOMAD Research Institute. A call for projects was distributed on October 10, 2016 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 2017 Institute include:

- Tim Walsh, Sandia National Laboratories
- Adam Brink, Sandia National Laboratories
- Matthew Brake, Rice University
- Wilkins Aquino, Duke
- Gustavo Castelluccio, Cranfield University

- John Emery, Sandia National Laboratories
- Jeff Smith, Sandia National Laboratories
- John Mersch, Sandia National Laboratories
- Rob Kuether, Sandia National Laboratories
- Matt Allen, University of Wisconsin-Madison
- Paolo Tiso, ETH Zurich
- Paul Heyliger, Colorado State University
- Ward Johnson, NIST
- Kevin Troyer, Colorado State University
- Dan Roettgen, Sandia National Laboratories
- Ben Pacini, Sandia National Laboratories
- Ryan Schultz, Sandia National Laboratories
- Micah Shepherd, Penn State University

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

- **Project 1: Inverse Methods for Characterization of Contact Areas in Mechanical Systems**

Contact interfaces in mechanical systems are significant sources of uncertainty in the linear vibration response of the system. In the linear setting, interfaces may be completely in contact, not in contact at all, or only partially in contact, all of which lead to different modal frequencies and overall vibration response. Inverse methods are a possible approach for characterizing the current state of the contact surfaces after construction. However, it is uncertain how many experimental measurements (e.g. accelerometers) would be needed to spatially resolve the contact areas in a complex system. This project would involve numerical studies to generate synthetic data on a set of simplified interface models, and extract the vibration histories on increasing sets of nodes that would emulate the process of progressively adding more accelerometers on a vibration test. Using this data, inverse methods will be developed to invert for the contact/non-contact areas based on the vibration responses, to ascertain how much measured data is needed to adequately resolve the contact areas, and thus avoid non-unique model calibration.

- **Project 2: From Macroscopic Tensile Tests to Microscopic Mechanical Response of Components**

The structural assessment of mechanical components is commonly based on finite element simulations that rely on experimental stress-strain curves. These highly non-linear curves are usually measured under monotonic loading using smooth specimens and standardized conditions. However, in-service components involve much more complex loading conditions and geometries that can promote failure at a local (e.g., fracture) or global scale (e.g., necking). Hence, how predictive is the information from stress-strain curves for modeling components? How much local variability is lost with macroscopic measurements? What are the implications for component assessments?

This project will address these questions by comparing the local response of different constitutive models such as nonlinear elasticity, J_2 plasticity, crystal plasticity, or other computational tools proposed by students. All models will be calibrated to match the same experimental macroscopic response. Then, students will investigate the response outside the experimental testing conditions by performing simulations with the various models. We aim to explore the limitation in predictive power of tensile stress-strain curves at macroscopic and microscopic scales under non-tensile loading, and non-smooth geometries.

The students will face the challenge of integrating experimental data and models to assess mock components. They will experience model limitations and variability at multiple length scales, geometries and loading conditions, despite their agreement with tensile tests. In addition, mentors are carefully selected with experience in material science, solid mechanics, mechanical testing, and computational methods to provide an ideal environment to nurture multidisciplinary work. NOMAD infrastructure in prior editions is particularly adequate to assure the success of this project. Finite element software will be based on Sierra and Abaqus, which will help expose the students to different environment. In addition, software developed at Sandia such as, Cubit, EulerRF, and microstructure generators will be employed.

- **Project 3: Investigation of CB Models with Interface Reduction for Contacting Structures**

Craig-Bampton (CB) substructuring in structural dynamics has long been used to produce reduced order models of large scale finite element models. Each subcomponent is reduced to a set of truncated fixed-interface modes and a set of static constraint modes that preserve the physical degrees-of-freedom (DOF) at the boundary. These CB subcomponent models are traditionally used for linear analyses, but have also been used to connect linear substructures with nonlinear elements at the interface (e.g. contact and friction). When the interface has a very fine and detailed mesh, the number of constraint modes can become prohibitively large and cause the critical time step to become very small for models with contact at the interface. In an effort to improve the efficiency of CB substructures with contact models at the interface, this project will seek to use interface reduction techniques to further reduce the interface DOF and increase the critical time step required for explicit time integration.

- **Project 4: Influence of Edge Boundary Conditions and Cracks in Ferroelectircally Excited Vibrational Modes**

Several important solids, including but not limited to layered capacitors, have resonant modal stresses that can be concentrated in a particular region either because of the boundary conditions along the edges and/or the presence of cracks between layers. In this study, finite element models will be used to implement these features and determine the level of influence that they can have. Of specific interest are predictions of whether the ferroelectrically excited modes will be sensitive to cracks that can commonly appear near either restrained or traction-free corners. This work is intended to supplement potential experiments on these structures, with the eventual goal of merging and analyzing the results from theoretical predictions and physical measurements.

- ❖ **Project 5: Experimentally Characterize a New Benchmark Structure for Prediction of Damping Nonlinearity**

A new benchmark structure has been proposed to aid in the development of predictive methods for structures with joints. In this project a team of students will use state of the art system identification methods to characterize the nonlinear dynamic response of the structure (including the nonlinearity of the joints). This will include the following tasks, derived based on the best practice from years past.

- Measure the roughness and flatness of the contacting surfaces.
- Measure the contact pressure distribution using pressure sensitive film.
- Perform a linear modal test with free-free boundary conditions to characterize the linear dynamic response.
- Excite the beam at various input locations and input amplitudes and characterize the modal natural frequency and damping ratio as a function of response amplitude. This will be done using impact excitation and Hilbert Transform analysis, as outlined in [2, 3].

The torque on the bolts (preload) will then be adjusted and the linear and nonlinear characterization will be repeated for at least three different preloads.

- ❖ **Project 6: Coupled Structural-Acoustic Modes**

A hollow structure can be thought of as a two component system: the first component is the structure itself and the second component is the fluid inside the hollow cavity. Just as the structure has modes of vibration, so does the fluid in the cavity. In many cases, the dynamics and modes of the structure are not affected by the acoustic modes of the cavity. However, if the structure and acoustic modes happen to be similar in shape and frequency, the two components will couple. This acoustoelastic coupling results in changes to the structural modes, including frequency shifts or mode splitting. Often, coupling of a structure with its internal cavity modes is not by design but by unfortunate happenstance.

In this project, researchers will perform a series of modal tests on a cylindrical test structure which exhibits acoustoelastic coupling. Modifications to the structure will be made to change the structural mode frequencies to change the coupling effect. Similarly, modifications will be made to the air cavity, altering the damping or boundary conditions, also to change the way the structure and acoustic volume couple. These modifications should experimentally demonstrate how to decouple a coupled system, resulting in the structure-only response. Researchers will also use microphones to measure the acoustic mode shapes and amplitudes during modal testing. Experimental results will be compared with finite element model predictions of the in-vacuo structure, acoustic cavity, and the coupled system.

Some tasks for this project include:

- Perform baseline modal testing of the cylindrical structure
- Develop separate structural and acoustic models and determine which modes may couple and identify those modes in the test FRFs
- Measure the acoustic mode using a roving microphone technique and compare with the model shapes to verify which acoustic modes are being excited and coupling with the structure

- Compute the coupling parameter value for the mode pairs and use this as a quantitative metric for identifying coupled modes in the measured FRFs
- Make changes to the acoustic cavity, changing boundary conditions or damping, and demonstrate the effect on the structure FRFs. Determine how to effectively decouple the air from the structure
- Change the structure modes (for example, by adding masses) and show how the acoustoelastic coupling effects change as the structure and acoustic mode frequency proximity changes

2.3. Student Participant Selection Process

The NOMAD committee strategized to begin student recruitment once the projects were down-selected to place students based on their research interests. The goal was to recruit three students per project, resulting in a target number of 18 participants to match with six projects. Two types of positions were available to the students: no-fee agreement visitors and summer interns. The visitors were not hired on-roll and allowed us to recruit foreign nationals to participate in the program. NOMAD budget allocated funds to pay for their housing at the Casas del Rio dormitories on UNM's campus at a rate of $38 USD per night, and reimbursed their local travel expenses up to $400 USD. No travel relocation or additional stipend was provided to these students. A limited number of student internships were available under the funding levels during FY17. A total of five internships were made available to improve recruiting numbers.

Recruiting efforts relied heavily on distributions to external university collaborators across the world. A flyer was crafted by Stephanie Blackwell in Creative Services that served as our main distribution material; 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. Printed flyers were also distributed at the 2017 International Modal Analysis Conference (IMAC) to students and professionals alike. A total of 24 students had applied in response to the flyer.

Additionally, a summer internship posting was created on the external Sandia website, resulting in an additional 20 student applications. The job posting is shown in Appendix B. A total of four students were hired through these openings. With these recruiting efforts, a total of 44 applications were received and 17 students were selected to participate in the 2017 NOMAD Research Institute. These students include:

- Kyle Starkey, Purdue University
- Matthew Fronk, Georgia Institute of Technology
- Kevin Eschen, University of Minnesota
- Melicent Stossel, University of Washington
- Alejandro Barrios, Georgia Institute of Technology
- Peter Grimmer, University of Wisconsin-Madison
- Wensi Wu, Cornell University
- Wes Scott, University of Wisconsin-Madison
- Patrick Hughes, University of California San Diego

- Jonel Ortiz, Texas A&M University
- Giuliana Davis, University of New Mexico
- Aabhas Singh, University of Wisconsin-Madison
- Matteo Scapolan, Politecnico di Torino
- Yuta Saito, University of Illinois at Urbana-Champaign
- Deborah Fowler, University of Massachusetts Lowell
- Garrett Lopp, University of Central Florida
- Dhiraj Bansal, University of Colorado Boulder

2.4. Facilities

The 2017 Institute was held at the MTTC building on the south campus of UNM. This off-site location provided easy access to the foreign and US students, and housed all the amenities needed to satisfy the requirements for the technical projects. A schematic of the space leased in MTTC is shown in Figure 2. The blocks in blue and red indicate space that was leased and not leased, respectively. The space in rooms 165, 169, 171, and the AIMs classroom in 175 all served as office space for the students to establish their workstations. Room 175 housed three project teams, two of which were experimental teams who spent most of their time in the laboratory. The lab space in room 156 provided sufficient space to set up the experimental equipment needed for Projects 5 and 6. A NEPA was generated for this building to cover this space in 2016 and is active through 2018. Each team utilized an isolation table 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. The AIMs classroom 160 served as an extra space to hold weekly meetings, trainings, tutorials and other informal gatherings.

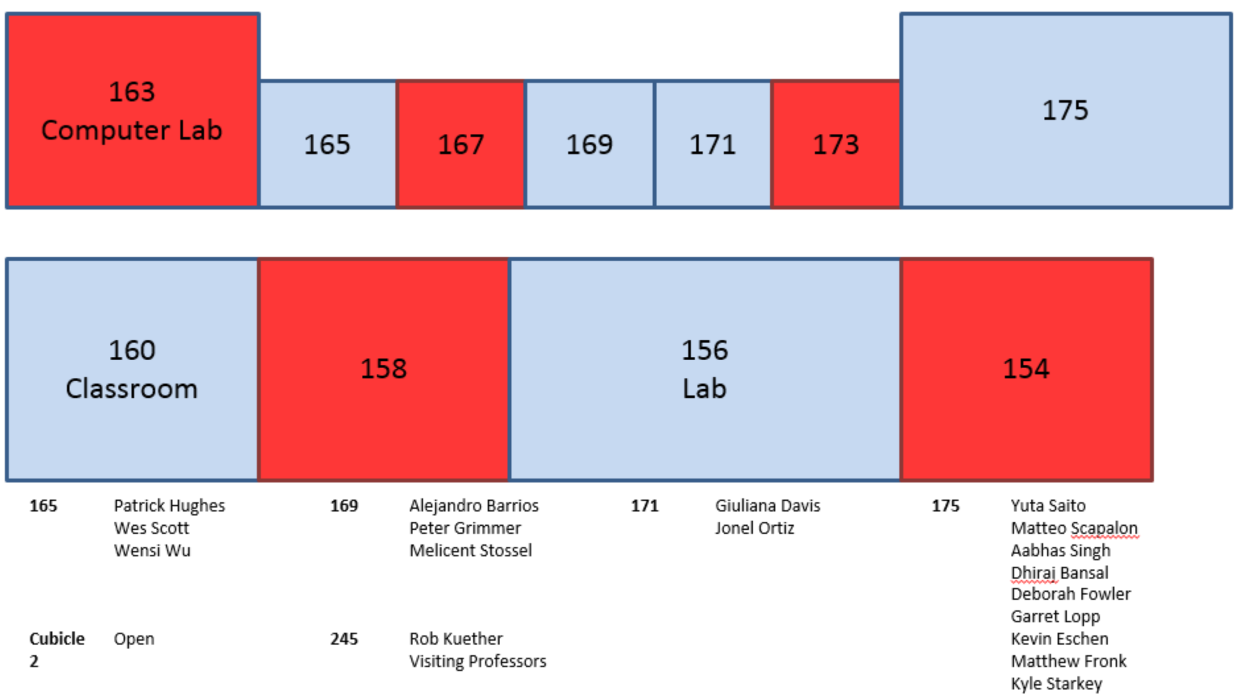

Figure 2. Floor plan and office assignments for the UNM MTTC space.

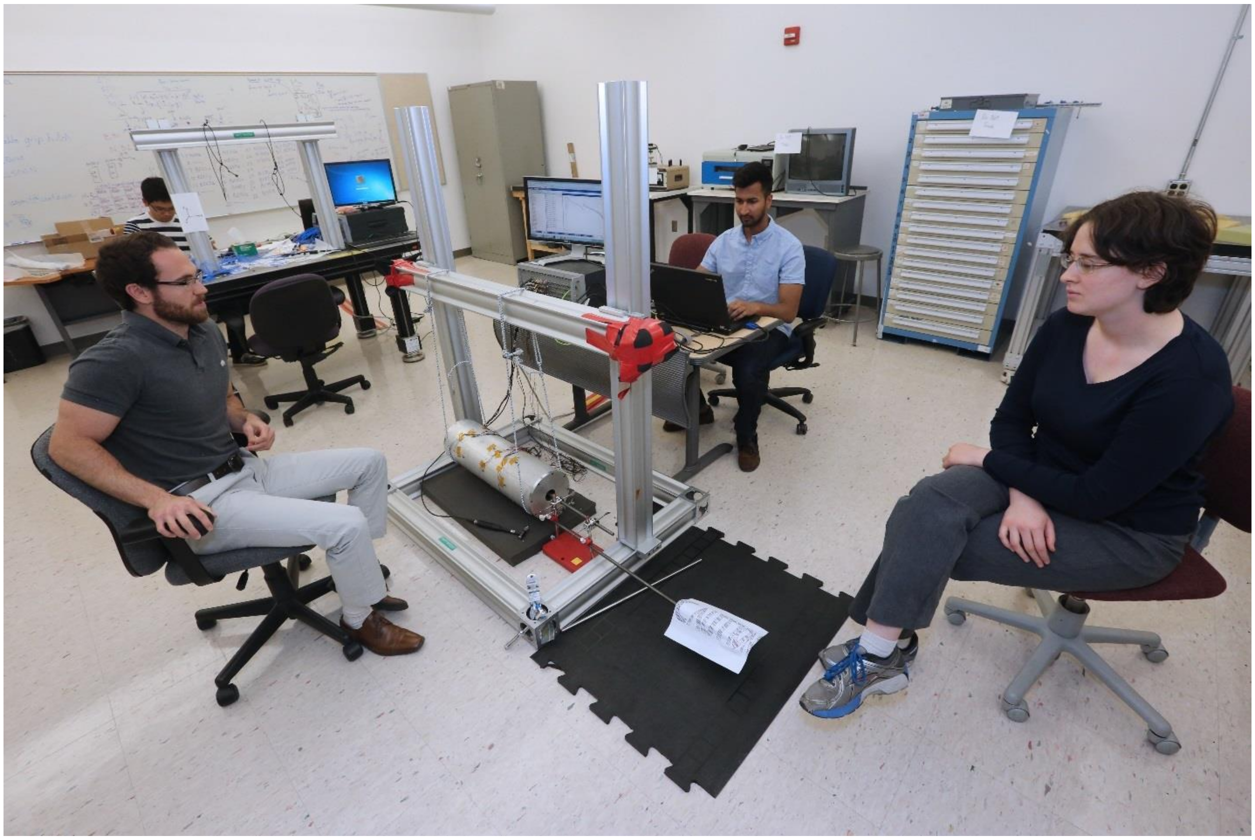

Figure 3. Lab space used at MTTC.

An office and cubicle were leased on the main level to provide office space to Rob Kuether and any visiting professors/researchers during the summer. A café inside the building provided students and mentors access to hot lunches, coffee and pastries, which proved very useful since there were no other dining options within walking distance. The auditorium space on the main floor served as a formal gathering space for our kick-off meeting, weekly technical seminars, and final student presentations. The auditorium space needed to be booked in advance, although the space was rarely used during the summer months. The building owner provided free parking in the lot just west of the building, making this space easily accessible to visiting Sandians and guests.

A couple of challenges arose during the duration of the program. First, the Wi-Fi signal in the lower level offices and lab space was very weak, and required UNM IT support to install signal boosters in two of the rooms. The IT response was slow so it is recommended to initiate this service request prior to the start of the Institute and consistently check on the status. The other challenge that occurred during the summer was the presence of ants across a number of the lower level office spaces. Students consistently complained about this issue and the building maintenance was slow to respond.

The visiting students were provided housing at the Casas del Rio dormitories on the north end of campus. The building was relatively new, 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. The student feedback was positive, and it was recommended that all the NOMAD participants stay in the same wing of the dorms to help build comradery amongst the group. The one downside to this space was the lack of free parking. A free UNM shuttle was available to the students to transport between the dorms and MTTC during their stay.

2.5. Calendar of Events

A summary of the events planned for the 2017 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 2017.

Monday, 6/19:	NEO Training for Interns Icebreaker Activities with non-interns
Tuesday, 6/20:	Official Start of NOMAD 2017 Kickoff Presentations and Training
Wednesday, 6/21:	Seminar by Matt Allen Siemens/LMS Tutorial by Bill Flynn Welcome Dinner at Sadie's of New Mexico
Friday, 6/23:	Altair Hyperworks Tutorial by Matt King
Tuesday, 6/27:	ATA Software Tutorial by David Najera
Wednesday, 6/28:	Seminar and Lab Tour by Fernando Moreu
Monday, 7/3:	Tour of National Museum of Nuclear Science & History by Chuck Loeber
Wednesday, 7/5:	Seminar by Scott Grutzik
Saturday, 7/8:	Isotopes Baseball Game
Wednesday, 7/12:	WSEAT Executive Visit Seminar by Peter Avitabile
Thursday, 7/13:	NOMAD Executive Visit
Wednesday, 7/19:	Seminar by D. Dane Quinn
Monday, 7/24:	Seminar by Kyle Johnson
Thursday, 7/27:	Final Student Presentations Farewell Dinner at El Pinto
Friday, 7/28:	Last Day of NOMAD 2017

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, including a mini shaker that attaches directly to a structure. Following his presentation, he provided 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.

- **“Altair HyperWorks Tutorial” by Matt King**

Matt King and John Brink visited NOMAD during the first week to give an overview of the HyperWorks software capabilities and provide a simple tutorial on running a solid mechanics analysis. Following the briefing, he met with individual computational teams to discuss their goals and see how HyperWorks could fit into their workflow. The Project #1 team used HyperWorks extensively for their research, and Matt made himself available to answer questions and provided tutorials throughout the Institute. Matt has supported NOMAD for a number of years by donating software licenses to HyperWorks.

- **“ATA Software Tutorial” by David Najera**

David Najera provided an overview of the Attune model updating software, and IMAT toolbox, both of which were developed and donated by ATA Engineering. David demonstrated the Matlab based tools on example data sets and answered questions from students interested in using the product. This was the first year that ATA Engineering has sponsored NOMAD by donating licenses to their software.

- **"An Introduction to Interface Modeling and Reduction in Structural Dynamics" 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. The Hurty/Craig-Bampton approach can be used to reduce the computational burden when studying assembled systems, but often the interfaces contain many nodes and so the reduced models provide little benefit.

This talk will present an overview of modeling methods for assembled structures with nonlinearities at the interfaces. The Hurty/Craig-Bampton (HCB) method will be reviewed and recent efforts to reduce the number of interface DOF in linear HCB models will be highlighted. This will be related to the ubiquitous and yet poorly documented “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 HCB 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.

- **"Performance Sensing and Safety Assessment of Critical Infrastructure Enabled by Experimental Structural Dynamics" by Professor Fernando Moreu**

This research explores the potential of measuring structural responses of critical infrastructure assets to inform management and prioritize decisions related to maintenance, repair, and replacement (MRR). This presentation will also include results about reference-free measurement of displacements using both accelerations and contact-free strategies. Examples include automatic/remote Structural Health Monitoring (SHM) and assessment and prognosis using wireless smart sensors (WSSs). These research demonstrates the potential of sensing technology to assist with critical infrastructure inspections and management practices. The presentation will cover future opportunities for adapting SHM and WSSs towards asset management, sustainability, and resilience practices.

Dr. Fernando Moreu, PE, started last Fall 2015 as Assistant Professor in structural engineering at the Department of Civil Engineering at the University of New Mexico (UNM) at Albuquerque, NM. His research interests include structural dynamics, structural health monitoring, wireless smart sensor networks, railroad bridges, infrastructure management, real-time performance monitoring, and structures smart design, monitoring, and construction. He received his BS in Civil and Environmental Engineering from the University of Granada in Spain and his MS and PhD degrees in structural engineering from the University of Illinois at Urbana-Champaign. In addition, his industry experience includes ESCA Consultants, Inc. for over ten years. He is the director of the Smart Management of Infrastructure Laboratory (SMILab) at UNM (http://smilab.unm.edu/).

- **"Fracture Mechanics: Central Concepts and Examples" by Dr. Scott Grutzik**

Linear elastic fracture mechanics (LEFM) can be summarized as trying to answer two questions: “If I have a crack in a brittle material, will it propagate?” and “If this crack propagates, will it do so in a stable manner or cause immediate catastrophic failure?” This seminar will briefly cover the core concepts and assumptions of LEFM. We will discuss early historical fracture criteria and how these led to the modern framework of crack tip stress fields, stress intensity factors, and energy release rate. The goal is to give a sense of when a fracture mechanics analysis is required and under what conditions is LEFM valid. Some strategies for performing simple, “back of the envelope” style analyses will be presented along with a number of short examples of problems and current research topics at Sandia.

Scott completed his BS with a dual degree in Engineering Physics and Physics at the University of Wisconsin – Madison in 2010. He then completed his PhD in Theoretical and Applied Mechanics under Prof. Alan Zehnder at Cornell University in 2015 where he studied the effect of native oxide layers on fracture strength of nanoscale silicon structures. He recently completed a post-doc at Sandia in the Material Mechanics and Tribology group, transitioning to a staff position in Component Science and Mechanics in January 2017.

- **"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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Director, Modal Analysis and Controls Laboratory

President Society for Experimental Mechanics 2016
Associate Editor – Handbook of Experimental Structural Mechanics

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

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

- **"Modeling Microslip and Dissipation in Structural Systems" by Professor D. Dane Quinn**

Jointed structures are everywhere. In applications as varied as truss systems, airplane wings, or vehicle frames, the overall structure is composed of components that are somehow connected together to form a single integrated whole. However, regardless of how carefully the joints and interfaces between the components are designed, the jointed structure differs from that of a corresponding monolithic piece. If the joints are designed properly, the difference between the load carrying capability of the component versus monolithic system is negligible. However, the dynamics of the jointed structure and in particular the observed dissipation can be significantly different. Unfortunately modeling the presence of an interface is complex and computationally expensive, but necessary if one wishes to pursue model-based design. This talk will introduce and highlight the role of microslip, highly localized slip at the interfaces, on the observed structural dynamics within jointed systems and develop various approaches to incorporate it into larger structural models.

D. Dane Quinn was awarded the B.M.E. degree from Georgia Tech in 1991 and, in 1995, a Ph.D. from Cornell University in the Department of Theoretical and Applied Mechanics. He is currently a Professor on the faculty of The University of Akron in the Department of Mechanical Engineering. His research interests lie in the area of applied dynamical systems and mechanics. Specifically, he has considered the effects of resonances in nonlinear systems with applications to micro-electro-mechanical system, rotordynamics, spacecraft dynamics, and the mechanisms by which energy is transferred through mechanical systems. In addition, he is currently collaborating with researchers at Sandia National Laboratories modeling the dynamic response and structural dissipation induced by mechanical interfaces such as lap joints and bolted *connections. When not thinking about nonlinear dynamics, he runs, plays soccer, and is the lead cowbell player in an Akron-area band.*

- **"Thermal and Structural Part-Scale Modeling of the Metal Additive Manufacturing Process" by Dr. Kyle Johnson**

Advances in metal Additive Manufacturing (AM) have made possible the design of parts with very complex geometries and tailored material and mechanical properties. In order to efficiently optimize the process to achieve desired performance, accurate computational models are necessary. Modeling the AM process presents a unique challenge due to the inherent multi-physics nature and the many available process parameters that are tightly coupled to the resulting properties. This talk will discuss recent work in solving these problems using the Sierra and SPPARKS code suites at Sandia, including methods for predicting accurate thermal histories, residual stresses, distortion, and microstructure. Successes and remaining challenges of modeling the AM process at the macroscale will be presented from both a thermal and solid mechanics point of view.

Kyle Johnson received his B.S. and Ph.D. degrees in Mechanical Engineering at Mississippi State University. He began his career at Sandia National Laboratories as a postdoctoral researcher in the Solid Mechanics department in 2016, and became a staff member in the Component Science and Mechanics department in 2017. Kyle's research interests are centered around computational solid mechanics, and include topics such as additive manufacturing process modeling, micromechanical foam modeling, integrated computational materials engineering, design optimization, and weapon component analysis.

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. In addition, two separate tours were organized for the students. The first was a tour of UNM's Structures Laboratory. The second was an off-campus visit to 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 situation. There were also a number of professors and sponsors visiting during this first week who were able to join in. The Sadie's of New Mexico location was chosen to introduce the students to New Mexican cuisine, something that is unique to the region. A photograph of the group is shown in Figure 4. The visiting students seemed to enjoy the New Mexican food and left them curious about other dishes and restaurants around town.

Figure 4. Group photograph of the Welcome Dinner at Sadie's of New Mexico.

- **Tour of UNM Structures Laboratory**

Following the seminar by Fernando Moreu on "Performance sensing and safety assessment of critical infrastructure enabled by experimental structural dynamics", the students were given a tour of the University's Structures Lab in the Centennial Engineering Center. Professor Moreu showed the students the test capabilities and ongoing researching in the Civil and Mechanical engineering departments, including a drone equipped with an impacting hammer to excite civil structures for vibration measurements.

- **National Museum of Nuclear Science & History Tour by Chuck Loeber**

During the week of Independence Day, 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 Chuck Loeber, a museum docent, who is a retired Sandian. Typically the museum requests 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 to 120 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.

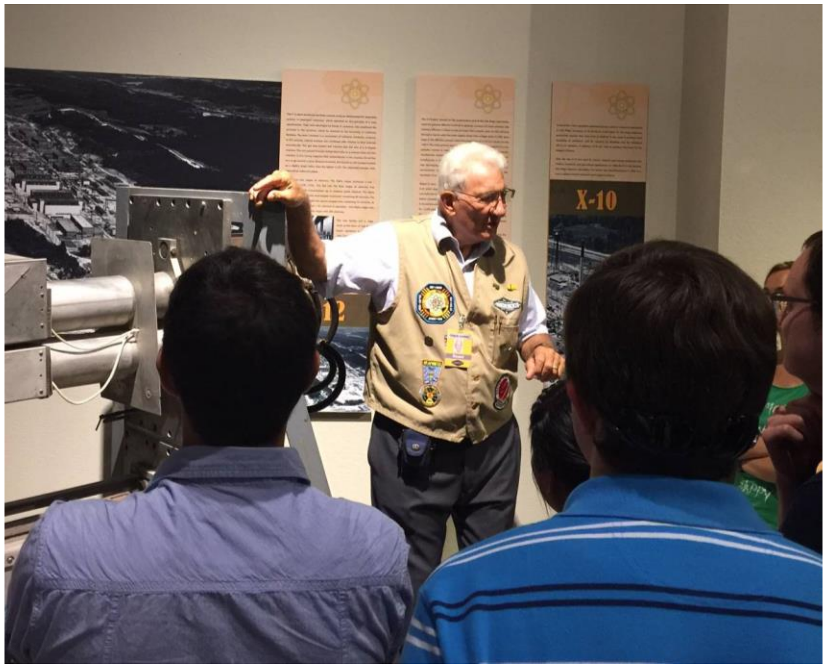

Figure 5. Nuclear Museum tour guided by Chuck Loeber.

❖ **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 win. 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.

Figure 6. Isotopes baseball game.

❖ **Farewell Dinner at El Pinto**

A farewell get together at El Pinto was a chance for the NOMAD group to reminisce about the 6 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 a Thursday night, as most students were leaving town over the weekend.

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 MTTC building on UNM's south campus. Each group was allotted thirty minutes for presentation and Q&A. The students were asked to submit their final slide materials to Rob Kuether by Monday July 24th in order to submit them to Sandia's R&A site for unlimited, unclassified release by Thursday, July 27th. 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. In past years, the students disseminated their research at a poster session held on-site at Sandia National Laboratories. Many challenges were faced in the past, including a strict deadline requirement to print the posters three weeks in advance with Creative Services and the added paperwork required to get all students SNL access. This led the organizing team to reconsider this event and replace it with a technical seminar.

Figure 7. Project #3 group photograph during the final student seminar.

2.6. Lessons Learned during 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.

3. CONCLUSIONS

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, learned new areas, learned research in different fields, transferable skills, networked with engineers, great guidance from mentors, will use these tools in the future, very smart mentors.

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

- Homework more rigorous to learn the tools, saving time during the project, more information about deliverables required and due dates. More direction from mentors about the homework, list of expected tasks. IIII
- More Python tutorials.
- More in-depth explanation of what is expected, more detailed problem description. II
- More updates between the groups to see their successes and struggles.
- All was good – IIIIII

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

- More SharePoint space or flash drives.
- Calendar of presentations, etc.
- Too short to complete for a paper, too long for a workshop.
- Make it 8 weeks. - III
- Put computational people in the same room.
- Make at least one week longer, more group activities/socials. - II
- All was good - IIIII

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

- Wi-Fi access could be better.
- Better access to journal papers.
- Access to printers.
- White boards.
- Sharing a room with 3 teams was distracting and noisy. - II
- Ants. IIII
- All was good - IIII

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

- First team meeting sooner.
- More targeted homework prior to program. - IIII
- Assignments before the program was good.
- The mentors were awesome. - IIII
- Assign more practical homework.
- Professors Tiso and Allen were practically absent from the whole project.
- More frequent meetings and communication would help with project progress.
- Clearer direction and denoting the goals. - II
- More detailed problem description.

6. What would have improved team dynamics?

- It depends on each member's work ethic and personalities.
- A few more social gatherings.
- Having a speaker discussing the importance of communication with younger students.
- Clearly set goals and tasks from mentors.
- A whiteboard.
- Splitting the interns and externals on day one w/o the team building exercise being done by everyone was noticeable.
- Give more time to learn the software before the program starts.
- Have mentor know Altair or provide licenses, for software like Abacus and ANSYS.
- All was good – IIIIIII

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

- Ideal amount of time, allows quarter system students to participate w/o missing school. The schedule encouraged productivity by having clear work/non-work hours. - IIIII
- Longer duration would be nice. – IIIII
- Want at least 8 weeks (start 6/1). – IIIIIII (some say 1-2 weeks longer)

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

- 3 Students. – IIIIIIIIIIIIIII

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

- Modal testing and analysis, interacting with the other students.
- Comradery with the NOMAD participants, social events (especially w/the Casa residents), the institute promoting a work/life balance.
- Finally getting good results after struggling to get things to work. - II
- Learning new things and meeting new people. - IIII
- Dinner at El Pinto.
- Weekly seminars. - II
- Cards at lunch, hiking and social activities. – II
- Actual research done. – II

- Working with a team, not being the assistant or working alone.
- Giving the executive visit presentation.
- Multiple mentors.

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

- No – will be looking for a full-time job.
- Yes. – IIIIIIIII
- Depends on projects.
- Depends on what I'm doing.
- No, other research interests.

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?

- Learned a lot about Sandia, very useful to get out of specific research area and will bring back tools and skills that will add to my other work.
- Not much, since the focus of field is a bit different.
- Introduced me to some of the interesting research that I have never heard of.
- Learned a huge amount, helped me grasp a better idea of how projects are done in this work atmosphere. I feel more prepared to go back to my research and view things from a different perspective.
- Tremendously. – I Significantly. - I
- I have gained a lot of knowledge that I can apply at grad school.
- A great amount, mentors helped a lot.
- Enhanced my experimental testing skills, exposed me to a new field.
- Somewhat, it was interesting to network with other students and mentors and hear about their work.
- A lot – I have a much better feel for other research labs compared to my own.
- It's given me a ton of knowledge about plasticity, the FEA skills will be useful for my research, as well as future employment.
- Great insight into contact mechanics and contact modality, which will be extremely helpful to my research.
- It provided a little insight into other students' research, interesting to see how they approached problems.
- Talking with other students diversifies my knowledge, as well as the seminars.

12. Do you have any additional comments?

- When considering the program, there was little information, other than the flyer. More details would be good.
- The program is a bit short, multiple mentor system was good.
- More group interactions and less differentiation between interns/visitors, this had a bit of an effect on the interactions. Mentor/student social night would be good.
- NOMAD is really awesome and a great way for grad students to both contribute to research that lends to additional publications, and to work with people who are at "the top of their game."
- I was external and brought my own computer, it would be nice to use Sandia's computational power for simulation. Need to select the correct fitting for the computer, a Surface is not ideal for running simulations and doing FEA.
- Keep up the great work! It was a great experience.
- I would like to have known beforehand about travel reimbursement, keep the weekly talks, MTTC is better than being on base, teammates staying at Casa was valuable, having mentors that are a mix of engineers and professors was very valuable.

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

Seminars:

Matt Allen's seminar on Interface Modeling and Reduction (Wednesday, June 21st)

5 – Very Useful	4	3 – Neutral	2	1 – Not Useful	Did Not Attend
5	***8***	***1***	***1***	***0***	***0***

Fernando Moreu's seminar on Critial Infrastructure (Wednesday, June 28th)

5	4	3	2	1	Did Not Attend
4	***5***	***3***	***1***	***2***	***1***

Fernando Moreu's tour of the UNM Structures and Composites Labs (Wednesday, June 28th)

5	4	3	2	1	Did Not Attend
3	***4***	***2***	***3***	***0***	***4***

Scott Grutzik's seminar on Fracture Mechanics (Wednesday, July 5th)

5	4	3	2	1	Did Not Attend
6	***2***	***2***	***4***	***1***	***1***

Peter Avitabile's seminar on Full-Field Dynamic Response/Strain (Wednesday, July 12th)

5	4	3	2	1	Did Not Attend
12	***3***	***1***	***0***	***0***	***0***

Dane Quinn's seminar on Microslip and Dissipation (Wednesday, July 19th)

5	4	3	2	1	Did Not Attend
4	***8***	***2***	***0***	***0***	***4***

Kyle Johnson's seminar on Metal Additive Manufacturing (Monday, July 24th)

5	4	3	2	1	Did Not Attend
4	***3***	***2***	***0***	***0***	***1***

<u>Tutorials:</u>

Bill Flynn's Siemens/LMS Tutorial (Wednesday, June 21st)

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

Matt King's Altair HyperWorks Tutorial (Friday, June 23rd)

5	4	3	2	1	Did Not Attend
3	***4***	***1***	***1***	***0***	***7***

David Najera's Attune and IMAT Tutorial (Tuesday, June 27th)

5	4	3	2	1	Did Not Attend
0	***0***	***2***	***2***	***1***	***10***

<u>Activities:</u>

Welcome Dinner at Sadie's (Wednesday, June 21st)

5 – Great	4	3 – Neutral	2	1 – Terrible	Did Not Attend
13	***2***	***0***	***0***	***0***	***1***

Nuclear Museum Tour (Monday, July 3rd)

5	4	3	2	1	Did Not Attend
8	***2***	***0***	***0***	***0***	

7

Isotopes Baseball Game (Saturday, July 8th)

5	4	3	2	1	Did Not Attend
10	***4***	***0***	***0***	***0***	***4***

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. Through their work, the students have answered several questions that I was very interested in. For example, Team 4 collected a rigorous data set that characterizes a new benchmark structure. We learned interesting things about how this system behaves, and which joints affect the damping and stiffness of each mode. This has already been useful to me as my students and I work on modeling this system. Similarly, Team 2 made interesting discoveries regarding what level of fidelity is needed in an interface to capture the stiffness of a preloaded joint.
- I'm not sure yet. It was a pretty big effort to design the project, write the homeworks, do the pre-institute meetings, be on site, try to be an engaged mentor, etc. Also, my time and my interns time had to be covered out of my own funding, which set back my own research objectives. Unless participation looks really good to management, I'm not sure it was worthwhile. Having push from management and funding arranged at the start of an

FY would help me plan for participation in NOMAD and would help me be more engaged.
- Yes; learned a few new things, renewed collaborations.

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

- I think the most important thing we can do is attract the best possible students. The teams were outstanding this year but there were a few individuals that weren't as well prepared as the others, and it made them uncomfortable because they were conscious of their lesser contributions. It would be nice if a limited number of international students could be invited, since they tend to be more senior and very capable.
- We can also continue to strive to identify projects that are doable in 6 weeks with three people dividing labor, and yet which have the potential for significant impact.
- I think this all went pretty well. Brooke, Diane, and Rob did a nice job pulling together projects and reminding mentors what we had to do to prepare.
- Details of the projects could have been worked out earlier, but it worked out just fine.

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

- I think the programmatic elements were good – no ideas.
- I think it depends on the goals of the institute. Personally, I'd like to see a larger emphasis on teaching the students general topics in modeling, structural mechanics and dynamics and testing. This would also be a good opportunity for SNL staff to prepare learning material and teach about things they are focused on or present their research. Something like 2-3 seminars and 1-2 tutorials each week would be good. Tutorials could be a couple hours with a bit of lecture and a bit of hands-on training. Good outings, etc were organized.
- Having all of the participants as interns. The mixed access that the students had was strange.

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

- The facilities seemed good. Make sure the students have internet access that is as fast as possible as early as possible – I think it was ok this year.
- Being remote is tough. Having something on site would have made it easier to see the students more frequently. Since it was off site, I could only get out there maybe once a week, which isn't great for the students. However, the UNM building was a nice space with the labs and office rooms, etc.

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

- I think things went very well. Going forward we should continue to try to make sure the projects were ready for this group of students, including thinking a little more about how each student might contribute, but this is difficult to do before we see how people perform.

- For my project, I should have had more of a theoretical component to supplement the experimental component since it turned out the students were very good and could have used that additional, different challenge. I designed the project initially to be very doable, but could have added some more complexity.
- More coherent effort before the institute. I felt as if there were some meetings that I wasn't privy to since I was offsite.

6. What would have improved team dynamics?

- See comment above – make sure that excellent students are recruited so there is a uniform level of ability. Also continue to encourage the students to begin to collaborate over email/skype before the summer.
- I wasn't around enough to get a good feel for the group dynamics, though they seemed to work well together and were productive.
- No real issues were observed.

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

- I think that the timing would work better for me later in the summer, but there are advantages to starting early or mid-June. The length is probably appropriate.
- Timing is pretty good (was hot this summer though!). The duration is just enough time for them to complete a project if it is well set up. Doing a longer session could be good to give them more freedom and take more ownership if that is an objective of the institute. I think having more lectures or seminars could be good to provide additional learning opportunities for the students.
- Personally, I would have liked it if it started a week earlier, but that's just me and my busy summer schedule.

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

- Three people is a great size. Perhaps we could have the option of having smaller teams for some project ideas, if needed. I can't imagine a project that would need four or more on the team, but that could also be an option.
- Three to four is good. No more than that.
- Three to four students per group seems to be the right size for these projects.

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

- Besides what I mentioned earlier, it was also enjoyable getting together for dinner at the start of the institute, and pursuing what opportunities there were for social events in the evenings and weekends. This was a great group of students, and it was excellent seeing them rise to the task and do great things.
- Seeing the progress made each week as surprising. They got a lot done and were curious researchers so they did experiments of their own design to explore the problem.
- The interactions with the diverse teams of students and mentors.

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

- Yes, although my travel schedule next year may preclude me from being as involved as I was this year. I would like to continue being as involved in future years.
- Possibly, but I'm not sure if it strikes the right balance of benefit to time/effort.
- Yes.

11. Do you have any additional comments?

- No. - II
- I would recommend providing some coaching to the students on how to be engaged audience members for technical talks – one thing we did at the Los Alamos summer school was each student had to ask a question for every seminar we saw, which made you pay better attention and get comfortable asking questions in a technical presentation environment, which I found useful. I also think some short tutorials on things like how to make good presentations, how to make good technical plots and how to take good laboratory photos could be useful and unique.

3.3. Final Remarks

Overall, the 2017 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 2017 NOMAD Institute produced six proceedings and presentations at international conferences. Five of the six projects published proceedings at the 2018 International Modal Analysis Conference (IMAC), and one of the projects will be submitting an extended abstract to The Conference on Advancing Analysis and Simulation in Engineering (CAASE). A summary of the documentation produced by each project team is provided in Appendix C-H. In the future, the mentors and organizers need to maintain awareness of technical conferences at which NOMAD research is appropriate for submission. In particular, the mentors should search for conferences whose publication deadlines align with the NOMAD calendar.

A number of continued collaborations and hires followed the 2017 NOMAD program. Patrick Hughes and Jonel Ortiz continued on as year-round virtual workers to continue working with Sandia and department 1556. In addition, full-time positions were both offered to and accepted by Peter Grimmer and Jonel Ortiz, both of whom participated in NOMAD for their first time in 2017. A university contract is currently being negotiated to fund another 2017 NOMAD alumni, Aabhas Singh, to investigate reduced order modeling strategies for jointed structures. Giuliana Davis continued on as a year-round intern in department 2342. Garrett Lopp and Deborah Fowler have been in communications with department 1522 regarding future post-doctoral and summer employment, respectively. These continued interactions with Sandia National Laboratories reveal the ability of NOMAD to engage highly qualified students with advanced technical degrees.

Planning is underway for the 2018 NOMAD Research Institute. Many of the lessons learned from 2017 are being integrated into the planning and decisions made for the upcoming program. As we move forward, we will continue to strive to provide the best experience for the students and engage the staff in Engineering Sciences Center 1500.

APPENDIX A: STUDENT RECRUITMENT FLYER

2017 NOMAD PROJECT LIST

Inverse Methods for Characterization of Contact Areas in Mechanical Systems.
This project will involve numerical studies to generate synthetic data on a set of simplified interface models to ascertain how much measured data is needed to adequately use inverse methods to resolve the contact/non-contact areas, and thus avoid non-unique model calibration.
Mentors: Tim Walsh (Sandia National Laboratories), Matt Brake (Rice University), and Adam Brink (Sandia National Laboratories).

From Macroscopic Tensile Tests to Microscopic Mechanical Response of Components.
This project will compare the local response of different constitutive models, matching the same experimental macroscopic response to explore the limitation in predictive power of tensile stress-strain curves at macroscopic and microscopic scales under non-tensile loading, and non-smooth geometries.
Mentors: Gustavo Castelluccio (Sandia National Laboratories), John Emery (Sandia National Laboratories), Jeff Smith (Sandia National Laboratories), and John Mersch (Sandia National Laboratories).

Investigation of Craig-Bampton Models with Interface Reduction for Contacting Structures.
In an effort to improve the efficiency of Craig-Bampton substructures with contact models at interfaces, this project will seek to use interface reduction techniques to further reduce the interface degrees-of-freedom and increase the critical time step required for explicit time integration.
Mentors: Robert Kuether (Sandia National Laboratories), Matt Allen (University of Wisconsin-Madison), and Paolo Tiso (ETH Zürich).

Influence of Edge Boundary Conditions and Cracks in Ferroelectrically-Excited Vibrational Modes.
In this study, finite element models will be used to implement boundary conditions along edges and cracks to determine the level of influence that they can have. Of specific interest are predictions of whether the ferroelectrically-excited modes will be sensitive to cracks that can commonly appear near either restrained or traction-free corners.
Mentors: Paul Heyliger (Colorado State University), Ward Johnson (National Institute of Standards and Technology), and Kevin Troyer (Sandia National Laboratories).

Experimentally Characterize a new Benchmark Structure for Prediction of Damping Nonlinearity.
In this project a team of students will use state of the art system identification methods to characterize the nonlinear dynamic response of a new benchmark structure that has been proposed to aid in the development of predictive methods for structures with joints.
Mentors: Matt Allen (University of Wisconsin-Madison), Robert Kuether (Sandia National Laboratories), Daniel Roettgen (Sandia National Laboratories), and Ben Pacini (Sandia National Laboratories).

Coupled Structural Acoustic Modes.
The objective of this study is to experimentally measure the acoustoelastic coupled modes from a structure with a hollow cavity. Modifications to the cavity will be made to damp the acoustic modes and mitigate the unwanted coupling.
Mentors: Ryan Schultz (Sandia National Laboratories), Matt Brake (Rice University), and Micah Shepherd (Pennysylvania State Univaersity).

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APPENDIX B: NOMAD INTERN JOB POSTING

NOMAD Student Intern Mechanical Analysis

About Sandia: Sandia National Laboratories is the nation's premier science and engineering lab for national security and technology innovation. We are a world-class team of scientists, engineers, technologists, post docs, and visiting researchers all focused on cutting-edge technology, ranging from homeland defense, global security, biotechnology, and environmental preservation to energy and combustion research, computer security, and nuclear defense.

The Component Science and Mechanics Department (1556) provides state-of-the-art mechanics/dynamics research and science-based engineering solutions for component development and assessment. Focus areas for the department include: viscoelastic mechanics, joining, deformation, fracture, failure, mechanical interfaces, constitutive materials models, reduced order models, multi-physics/multi-scale models, component reliability, margin assessment, uncertainty propagation, and nonlinear dynamics. Computational and physical simulations, including solid mechanics and structural dynamics for both linear and nonlinear systems, are utilized in a dynamic multidisciplinary teaming environment.

The Nonlinear Mechanics and Dynamics (NOMAD) Research Institute is a six-week long program that brings together researchers from around the world to work on challenging research problems in the engineering sciences. Department 1556 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:

- “Inverse Methods for Characterization of Contact Areas in Mechanical Systems”
- “From Macroscopic Tensile Tests to Microscopic Mechanical Response of Components”
- “Investigation of Craig-Bampton Models with Interface Reduction for Contacting Surfaces”
- “Influence of Edge Boundary Conditions and Cracks in Ferroelectrically-Excited Vibrational Modes”
- “Experimentally Characterize a new Benchmark Structure for Prediction of Damping Nonlinearity”
- “Measurements of Coupled Structural-Acoustic Modes”

Required:

- The successful candidate will be working towards a Ph.D or master’s degree in mechanical engineering, civil engineering, aerospace engineering, materials science, engineering mechanics, applied mathematics or other applicable branches of engineering.
- The successful candidate must meet the general Sandia student intern requirements: full-time student status with at least 3.2/4.0 GPA for undergraduate work and a 3.5/4.0 GPA for graduate work.

Desired:

- 3.5/4.0 or better GPA for undergraduate work and a 3.7/4.0 or better GPA for graduate work.
- Experience (or academic focus) in the area of 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.
- Candidate should be able to work independently, with the ability to integrate effectively into a dynamic multidisciplinary teaming environment.
- This individual must demonstrate strong interpersonal, organization, and communication skills (both oral and written).

APPENDIX C: PROJECT #1 DOCUMENTATION

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

M. Fronk, K. Eschen, K. Starkey, R.J. Kuether, A.R. Brink, T. Walsh, W. Aquino, M.R.W. Brake, "Inverse Methods for Characterization of Contact Areas in Mechanical Systems," in *36th International Modal Analysis Conference (IMAC XXXVI),* Orlando, FL, February 2018.

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

- NOMAD Final Seminar – SAND2017-7814 C
- IMAC Conference Proceeding – SAND2017-11517 C
- IMAC Conference Presentation – SAND2018-1381 C

IMAC Abstract:

In computational structural dynamics problems, the ability to calibrate numerical models to physical test data often depends on determining the correct constraints within a structure with mechanical interfaces. These interfaces are defined as the locations within a built-up assembly where two or more disjointed structures are connected. In reality, the normal and tangential forces arising from friction and contact, respectively, are the only means of transferring loads between structures. In linear structural dynamics, a typical modeling approach is to linearize the interface using springs and dampers to connect the disjoint structures, then tune the coefficients to obtain sufficient accuracy between numerically predicted and experimentally measured results. This work explores the use of a numerical inverse method to predict the area of the contact patch located within a bolted interface by defining multi-point constraints. The presented model updating procedure assigns contact definitions (fully stuck, slipping, or no contact) in a finite element model of a jointed structure as a function of contact pressure computed from a nonlinear static analysis. The contact definitions are adjusted until the computed modes agree with experimental test data. The methodology is demonstrated on a C-shape beam system with two bolted interfaces, and the calibrated model predicts modal frequencies with < 3% total error summed across the first six elastic modes.

APPENDIX D: PROJECT #2 DOCUMENTATION

Details of the research from Project #2 were documented as a CAASE extended abstract published as:

P. Grimmer, A. Barrios, M. Stossel, J.P. Mersch, J. Smith, J.M. Emery, G. Castelluccio, "Evaluation of the Nonlinear Mechanical Response in Threaded Fasteners," in *The Conference on Advancing Analysis and Simulation in Engineering*, Cleveland, OH, June 2018.

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

- NOMAD Final Seminar – SAND2017-7893 C
- Conference Abstract – SAND2017-12115 A
- Conference Extended Abstract – TBD
- Conference Presentation – TBD

CAASE Abstract:

The mechanical behavior of complex assemblies depends on the constitutive response of the fasteners joining the components. The modeling of all components and threaded fasteners in detail is often too computationally demanding and rarely practical. Instead, reduced-order models like springs, beam elements, or plugs are commonly used. Linear reduced-order models are usually straightforward and accurate in the elastic regime, but the emergence of plastic deformation creates a strong nonlinear mechanical response. Hence, the accuracy of reduced-order models for threaded fasteners at medium to high strains is dictated by the constitutive behavior of the bulk material. Although the specification of metallic threaded fasteners typically includes alloy grade, manufacturing procedures often work harden the fastener material and increase the uncertainty of the material properties. These effective properties for a given fastener can be obtained by performing fastener tensile tests, but this is a time-consuming process that quickly becomes infeasible as the number of fasteners of interest continues to grow. Hence, an assumed hardening curve must be used to model the plastic response of the fastener. This assumed constitutive behavior will introduce epistemic uncertainty into simulations involving fastened joints. By identifying trends in fastener constitutive behavior the material properties for a fastener model can be more confidently assumed from limited test data.

This investigation explores the modeling of fasteners with various sizes by developing finite element models in which material parameters were calibrated to match tension test data on stainless steel A286 fasteners. Sizes ranging from #0 to #6 UNF are considered with two models of varying geometric fidelity: a smooth plug of elements, and a higher-fidelity model including thread geometry. The material calibrations were similar for the plug and the threaded models, consistent with previous findings that the material nonlinearities dominate the tensile response of fasteners. The material model for a smooth annealed steel A286 specimen was calibrated to compare the original material to the fastener material after manufacturing. This investigation reveals that the fasteners have higher yield stresses than the smooth specimen, indicating various degrees of work hardening during manufacturing. This conclusion is extended to the analysis by estimating the fasteners' hardening curves through a shift to the hardening curve of the annealed specimen to match the yield stress, and these curves are compared to independent calibrations of the same fastener. This study indicates that for the fasteners considered, when given the hardening curve of the original material, knowledge of the load versus displacement response of the fastener is unnecessary for calibration; the yield stress of the fastener is the essential piece of information required to estimate its hardening curve.

APPENDIX E: PROJECT #3 DOCUMENTATION

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

P.J. Hughes, W. Scott, W. Wu, R.J. Kuether, M.S. Allen, P. Tiso, "Interface Reduction on Hurty/Craig-Bampton Substructures with Frictionless Contact," in *36^th^ International Modal Analysis Conference (IMAC XXXVI)*, Orlando, FL, February 2018.

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

- NOMAD Final Seminar – SAND2017-7824 C
- IMAC Conference Proceeding – SAND2017-11361 C
- IMAC Conference Presentation – SAND2018-1006 C

IMAC Abstract:

Contact in structures with mechanical interfaces has the ability to significantly influence the system dynamics, such that the energy dissipation and resonant frequencies vary as a function of the response amplitude. Finite element analysis is commonly used to study the physics of such problems, particularly when examining the local behavior at the interfaces. These high fidelity, nonlinear models are computationally expensive to run with time-stepping solvers due to their large mesh densities at the interface and because of the high expense required to update the tangent operators. Hurty/Craig-Bampton substructuring and interface reduction techniques are commonly utilized to reduce computation time for jointed structures. In the past, these methods have only been applied to substructures rigidly attached to one another, resulting in a linear model. The present work explores the performance of a particular interface reduction technique (system-level characteristic constraint modes) on a nonlinear model with node-to-node contact for a benchmark structure consisting of two c-shape beams bolted together at each end.

APPENDIX F: PROJECT #4 DOCUMENTATION

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

J. Ortiz, G. Davis, K.L. Troyer, P. Heyliger, "The Influence of Edge Boundary Conditions and Cracks on Vibrational Modes of Multilayer Ceramic Capacitors," in *36^th^ International Modal Analysis Conference (IMAC XXXVI)*, Orlando, FL, February 2018.

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

- NOMAD Final Seminar – SAND2017-7971 C
- IMAC Conference Proceeding – SAND2017-11498 C
- IMAC Conference Presentation – SAND2017-7971 C

IMAC Abstract:

Electrical failure of layered capacitors is often a limiting factor in the design of many important electronic devices. Manufacturing processes, soldering, and service conditions have been shown to induce cracks in the dielectric material of the capacitor, providing conductive pathways that result in electrical leakage. In addition to the crack itself, edge boundary conditions can cause modal stress concentrations in a particular region of the capacitor that can initiate new cracks or propagate existing ones. Small but potentially damaging cracks can be very difficult to detect, and their presence may only become evident when they grow large enough to impact the capacitor's performance. Recent experimental studies have demonstrated that cracks in layered capacitors can be detected nondestructively by measuring a shift in the resonant frequency of the structure via ferroelectric transduction. This study seeks to extend these recent findings by developing finite element models of layered capacitors in order to determine the level of influence that cracks and edge boundary conditions have on their frequency spectrum and their localized stress fields. Of particular interest is determining if ferroelectrically excited modes will be sensitive to cracks that can commonly appear near either restrained or traction-free corners. Computational investigation is intended to supplement future experiments on these structures, with the eventual goal of merging and analyzing the results from theoretical predictions and physical measurements. Specifically, three different crack types were simulated (endcap crack, inner crack, corner crack) along with three boundary conditions (free-free, fixed surface, and soldered). Results indicated that a fractured capacitor yielded lower natural frequency values in comparable modes to an uncracked capacitor, and that this shift in natural frequency values could be magnified depending on the applied boundary conditions. This finding is an important contribution toward the effort of non-destructively detecting cracks in the MLCCs and for future research to confidently utilize MLCCs in future applications.

APPENDIX G: PROJECT #5 DOCUMENTATION

Details of the research from Project #5 were documented as an IMAC proceeding published as:

A. Singh, M. Scapolan, Y. Saito, M.S. Allen, D.R. Roettgen, B.R. Pacini, R.J. Kuether, "Experimental Characterization of a new Benchmark Structure for Prediction of Damping Nonlinearity," in *36th International Modal Analysis Conference (IMAC XXXVI)*, Orlando, FL, February 2018.

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

- NOMAD Final Seminar – SAND2017-7813 C
- IMAC Conference Proceeding – SAND2018-1152 C
- IMAC Conference Presentation – SAND2018-1239 C

IMAC Abstract:

Spacecraft, airplanes, automobiles, machines and civil structures are all constructed from multiple parts joined by bolts, rivets or other fasteners and these joints lead to large uncertainties in the structural stiffness, damping and can even introduce nonlinearity. Even with the best available simulation tools, it is still difficult to predict the effective stiffness and damping of bolted interfaces, and so these parameters are often assumed and updated after tests have been performed. Damping estimates are critical to limit the resonant vibration response of a structure and thus prevent failure. Even so, it remains poorly understood and available methods for modeling damping are inaccurate and computationally expensive. A new benchmark structure has been created that is designed so as to be predictable with current simulation tools. This paper presents a thorough experimental characterization of this new benchmark structure using the Hilbert transform method applied to modally filtered time data. The nonlinear frequency and damping of each mode is characterized for various levels of bolt preload and excitation amplitude. The interfaces of the bolted structure are also characterized in detail by measuring the contact pressure distribution using pressure sensitive film. The resulting data presents a set of well characterized tests that can be used to validate numerical methods that seek to predict the nonlinear behavior of bolted interfaces.

APPENDIX H: PROJECT #6 DOCUMENTATION

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

D. Fowler, G. Lopp, D. Bansal, R. Schultz, M.R.W. Brake, M. Shepherd, "Experimental Demonstration of a Tunable Acoustoelastic System," in *36th International Modal Analysis Conference (IMAC XXXVI)*, Orlando, FL, February 2018.

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

- NOMAD Final Seminar – SAND2017-7807 C
- IMAC Conference Proceeding – SAND2017-11607 C
- IMAC Conference Presentation – SAND2017-7807 C

IMAC Abstract:

Acoustoelastic coupling occurs when a hollow structure's in-vacuo mode aligns with an acoustic mode of the internal cavity. The impact of this coupling on the total dynamic response of the structure can be quite severe depending on the similarity of the modal frequencies and shapes. Typically, acoustoelastic coupling is not a design feature, but rather an unfortunate result that must be remedied as modal tests are often used to correlate or validate finite element models of the uncoupled structure. Here, however, a test structure is intentionally designed such that multiple structural and acoustic modes are well-aligned, resulting in a coupled system that allows for an experimental investigation. Coupling in the system is first identified using a measure termed the magnification factor and the structural-acoustic interaction for a target mode is then measured. Modifications to the system demonstrate the dependency of the coupling with respect to changes in the mode shape and frequency proximity. This includes an investigation of several practical techniques used to decouple the system by altering the internal acoustic cavity, as well as the structure itself. Furthermore, acoustic absorption material effectively decoupled the structure while structural modifications, in their current form, proved unsuccessful. The most effective acoustic absorption method consisted of randomly distributing typical household paper towels in the acoustic cavity; a method that introduces negligible mass to the structural system with the additional advantages of being inexpensive and readily available.

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