SANDIA REPORT
SAND2021-15188
Printed December 2021

Sandia National Laboratories

The 2020 Nonlinear Mechanics and Dynamics Research Institute

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ABSTRACT

The 2020 Nonlinear Mechanics and Dynamics (NOMAD) Research Institute was successfully held from June 15 to July 30, 2020. NOMAD brings together participants with diverse technical backgrounds to work in small teams to cultivate new ideas and approaches in engineering mechanics and dynamics research. NOMAD provides an opportunity for researchers – especially early career researchers - to develop lasting collaborations that go beyond what can be established from the limited interactions at their institutions or at annual conferences. A total of 11 students participated in the seven-week long program held virtually due to the COVID-19 health pandemic. The students collaborated on one of four research projects that were developed by various mentors from Sandia National Laboratories, the University of New Mexico, and other academic and research institutions. In addition to the research activities, the students attended weekly technical seminars, various virtual tours, and socialized at virtual gatherings. At the end of the summer, the students gave a final technical presentation on their research findings. Many of the research discoveries made at NOMAD 2020 are published as proceedings at technical conferences and have direct alignment with the critical mission work performed at Sandia.

ACKNOWLEDGEMENTS

The authors would like to acknowledge a number of people and programs for their support of the 2020 Institute. First, we would like to thank the DE and ASC P&EM subprograms for their continued funding support to host the Institute. Additional thanks go to Mike Pasik for his financial support toward one of the NOMAD projects. Next, we would like to acknowledge Scott Klenke and Dennis Croessmann for their leadership and guidance throughout the planning and execution stage. A number of staff and faculty from the University of New Mexico also help make NOMAD possible each year. The authors would like to thank Tariq Khraishi, Yu-Lin Shen, Elsa Castillo, and Nada Hack for their continual support in helping arrange facilities and administrative assistance on campus. Unfortunately, this year was limited to virtual attendance due to the world health pandemic. We would like to thank Bill Flynn from Siemens who intended to offer his time and resources to the betterment of the NOMAD Institute.

In addition, we owe gratitude to all those listed below who helped contribute to the success of the program:

Sandia National Laboratories Staff and Management:

Dan Roettgen, HC Chamberlin, Michael Freund, Ben Pacini, Sara Jensen and Daniel Clarke.

University of New Mexico Staff:

Kaydra Townsend, Cindi Sanchez, Christos Christodoulou, Kim Delker

Student Participants:

Aabhas Singh (UW-Madison), Kayla Wielgus (Washington), Ziad Ghanem (UT-Dallas), Walker Powell (NC State), Stuart Montgomery (GA Tech), Eric Robbins (UNM), Arun Malla (Virginia Tech), Trent Schreiber (GA Tech), Kevin Moreno (VT), Michael Sheng (UCLA) and Avaneesh Murugesan (UCLA)

Project Mentors:

Ignazio Dimino (CIRA), Matt Allen (UW-Madison), Rob Kuether (SNL), Adam Brink (SNL), Carianne Martinez (SNL), D. Dane Quinn (Akron), Eleni Chatzi (ETH Zurich), Dan Roettgen (SNL), Simone Manzato (SISW), Ben Pacini (SNL), Fernando Moreu (UNM), Tariq Khraishi (UNM), John Mersch (SNL), Jeff Smith (SNL), Jonel Ortiz (SNL), Neal Hubbard (SNL), Emily Miller (SNL)

Sandia National Labs Seminar and Tutorial Speakers:

Judy Brown, Nate Crane, Rob Kuether, Dan Roettgen, Amanda Jones, Cari Martinez, Jonel Ortiz, and Cory Medina

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ACRONYMS AND DEFINITIONS

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

1. INTRODUCTION

The Nonlinear Mechanics and Dynamics (NOMAD) Research Institute united graduate-level and highly qualified undergraduate-level students from around the nation to work on challenging research problems in engineering mechanics and dynamics. Students worked in teams of three under the guidance of mentors from Sandia National Laboratories, the University of New Mexico, and other universities and research institutions from around the world to address research activities defined by the project leaders and NOMAD organizers. The Institute ran virtually for seven weeks during the summer of 2020.

Due to the COVID-19 health pandemic, the Institute was not held at the Mechanical Engineering building on the University of New Mexico campus as originally planned. During March 2020, the pandemic introduced a vast amount of uncertainty regarding the program and how it would be executed. The organizers pivoted to accommodate a completely virtual program in which the students could participate remotely from their home institutions. As a result of the virtual format, a decision was made to remove all experimental aspects of the projects. This resulted in a reduction of projects and students for NOMAD 2020. There was a total of four projects which were completely based on computations and analyses of existing test data collected by the project teams and mentors. There were a total of 11 students hired to participate, and all hiring commitments and offers made prior to the health pandemic were honored.

Throughout the summer, students attended weekly technical seminars and presented their research progress within their project teams on a weekly basis. At the end of the program, most of the project teams completed a proceeding document for a technical conference and presented their work at the final NOMAD seminar that was broadcast virtually to Sandia and external collaborators. Students who participated in the Institute developed as researchers by gaining technical knowledge in nonlinear mechanics and dynamics, while improving their written and oral communication skills. Sandia benefited from NOMAD through the development of collaborative relationships with the external engineering community and within Sandia. Engagement with technically skilled students enhanced the staff recruiting pipeline for Center 1500: Engineering Sciences, and beyond. The photograph in Figure 1 shows some of those who participated from NOMAD 2020.

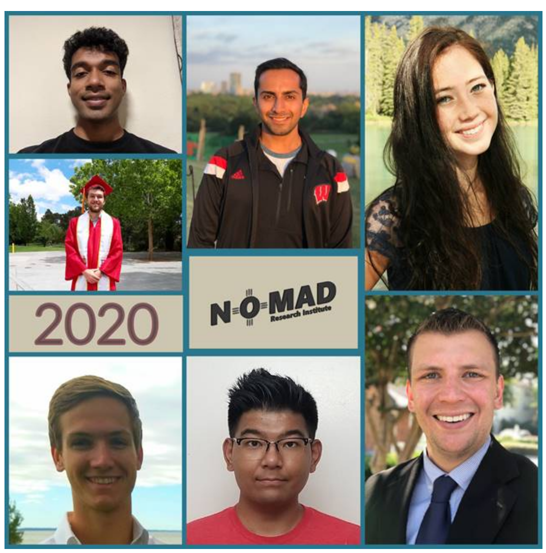

Figure 1. Some of the participants of the 2020 NOMAD Research Institute

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2. PROGRAMMATIC DETAILS

2.1. Lessons Learned and Changes from 2019

Several lessons were learned from the previous NOMAD 2019 Institute. It is noted that these were observations from an in-person program, and several adaptations to a completely virtual format raised additional challenges to overcome these concerns. Regardless, a summary of these lessons is provided below including the efforts made in 2020 to address them:

- ❖ There were several challenges noted in 2019 in which the experimental projects did not have the appropriate test equipment to complete their research. Since NOMAD 2020 omitted all experimental aspects of the projects, this was not an issue. The NOMAD organizers continue to be cognizant of this and plan to address it by requiring pre-institute experiments to scope the equipment needed for the projects. This pre-institute testing requires sufficient lead time to get hardware into the laboratories for the organizers to perform preliminary tests on the structures of interest.

- ❖ The NOMAD organizers had observed variable commitment from the mentors across the project teams. A new mentor/mentee agreement was drafted and established to outline the expectations of the mentors and mentees. This document was reviewed by each team member and signed by all participants at the beginning of the Institute. It is meant to initiate the discussion regarding the expectations and time commitments of everyone during the summer.

- ❖ In addition to the bullet above, the mentors showed inconsistency around the amount of pre-planning put into the projects. The organizers hosted a mentor kickoff meeting to outline expectations and deadlines in preparation for the NOMAD Institute. The organizing team will build on this practice to help both returning and new mentors to the program. The students requested appropriate training material prior to the start of the program, so the mentor teams were encouraged to share this material with the students prior to their start date.

- ❖ There were concerns regarding the lab space from 2019, as there was a total of four experiments set up in a single room. This was not an issue for the 2020 Institute, but we are cognizant of space concerns and keep open discussions with our partners at UNM.

- ❖ Previous Institutes noted concerns regarding their engagement with Sandia and comprehension of the various roles/positions at the labs. A new Manager Talk series was established in 2020 to invite managers from 1550 to share more about their departments and the type of work done by their staff. Other opportunities for awareness of the work culture at Sandia will be sought, especially when the program returns as an in-person event.

- ❖ A few comments noted that the students should be given more opportunities to present their research throughout the course of the summer in preparation for the final presentation. No efforts were made to address this issue in 2020, but the organizers are cognizant of this and will look to address this in future Institutes.

- ❖ The organizers are improving their ability to address connectivity issues via computing resources during the first days of the program. This is always a top priority for the first week of NOMAD, and we will continue to seek ways to decrease the required lead time to get students connected to the necessary resources.

2.2. Project Selection Process

A total of four projects were selected for the 2020 NOMAD Research Institute. Several interested parties were contacted early in the Fall of 2019 to solicit ideas and organize mentor teams. The organizing team sought projects that satisfied the following requirements: 1.) Safety and Security, 2.) Quality, 3.) Impact, and 4.) Likelihood of Success. The mentors who participated in the 2020 Institute include:

- Adam Brink (SNL)
- Ben Pacini (SNL)
- Carianne Martinez (SNL)
- D. Dane Quinn (Akron)
- Dan Roettgen (SNL)
- Eleni Chatzi (ETH Zurich)
- Emily Miller (SNL)
- Fernando Moreu (UNM)
- Ignazio Dimino (CIRA)
- Jeff Smith (SNL)
- John Mersch (SNL)
- Jonel Ortiz (SNL)
- Matt Allen (UW-Madison)
- Neal Hubbard (SNL)
- Rob Kuether (SNL)
- Simone Manzato (SISW)
- Tariq Khraishi (UNM)

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

- ❖ **Nonlinear Analysis of Mechanical Joints in Finger-Like Mechanism-Based Morphing Wing Devices**

Mentors:
Ignazio Diminio (CIRA), Robert Kuether (SNL), Matthew Allen (UW-Madison), and Aabhas Singh (UW-Madison)

Morphing wings have the greatest ambition to significantly alter design and operation of future generations of aircraft. Their ability to adaptively change the wing geometry and reconfigure themselves in multiple and optimal shapes in every specific flight condition may dramatically contribute to tackle some of aviation's biggest environmental challenges including fuel efficiency, noise, and emissions.

Many challenges are associated with the design of morphing aero-structures. One for all, the added DOFs generate systems with increased modal density and therefore with more complex aeroelastic behavior which may result in flutter instabilities. In finger-like mechanism-based morphing structures, the inner structure is articulated in different rigid parts moving according to a pre-defined mechanical law. Additionally, a morphing skin enveloping the skeleton preserves a regular geometry during shape adaptation.

The kinematic system at the basis of any morphing structure is mainly driven by an actuation chain which dominates its aeroelastic response. Furthermore, the kinematic subsystems and components, as torsion bars, bushings, bearings, joints, that significantly affects the dynamic characteristics of the structure, are typically assumed rigid in traditional simulation strategies. From a modeling perspective, in fact, inexpensive rigid connectors replace fully discretized hinges and bushings to reduce computational costs while globally capturing its macroscopic response. If such an approach may be supposed valid for relatively simple layouts (as in the case of traditional flap systems), it cannot be held for adaptive systems integrating several mechanical parts. The presence of frictional slip, contact interactions and the hyperelastic behavior of the skin, causes such mechanical joints to have a nonlinear damping and a nonlinear stiffness, which makes their behavior difficult to model accurately.

This research proposes a detailed simulation of some selected components of morphing wing systems, trying to predict the nonlinear response of the adaptive structure with mechanical joints. Schematization effects are investigated in terms of both static and dynamic response. High fidelity models are envisaged to capture non-linear aspects in the structural dynamics, such as the amplitude dependent natural frequencies and nonlinear damping ratios, which may substantially impact on aeroelastic stability margins. The variation of the achieved shapes is also examined, identifying the strain map and internal forces distribution changes, essential for design purposes and stress analysis.

- **Neural Network Informed Uncertainty Quantification for Structural Dynamics Reduced Order Models**

Mentors:
Adam Brink (SNL), Carianne Martinez (SNL), D. Dane Quinn (Akron), and Eleni Chatzi (ETH Zurich)

Reduced order models (ROMs) are often utilized to reduce the computational cost of performing numerical simulations of engineering systems. These ROMs can be developed with discrete single-valued parameters, stochastic parameters (sROMs) or varying parameters (PROMs). ROMs are of particular interest for digital twin applications, where the deployed systems are continuously monitored over their life via numerical calculations and sensor array values to determine the current and future health of the system. It is evident that the parameters used to develop the ROMs, whether they be discrete, stochastic or variable, will likely not match the deployed system exactly. This research seeks to leverage data science, specifically machine learning, to update the ROM parameter space based on actual sensor reading from the deployed system.
Students will be given developed ROMs, detailed finite element models, basic system information and sensor data from a deployed system. They will be asked to develop a machine learning framework that can link to the ROM and suggest updated parameter values or distributions. It is of

interest to produce physically realizable parameters which reduce the overall error of the numerical simulations.

❖ Nonlinear Normal Mode Force Appropriation Techniques to Investigate Wing-Pylon Assembly

Mentors:
Benjamin Pacini (SNL), Daniel Roettgen (SNL), Robert Kuether (SNL), Simone Manzato (Siemens), and Fernando Moreu (UNM)

Industrial considerations of nonlinearity in structural dynamics are very conservative. Further development of experimental measurement and identification techniques, as well as computational methods, are essential to understanding the complicated physics associated with nonlinear structural dynamics. This project continues a 2019 NOMAD study that characterized the nonlinear dynamics of a pylon subassembly that was isolated from the global aircraft structure. The new project will investigate the dynamics of a wing-like structure designed to replicate the next level subassembly of the pylon where nonlinearities are concentrated at the connection to the wing. Nonlinear normal mode theory will be utilized to characterize the frequency-amplitude backbones and presence of internal resonances of both the isolated pylon and the next-level wing-pylon subassembly. Experimental techniques such as nonlinear force appropriation will allow the models to be correlated to experimental data to evaluate the predictive capability of the models. The project will lead to a better understanding of the use of isolated, nonlinear experiments to calibrate a localized nonlinear element to be used in a next-level assembly model and provide a better understanding of the system dynamics.

❖ Correlation of Reduced-Order Model of Threaded Fastener

Mentors:
Neal Hubbard (SNL), John Mersch (SNL), Jonel Ortiz (SNL), Emily Miller (SNL), Jeff Smith (SNL), and Tariq Khraishi (UNM)

The team will correlate three reduced-order models (ROM) of a threaded fastener to test data. Models of varying degrees of complexity have been made to simulate the failure of a fastener. In system-level models, the fasteners need to be greatly simplified for computational efficiency. They may be represented by cylinders or spring elements, but high-fidelity models with threads take too much computation time. The three models to implement in this project are (1) a nonlinear elastic 3-DOF spring element, (2) a cylindrical shank with a single set of properties, and (3) a cylindrical shank with unique properties for tension and shear—the shear properties will only apply in the local area near the joint interface plane. The properties of each ROM must be carefully selected to achieve a good correlation with test data in combined tensile and shear loading. Tests will be performed in advance of the NOMAD institute with the fastener of interest loaded in tension and shear. Each member of the team will run simulations of the test conditions with one of the ROM in place of the fasteners and adjust the model parameters until it agrees with the test results. Together, the team will contrast the advantages and limitations of each model.

2.3. Student Participant Selection Process

The NOMAD committee began recruiting students once the projects were down selected so the students could be placed based on their research interests and skillset. The goal was to recruit three students per project, resulting in a target of 12 participants. All students were hired in as summer interns, except for one student who was working under a research contract with Sandia. Summer internship hires were handled through the Student Intern Program (SIP) at Sandia. Fall recruiting included a job posting for graduate level students, and a winter/spring posting included postings for both graduate and undergraduate students.

Recruiting efforts relied heavily on distribution material sent to external university collaborators. A flyer crafted by Stephanie Blackwell in Creative Services served as our main distribution; the flyer is shown in Appendix A. Information on the flyer included dates, benefits, targeted disciplines, website and short project descriptions. All project mentors were asked to distribute the flyer to any university contacts who may have interested students. The summer internship positions were posted to the external Sandia website; the job posting is shown in Appendix B. With these recruiting efforts, about 280 students applied to the NOMAD program and 11 students were selected to participate in the 2020 Institute:

- Aabhas Singh, University of Wisconsin-Madison
- Arun Malla, Virginia Tech
- Avaneesh Murugesan, UCLA
- Eric Robbins, University of New Mexico
- Kayla Wielgus, University of Washington
- Kevin Moreno, Virginia Tech
- Michael Sheng, UCLA
- Stuart Montgomery, Georgia Tech
- Trent Schreiber, Georgia Tech
- Walker Powell, NC State
- Ziad Ghanem, University of Texas-Dallas

2.4. Facilities

The 2020 Institute was held virtually due to the COVID-19 health pandemic. The original plan was to continue to hold the Institute in the ME building on the north campus of UNM, as was done in the previous 2019 Institute. As a result, the students worked from their home institutions and connected to Sandia networks and resources using DaaS. All experimental aspects of the research were cancelled due to the complications of off-site testing and access restrictions during the health pandemic. All project work could be completed using computer resources. The students attended teleconference meetings using either Skype for Business or Microsoft Teams.

2.5. Calendar of Events

A summary of the events planned for the 2020 NOMAD Research Institute is given in Table 1. The following subsections provide further detail of the seminars, tutorials, virtual lab tours and final student presentations.

Table 1. Event calendar for NOMAD 2020

Monday, 6/15:	Meet and Greet – Team Building
Tuesday, 6/16:	NEO Training for New Hires CI Training Awareness Training
Wednesday, 6/17:	Sierra/CUBIT Tutorial by Cory Medina and Jonel Ortiz Kickoff Presentations Beginner HPC User Training
Thursday, 6/18:	Seminar by Judith Brown Discuss and Fill Out Timesheets
Tuesday, 6/23:	Virtual Tour of TA3
Wednesday, 6/24	Seminar by Nate Crane
Wednesday, 7/1:	Seminar by Robert Kuether
Thursday, 7/2:	Manager Talk – Eliot Fang
Wednesday, 7/8:	Seminar by Dan Roettgen
Thursday, 7/9:	Manager Talk – Lili Heitman
Tuesday, 7/14:	Manager Talk – Kim Mish
Wednesday, 7/15:	Seminar by Amanda Jones
Thursday, 7/16:	Manager Talk – Aaron Brundage
Wednesday, 7/22:	Virtual Robotics Tour Seminar by Carianne Martinez
Thursday, 7/23:	Manager Talk – John Pott
Tuesday, 7/28:	NOMAD Final Presentations
Thursday, 7/30:	Last Day of NOMAD 2020

2.5.1. Seminars and Tutorials

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

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

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

- **"A Researcher's Journey From Designing Airplanes to Modeling Explosives—The Exciting Possibilities of a Career in Engineering Science" by Dr. Judith Brown**

A research career in engineering science offers many exciting opportunities. I will share excerpts from my own journey following this career path and how the diverse breadth of experiences led me to a very cool career at Sandia National Laboratories. The work we do here is both technically challenging and important to the Nation, which I very much enjoy being a part of. I will also discuss a few of my current research projects and how computational simulations (solid mechanics, thermal, shock, multi-physics) play a key role in Sandia's mission. Examples include mesoscale modeling of the shock-to-detonation transition as well as mechanical and thermal damage evolution in explosives.

Judith Brown is a Senior Member of the Technical Staff in the Fluid and Reactive Processes Department at Sandia National Laboratories, Albuquerque, NM. She holds a B.S. in Aerospace Engineering (2009), and both M.S. (2012) and Ph.D. (2015) degrees in Mechanical Engineering from North Carolina State University, where she developed a novel modeling approach to study laser interaction with energetic aggregates. She joined Sandia in 2015 as a post-doc and studied heterogeneous materials (foams, additively manufactured metals) through mesoscale modeling, with the goal of developing predictive, macroscale constitutive models. She moved to a staff position in the Fluid and Reactive Processes Department in 2018 and currently develops advanced multi-physics models (thermo-mechanical-chemical, shock physics) for energetic materials.

- **"Engineering Analysis Code Research and Development at Sandia" by Dr. Nate Crane**

Computational simulation plays a key role in engineering design. Sandia develops and maintains a large suite of engineering analysis codes for structural dynamics, solid mechanics, fluid dynamics, and other engineering physics areas. This talk will give a brief overview of the structural analysis tools developed at Sandia including why and how we develop these tools. Additionally, will highlight work on an ongoing research topic in computational solid mechanics, predictive fracture and dynamic remeshing.

Nate has worked at Sandia for 18 years in the computational mechanics and structural dynamics group. His background is in civil engineering with a focus on computational mechanics. Nate has been involved in the development and support of several engineering analysis codes at Sandia and is currently product owner for the Sierra Structural Dynamics integrated code.

- **"Nonlinear Modal Analysis for Structural Dynamics Applications" by Dr. Robert Kuether**

In structural dynamic theory, linear modal analysis has been the cornerstone of computational and experimental analysis for over fifty years. Computationally, it is used to efficiently simulate responses to time-varying loads and decompose problems into a few important mode shapes, natural frequencies, and damping ratios. Experimentally, modal test methods have matured to identify modal properties of hardware to characterize dynamic behavior of structures. Both test and analysis are highly integrated via modal analysis methods, which are rooted in linear system theory. In reality, structures may disobey the foundational assumptions of linear theory due to structural nonlinearities such as frictional contact, large deformations, coupled physics, etc.. This talk will discuss research in the area of nonlinear modal analysis that looks to bridge the concepts from modal analysis to structures exhibiting nonlinear behavior.

Rob has been a staff member in the Computational Science & Mechanics department since he joined Sandia back in 2015. His background is in computational structural dynamics and has various projects that involve a deep technical understanding of computational mechanics and dynamics. Rob is involved in several applied projects in support of component design analysis, as well as research projects in the areas of nonlinear dynamics, reduced order modeling, and contact/interface mechanics. In addition, Rob has been the director of the NOMAD program since 2016.

- **"Research in Experimental Structural Dynamics: Past, Present and Future" by Dr. Dan Roettgen**

This talk covers the topic of experimental modal analysis and deep dives into the role of the modal testing group at Sandia. We briefly look at three tools developed by the team:

- Hybrid System Modeling – How to connect test and analysis
- Nonlinear Modal Testing – How to characterize the nonlinearity in the dynamics mechanical system
- Digital Twin Testing – A cursory glance at the future use of these tools to enhance vibration testing

All of these topics require a balanced approach to test and analysis which creates and informed diagnostic toolbox for structural dynamics.

Dan became a staff member in the Experimental Structural Dynamics group at Sandia in 2018 after a year of post-doc work in the same team. His background is in experimental structural dynamics with a focus on dynamic substructuring, diagnostics, and nonlinear identification. Dan is involved in many projects both applied and research related to the combination of test models and analytical models to predict dynamic response. Dan has been involved in NOMAD as a student, mentor, and team lead beginning in 2014.

- **"Structural Mechanics: Characterization of materials, joints, and assemblies with full-field diagnostics" by Dr. Amanda Jones**

The structural mechanics lab provides foundational studies on materials, joints, and assemblies often using full-field diagnostics such as digital image correlation (DIC) and infrared (IR) thermal imaging. The work spans from material property characterization following ASTM standards to unique specimen geometries used to evaluate complex loading paths to full assemblies/ joints in mock loading conditions. Testing ranges from quasi-static, well-controlled experiments, which allow careful and thorough evaluation of mechanical response, to faster tests conducted at strain rates around 1 s^{-1}, for metals, polymers, and composites. In this presentation, I will discuss two uses of full-field diagnostics: a new shear test specimen and simultaneous IR/DIC measurements for thermomechanical characterization.

Amanda has been a staff member since 2017 in the Structural Mechanics Lab. Her background is in experimental solid mechanics, including material characterization and mechanical testing, as well as advanced diagnostics such as Digital Image Correlation (DIC). Amanda is involved in applied projects to understand the mechanical response of joints and assemblies, as well as research projects in the areas of thermomechanical material response, laser weld joints, and ductile failure.

- **"Deep Learning for Characterization of Geometric Uncertainty" by Carianne Martinez**

Applied machine learning (ML) research at Sandia is a truly interdisciplinary effort, drawing expertise from many science and engineering fields to be successful. Highlights of Cari's path to becoming a research scientist at Sandia along with a broad overview of some Sandia Interdisciplinary Machine Learning Research (SIMLR) group projects will be presented.

One of these projects, the Credible Automated Meshing of Images (CAMI) LDRD, will be discussed in depth with a focus on the deep learning portion of the project. The context of this work is that accurate modeling of as-built parts often requires high resolution Computed Tomography (CT) scans comprised of billions of voxels of data. Recent advances in deep learning have enabled the automated segmentation of these scans wherein each voxel is labeled by material, but standard deep learning implementations do not provide information about the uncertainty of the model's predictions. We present several methods to characterize the geometric uncertainty in deep learning segmentations of large volumetric images. We leverage prior state-of-the-art techniques such as employing dropout layers at inference time to quantify the variance in resulting predictions. At Sandia, we have developed a Bayesian Convolutional Neural Network (BCNN) where the weights of the network are learned as distributions rather than point estimates. We have also developed methods to extend the utility of trained models to shifted or broader image domains and have used existing CycleGANs as well as discovered a novel segmentation refinement technique to improve segmentation results without the need for additional model training.

Cari Martinez is a founding member of the Sandia Interdisciplinary Machine Learning Research (SIMLR) team with degrees in theoretical mathematics and computer science. Her research focuses on advancing deep learning methods for use in scientific applications to inform high-consequence decisions. Specific areas of interest include volumetric image segmentation, geometric uncertainty quantification, and data-driven modeling of physical systems. Cari looks forward to working with more diligent focus on model explainability, thereby increasing trust in deep learning models and empowering customers who make high-consequence decisions with an understanding of the reasons behind deep learning predictions.

2.5.2. Tours and Extracurricular Activities

In-person Institutes often involve a variety of social activities planned by the NOMAD organizers. However, due to the health pandemic, there were no extracurricular activities planned throughout the summer of 2020. The only supplemental activities planned were virtual guided tours of various facilities at Sandia. A brief description of each event is provided below.

- **Virtual Tour of Tech Area III**

Various tours were given of the facilities by SMEs who work in the labs. Patrick Barnes gave a virtual tour of the Mechanical Shock laboratory, while Richard Jepsen guided the students through the Centrifuge. The tour concluded with Walt Gill sharing information about the Thermal Test Complex.

- **Virtual Robotics Tour**

A guided, virtual robotics tour was hosted by Jon Salton and Kristopher Klingler.

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 held on Tuesday, July 28th. The event was held virtually using Skype for Business. Each group was allotted twenty minutes for presentation and Q&A, typical of what is offered at a technical conference. The students were asked to submit their final slide materials to Rob Kuether by Wednesday July 22nd to allow sufficient time for R&A to approve the material for unlimited, unclassified release. On the day of the seminar, many attendees from Sandia, UNM and other universities were present to view the student's presentations highlighting their summer work. Each of the project's final presentations are uploaded to the external NOMAD website to showcase the projects to prospective students and mentors.

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3. FEEDBACK

3.1. Participant Feedback

Following the Institute, the **participants** were asked to complete a survey consisting of approximately 12 questions (7 provided feedback). Below is a compilation of their answers paraphrased for succinctness:

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

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

"This was very worthwhile for me. I learned a lot about advanced topics I was unfamiliar with and learned how to implement them in a real engineering framework."

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

Some students would have liked to know the project's topic earlier on to have enough time to do some personal literature review. The virtual format was difficult at first, harder to navigate and communication was more of a challenge. Provide a little more time to complete the pre-homework and digest the overall project. Textbooks would have been easier to follow than technical papers when you're new to the topic.

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

Most students felt the seminars, tutorials, manager talks were good. Some felt it was hard to concentrate on these presentations during periods of high workload.

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

The mentors did a great job providing assistance and perspectives when needed and directed them well towards the long-term goals. Some teams got conflicting advice from different mentors and stated that a clearer vision of the goal would have been helpful. Some felt they would have liked the mentors to provide some of their resources earlier on.

5. What would have improved team dynamics?

Not being virtual was the largest factor for most students. One suggested better messaging/chat programs and more social virtual meetings.

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

All of the students said it should be longer, as the first week is mostly onboarding and training. Most said longer by one week. One student suggested starting near the end of the fall semester or end near the beginning of the spring semester.

"It went by very fast!"

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

All students said 3 was good.

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

"The tech talks had some really interesting and relevant topics."

"The highlight was being able to learn from the other students offer my specialties to help further our goals."

"Being involved in such a high caliber institute really helped me understand what it's like to conduct research at a high level. Also, being able to learn and accomplish a great amount in such a short time period has been an awesome experience."

"All the new technical topics I learned, the Sandia lab tours, and manager seminars."

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

Most said "yes"/"absolutely" and one said yes, but would only want to do it in person.

10. 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?

"I know my time here at NOMAD has made me more confident in the work I do."

Students learned a great deal about other research at Sandia.

"I think that this institute improved my leadership and managerial skills immensely."

11. Do you have any additional comments?

Some wanted more interaction with the other NOMAD students outside of just the weekly updates. And the Sierra tutorial could have been longer / more robust; at least for the students who used it a lot during the summer.

"I think the mentors were great, they put in a ton of work to make sure the students were on track, getting needed help, and sharing information. I think this is a brilliant institute!"

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

Seminars:

"A Researcher's Journey From Designing Airplanes to Modeling Explosives—The Exciting Possibilities of a Career in Engineering Science"
Judith Brown

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

"Engineering Analysis Code Research and Development at Sandia"
Nate Crane

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

"Nonlinear Modal Analysis for Structural Dynamics Applications"
Robert Kuether

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

"Research in Experimental Structural Dynamics: Past, Present and Future"
Daniel Roettgen

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

"Structural Mechanics: Characterization of materials, joints, and assemblies with full-field diagnostics"
Amanda Jones

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

"Deep Learning for Characterization of Geometric Uncertainty"
Carianne Martinez

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

Tutorials:

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

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

Beginner HPC User Training

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

Activities:

Virtual Tour of Mechanical Shock Complex, Superfuge/Centrifuge & Thermal Test Complex

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

Virtual Robotics Tour

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

Manager Talk Series

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

3.2. Mentor Feedback

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

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

All mentors said yes.

I always find NOMAD worthwhile. I love the mentorship and being able to be involved in interesting research. Even as a mentor, I always learn something from the experience both from a technical and leadership perspective.

Even though it was a completely new setup the students did an excellent job.

Effective program coordination and management.

The students worked on a very interesting project, and it was excellent for me to see how our technologies worked on this challenging system. It connected me with people at Sandia and at other universities and I got to know some excellent grad students a little better.

Yes, in principle, but the students have not been able to finish a great deal of work to squeeze out a publication.

2. From a technical standpoint, what could have been better (e.g. adequate tools provided, sufficient background for student researchers, etc.)?

I would have liked to work through the fastener test results in advance of the NOMAD Institute, but the data were available in time for some quick post-processing before the students tuned their models.

For the most part all of the technical aspects were well covered. The only thing I would mention is that it could be beneficial in the future to have external NOMAD participants (i.e. non-interns) to have access to Sierra somehow.

Considering the situation at hand, I think the Sandia mentors made an excellent job in providing the students with the best tools and support possible to execute their tasks.

Things went very well for our team. The students on my team never took advantage of our office hours. Perhaps, I should have had a mandatory touch base meeting with them.

Given the unusual circumstances surrounding this year's NOMAD, I think that everyone did an amazing job pulling this off. I was surprised at how well the students and mentors adapted to the situational constraints and it's good to know that face-to-face interaction is still valuable.

I think the background for students is prime for such short-time institute. This is critical if we were to expect any good productivity out of them including the prospect of getting any conference or journal paper

3. From a programmatic standpoint, what could have been better (e.g. better communication about Institute, number of students, etc.)?

I can see why NOMAD is typically open to graduate students only. They have a stronger drive to succeed and a greater ability to invent solutions.

I think overall the programmatic aspects were well executed. There was adequate communication between mentors and students.

I think it was very well balanced and organized.

Helpful presentation about the Institute at the project start.

Suggestion: Student Project Award

The NOMAD staff did a great job adjusting both the project scope and teams to allow this to come together.

The institute was well-communicated thanks to Rob and Brooke.

Giving the students 8 or 9 weeks would do wonders for their technical achievement.

4. From a facilities standpoint, what could have been better (e.g. better meeting space, test setup, etc.)?

Since this was an all virtual NOMAD, we didn't have the test-setup issues as in the past. The only thing I can think of is access to Sierra for non-intern students.

5. What could the students have done better (e.g. better communication, more frequency updates, etc.)?

I would have liked them to ask more questions and respond when I ask them questions. There was some real distance when communicating by teleconference.

I think the students did a good job keeping the mentors up to date and they seemed to stay on track.

Being scattered around was probably more difficult to work as a team, but they managed to do so, nevertheless. One thing I noticed was that they seemed to wait for the weekly meeting to report issues and ask for suggestions to the mentor, which probably caused the work to get stalled.

At least, one abstract for a scientific paper to be produced by each student.

Listen when we advised them to scale back the model complexity a little to make sure they could get finished.

Better prep by them but more importantly better existing technical background possessed by them.

6. What would have improved team dynamics?

Meeting in person and working near each other.

The virtual aspect was less ideal than in-person, but nothing can be done about that. I would rather have virtual NOMAD than no NOMAD at all. It is hard to have good team dynamics in a virtual-only environment, but I think given the circumstances, the team dynamics this year were much better than I expected.

Lacking the institute atmosphere and being forced to work remotely, not much more than it wasn't already done.

Web cameras activated during kick-off and final presentations to give a good combination between virtual and physical meetings.

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

I always wish for another week or two.

I think the timing and duration were good. It seemed like the students had enough time to complete their tasks and yet not infringe on their academic schedule.

Perhaps if future editions remain remote, the duration could be slightly extended, as in a remote environment obviously the level of dedication and focus can be less. 1 or 2 weeks extra might ensure that the same achievement as during a live event are achieved.

Duration and schedule are adequate.

Nothing

I mentioned above using 8 or 9 weeks. Summer is perfect for such institute. The all-day work by the students with occasional breaks is commensurate with what SNL does otherwise.

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

All agreed the ideal size is 3, or 2-3.

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

Seeing the students think deeply about the problem and come up with solutions.

I always like seeing the results the students come up with and seeing how the project evolves/deviates from the original plan as the summer unfolds.

Again, following remotely is a bit difficult to answer, but I enjoyed anyhow the interactions with the students and the other mentors.

Great adaptability in creating Virtual NOMAD.

Seeing the results of attempting to use quasi-static analysis on a very challenging system and working with the collaborators.

The final project reports.

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

All mentors said, yes.

11. Do you have any additional comments?

We should hang on to a good program, despite restrictions on working together.

I am impressed with the NOMAD leadership team for being able to pull off a virtual NOMAD on such short notice. I appreciate your efforts!

Thanks to Brooke and Rob for their leadership and organization.

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

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

We had more mentors and they supported the students while I was away.

This year is so hard to compare to previous years because of the different format.

Considering the situation, it was impressive to "see" how the whole organization and execution was managed in a very efficient way.

Organization seemed to be a little cleaner, and we got students who were well matched to their projects – they really hit the ground running.

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

I think everyone did the best they could; it was difficult because we took on a calculated risk with the project plan, but we made the most of it.

Any negatives from this year relative to years past is solely the fault of the global pandemic and not of the institute itself (e.g. not having experiments, no in-person interactions, etc.). Given the circumstances, this was an excellent NOMAD.

3.3. Lessons Learned during 2020

Based on the feedback from the students and mentors, and general observations during the 2020 program, the NOMAD organizing team was able to identify several lessons learned. A summary of these are provided below:

- Several teams noted challenges around communication both amongst the research groups and the broader NOMAD participants. Given the virtual nature of the program, NOMAD was organized in a completely new format by having all students work remotely. The organizers should seek ways to overcome these communication barriers if the program is to continue to be virtual. Many agree that an in-person program is much preferred and that communications occur naturally in that environment.
- In addition to the communications, mentors noted that the students struggled to relay critical information regarding challenges with the project. The students should be encouraged to raise issues promptly since the program is only seven weeks long. Lost time is difficult to overcome and therefor it is critical to address issues immediately. This should be encouraged by both the mentor teams and NOMAD organizers.
- The students continue to note that additional project pre-planning is needed to better understand the research goals and background material. Students mention that textbooks may serve as better reference material instead of journal articles. There seems to be a consistent theme that the students have the desire to prepare for NOMAD by studying the required material beforehand, and they are not getting that from their mentor teams.
- Some of the comments have noted conflicting advice from mentors on their project teams. It is important that the mentors assign a PI to guide the direction of the research, and that the supporting mentors are aware of these directions.
- Both mentors and students agree that extending the Institute one or two weeks would give the teams adequate time to complete their project goals.
- During many of the virtual meetings, most/all students would not activate their web cameras. As a result, it made communication more difficult and made it more challenging for the mentors to learn the faces of all the students.

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4. FINAL REMARKS

The 2020 NOMAD Research Institute was much different than any of the previous Institutes due to the virtual format. Many adaptations were required to continue to hold the program. In light of these changes, the organizers felt that the program was successful and provided a meaningful experience for the students and mentors alike. The organizing team received positive feedback from both parties, most of which stated that they would be willing to participate in future programs. The research completed during NOMAD was published both in seminar presentations as well as some conference proceedings. As results of their efforts, the 2020 NOMAD Institute produced three proceedings and presentations at international conferences. Two of the four projects published proceedings at the 2021 SEM IMAC, while one of the other projects presented at the 2021 ASME IDETC conference. A summary of the documentation produced by each project team is provided in Appendices C-F. Planning is underway for the 2021 NOMAD Research Institute with the intention to make improvements based on the feedback from 2020. As we move forward, we will continue to strive to provide the best experience for the students and engage staff and external collaborators to perform meaningful research in the interest of the Engineering Sciences Center at Sandia National Laboratories.

APPENDIX A. STUDENT RECRUITMENT FLYER

NOMAD RESEARCH INSTITUTE

CUTTING EDGE RESEARCH. COLLABORATION. NETWORKING. SOUTHWEST CULTURE.

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

The Program.

- Held from **June 15, 2020** to **July 30, 2020** at the University of New Mexico Campus in Albuquerque, NM
- You are matched with research projects based on **your research interests and skills**
- **Internships available** to U.S. citizens (see job posting ID 670828 for undergrad, 670584 for grad)

The Benefit.

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

The Engineering Disciplines.

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

The Contacts.

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

2020 NOMAD PROJECT LIST

Nonlinear Analysis of Mechanical Joints in Finger-Like Mechanism-Based Morphing Wing Devices

Morphing wing designs can adaptively change the wing geometry and reconfigure themselves into multiple and optimal shapes for specific flight conditions. The NOMAD team will experimentally and computationally investigate the nonlinear response within a finger-like mechanism subassembly with several jointed connections. The goal of the project is to better understand the influence of nonlinearity on the modal characteristics, such as damping and resonant frequency.

Neural Network Informed Uncertainty Quantification for Structural Dynamics Reduced Order Models

Reduced order models (ROMs) with discrete single-valued parameters, stochastic parameters (sROMs) or varying parameters (PROMs) are of interest for digital twin applications. This research project seeks to leverage data science to update the ROM parameter space based on actual sensor readings from a deployed system. The team will develop a machine learning framework that links to the ROM and suggests updated, physically realizable parameter values or distributions.

Assessment of Bolted Joint Integrity using Modal Filtering Techniques

Previous work has shown that estimates of modal contributions obtained by modal filtering can be used to successfully locate applied forces, local system changes, and nonlinear contact/forces. An application of these techniques will be explored to assess the integrity of bolted joints. Experiments will be performed on a jointed steel tube assembly in several bolt preload or loosening scenarios with the intention to determine the technique's robustness, reliability, and limitations.

Nonlinear Normal Mode Force Appropriation Techniques to Investigate Wing-Pylon Assembly

Nonlinearity in structural dynamics require alternate approaches to system identification and computational modeling to better understand complicated, nonlinear physics. This project will investigate the dynamics of a wing-like structure designed to replicate the next level subassembly of a pylon with concentrated nonlinearity at the wing connection. The team will use nonlinear normal mode theory to characterize the frequency-amplitude backbones and internal resonances of both the isolated pylon and the next-level wing-pylon subassembly.

Using Modal Analysis to Inform the Design of Electrical Switches

Electrical switches function by mechanically connecting two electrically conductive metal contacts together and provide a means of opening and closing electrical circuits. The objective of this project will be to assess whether linear or nonlinear modal analysis can inform the design of electrical switches to mitigate contact chatter in severe vibration environments. The NOMAD team will develop computational models and perform experiments of a pin-receptacle contact pair to explore the resonant behavior.

Correlation of Reduced-Order Model of Threaded Fastener

Models of threaded fasteners in system-level models need to be greatly simplified for computational efficiency but also need to resolve multiaxial behavior to capture the potentially tortuous ways the fastener can be loaded. The NOMAD team will develop and correlate three variants of reduced-order models of a threaded fastener to test data obtained in combined tensile and shear loading. The goal of the project will be to contrast the advantages and limitations of each model when considering the multiaxial load scenarios.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND2019-15090 HR SB

APPENDIX B. STUDENT INTERN JOB POSTINGS

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

Sandia National Laboratories

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

Summer projects for the 2020 Institute include:

- Nonlinear Analysis of Mechanical Joints in Finger-Like Mechanism Based Morphing Wing Devices (experimental and computational).
- Neural Network Informed Uncertainty Quantification for Structural Dynamics Reduced Order Models (computational).
- Assessment of Bolted Joint Integrity using Modal Filtering Techniques (experimental and computational).
- Nonlinear Normal Mode Force Appropriation Techniques to Investigate Wing-Pylon Assembly (experimental and computational).
- Using Modal Analysis to Inform the Design of Electrical Switches (experimental and computational).
- Correlation of Reduced-Order Model of Threaded Fastener (computational).

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

Qualifications We Require

- Currently attending and enrolled full time (or scheduled to graduate in the spring) in an accredited science, engineering, or math undergraduate program
- Minimum cumulative GPA of 3.3/4.0
- Ability to work 40 hours per week during the summer
- You must be working towards a bachelor's degree in mechanical engineering, civil engineering, aerospace engineering, materials science, engineering mechanics, applied mathematics or other applicable branches of science or engineering
- You are available to participate in the Institute from June 15, 2020 to July 31, 2020

Qualifications We Desire

- Experience (or academic focus) in structural dynamics, mechanical vibrations, modal analysis, solid mechanics, or failure analysis is desired
- Experience with finite element analysis, experimental methods, signal processing, model validation and calibration, numerical methods, and measurement systems
- Undergraduate research that aligns with state-of-the-art research in nonlinear mechanics or dynamics
- You should be able to work independently, with the ability to integrate effectively into a dynamic multidisciplinary teaming environment
- You should demonstrate strong interpersonal, organization, and communication skills (both oral and written)

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

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

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

Sandia National Laboratories

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

Summer projects for the 2020 Institute include:

- Nonlinear Analysis of Mechanical Joints in Finger-Like Mechanism Based Morphing Wing Devices (experimental and computational).
- Neural Network Informed Uncertainty Quantification for Structural Dynamics Reduced Order Models (computational).
- Assessment of Bolted Joint Integrity using Modal Filtering Techniques (experimental and computational).
- Nonlinear Normal Mode Force Appropriation Techniques to Investigate Wing-Pylon Assembly (experimental and computational).
- Using Modal Analysis to Inform the Design of Electrical Switches (experimental and computational).
- Correlation of Reduced-Order Model of Threaded Fastener (computational).

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

Qualifications We Require

- Earned bachelor's degree
- Currently attending and enrolled full time (or scheduled to graduate in the spring) in an accredited science, engineering, or math graduate program
- Minimum cumulative GPA of 3.7/4.0
- Ability to work 40 hours per week during the summer
- You must be working towards a Ph.D or master's degree in mechanical engineering, civil engineering, aerospace engineering, materials science, engineering mechanics, applied mathematics or other applicable branches of science or engineering
- You are available to participate in the Institute from June 15, 2020 to July 31, 2020

Qualifications We Desire

- Experience (or academic focus) in structural dynamics, mechanical vibrations, modal analysis, solid mechanics, or failure analysis is desired
- Experience with finite element analysis, experimental methods, signal processing, model validation and calibration, numerical methods, and measurement systems
- Graduate research that aligns with state-of-the-art research in nonlinear mechanics or dynamics
- You should be able to work independently, with the ability to integrate effectively into a dynamic multidisciplinary teaming environment
- You should demonstrate strong interpersonal, organization, and communication skills (both oral and written)

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

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APPENDIX C. PROJECT #1 DOCUMENTATION

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

A. Singh, K.M. Wielgus, et al., "Nonlinear Dynamic Analysis of a Shape Changing Finger-like Mechanism for Morphing Wings," in *39th International Modal Analysis Conference (IMAC XXXIX)*, February 2021.

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

- NOMAD Final Seminar – SAND2020-7662 PE
- IMAC Conference Proceeding – SAND2020-13181 C

IMAC Abstract:

Morphing wings have great potential to dramatically improve the efficiency of future generations of aircraft and to reduce noise and emissions. Among many camber morphing wing concepts, shape changing finger-like mechanisms consist of components, such as torsion bars, bushings, bearings, and joints, all of which exhibit damping and stiffness nonlinearities that are dependent on excitation amplitude. These nonlinearities make the dynamic response difficult to model accurately with traditional simulation approaches. As a result, at high excitation levels, linear finite element models may be inaccurate, and a nonlinear modeling approach is required to capture the necessary physics. This work seeks to better understand the influence of nonlinearity on the effective damping and natural frequency of the morphing wing through the use of quasi-static modal analysis and model reduction techniques that employ multi-point constraints (i.e. spider elements). With over 500,000 elements and 39 frictional contact surfaces, this represents one of the most complicated models to which these methods have been applied to date. The results to date are summarized and lessons learned are highlighted.

APPENDIX D. PROJECT #2 DOCUMENTATION

Details of the research from Project #2 were documented in the NOMAD Final Seminar as:

Z. Ghanem, S.M. Montgomery, W. Powell, et al., "Neural Network Informed Uncertainty Quantification for Structural Dynamics Reduced Order Models," in *2020 NOMAD Final Seminar Series*, Albuquerque, NM, July 2020.

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

- NOMAD Final Seminar – SAND2020-7662 PE

APPENDIX E. PROJECT #3 DOCUMENTATION

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

E. Robbins, T. Schreiber, A. Malla, et al., "Pre-test Predictions of Next-Level Assembly Using Calibrated Nonlinear Subcomponent Model," in *39th International Modal Analysis Conference (IMAC XXXIX)*, February 2021.

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

- NOMAD Final Seminar – SAND2020-7662 PE
- IMAC Conference Proceeding – SAND2020-13505 C

IMAC Abstract:

A proper understanding of the complex physics associated with nonlinear dynamics can improve the accuracy of predictive engineering models and provide a foundation for understanding nonlinear response during environmental testing. Several researchers and studies have previously shown how localized nonlinearities can influence the global vibration modes of a system. This current work builds upon the study of a demonstration aluminum aircraft with a mock pylon with an intentionally designed, localized nonlinearity. In an effort to simplify the identification of the localized nonlinearity, previous work has developed a simplified experimental setup to collect experimental data for the isolated pylon mounted to a stiff fixture. This study builds on these test results by correlating a multi-degree-of-freedom model of the pylon to identify the appropriate model form and parameters of the nonlinear element. The experimentally measured backbone curves are correlated with a nonlinear Hurty/Craig-Bampton (HCB) reduced order model (ROM) using the calculated nonlinear normal modes (NNMs). Following the calibration, the nonlinear HCB ROM of the pylon is attached to a linear HCB ROM of the wing to predict the NNMs of the next level wing-pylon assembly as a pre-test analysis to better understand the significance of the localized nonlinearity on the global modes of the wing structure.

APPENDIX F. PROJECT #4 DOCUMENTATION

Details of the research from Project #4 were documented as an ASME IDETC conference paper as:

A. Murugesan, K. Moreno, and M. Sheng, "Correlation of Reduced-Order Models of a Threaded Fastener in Multi-axial Loading," Proceeding in the ASME IDETC Conference, August, 2021.

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

- NOMAD Final Seminar – SAND2020-7662 PE
- Conference Paper – SAND2021-2570 C

Abstract:

Different fastener reduced-order models and fitting strategies are used on a multi-axial test dataset to evaluate how these multiple correlation techniques and strategies can capture the plastic-hardening region of load displacement behavior and its failure. Throughout this study, the plug and the spot weld reduced-ordered models are studied through calibration and refinement in a comparison to the more flexible method—the "two-block" plug. A correlation workflow utilizing iteration and digital signal processing was implemented on a set of quasi-static data where fasteners were stretched at angles from 0° to 90° in 15° increments until failure to gather material parameters for load-displacement behavior. The one-block plug is calibrated to just the hardening data of the tensile pull data, whereas the spot weld and two-block plug is calibrated to the tensile and shear pull data. These calibrations are assessed by comparing the peak-loads and failure displacements to the experimental load-displacement data.

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