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Enhancing Durability and Mobility through Optimized Plasticity

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14. ABSTRACT
U.S. Air Force platforms that involve structural components are designed to withstand a variety of static and cyclic loading conditions where thermal management is simultaneously required. Current designs for metallic and multi-material hybrid structures based on elastic (yield-limited) analysis lead to bulky structures that are sub-optimal for weight-critical applications. These applications range from hypersonic thermal protection systems to stiffeners for exhaust wash structures on embedded engine aircraft with optimized payload capabilities. This project sought to overcome these limitations by providing experimentally validated inelastic design guides and parametric/topology optimization tools. In this way, inherent material and structural capabilities are fully exploited in design methodologies. The fundamental research objective of the proposed project was to improve the understanding of the cyclic elastoplastic shakedown response of materials and structures to enable greater performance and durability. The major accomplishments include the creation of analytic, numerical, and experimental design tools and guides that exploit elastoplastic shakedown. These tools and guides were used on test case structures and aerospace metals at an elevated temperature of 600C to demonstrate the potential to support lightweighting or expand feasible design space 1.25--4 times that constrained by first-yield. The results of these studies were published in 5 journal articles or chapters, with another 2 currently under review and 4 more in preparation with planned submission in the coming weeks. The work was also communicated through 2 conference proceedings papers, 5 conference presentations, 5 invited talks and supported the completion of 1 doctoral dissertation. In total, 2 doctoral students were partially supported along with one postdoc under this program. During the award pr

15. SUBJECT TERMS
elastoplastic analysis, topology optimization, cyclic loading

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Enhancing Durability and Mobility through Optimized Plasticity

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FINAL REPORT

Project Abstract: U.S. Air Force platforms that involve structural components are designed to withstand a variety of static and cyclic loading conditions where thermal management is simultaneously required. Current designs for metallic and multi-material hybrid structures based on elastic (yield-limited) analysis lead to bulky structures that are sub-optimal for weight-critical applications. These applications range from hypersonic thermal protection systems to stiffeners for exhaust wash structures on embedded engine aircraft with optimized payload capabilities. This project seeks to overcome these limitations by providing experimentally validated inelastic design guides and parametric/topology optimization tools. In this way, inherent material and structural capabilities are fully exploited in design methodologies. The fundamental research objective of the proposed project is to improve the understanding of the cyclic elastoplastic response of materials and structures to enable greater performance and efficiency. In this project, computational and experimental methods are integrated to provide a new framework for thermostructural design that allows for broad and rapid evaluation of the design space as well as more accurate assessments of the structural integrity of components. This framework addresses the need to extend the range, mobility, and durability capabilities of U.S. Air Force flight structures.

Project Overview

Problem Statement: Many U.S. Air Force platforms involve structural components are subjected to cyclic loading conditions where thermal management is simultaneously required. Current designs for metallic structures based on elastic (yield-limited) analysis lead to bulky and inefficient structures that are sub-optimal for weight-critical applications in complex loading environments.

Technical Approach: Employ experimentally validated elastoplastic analysis in parametric/topology optimization to promote an alternative (shakedown) design strategy for metallic aerospace structures. With this approach, this project aims to improve the understanding of the cyclic elastoplastic response of materials and structures.

Technical Issues: To promote alternative shakedown design strategies, experimental demonstrations vetting shakedown at the macroscale for areospace materials over a range of thermomechanical loadings is required; the project is the first to do this for IN625 and a single crystal Ni-based superalloy. Plastic shakedown design theorems, which are simplified but exact methods of plasticity, have never been implemented in modern structural optimization frameworks (topology optimization or parametric sizing optimization) for aerospace applications.

Background State-of-the-Art & Technical Gaps:

For cyclic loading conditions, plastic design theorems have provided game-changing solutions for civil, automotive, and nuclear industries. They are used in applications ranging from:

vessels for the demilitarization of munitions, tribology, multilayer semiconductor devices, pavement design, shape memory alloy components, to nuclear pressure vessels. ***However, these design rules have not been leveraged and understood in the context of higher temperature aerospace applications.*** The typical approach is to create Bree Interaction Diagrams (see Figure 1) for any structure subject to combined loading environments (usually thermomechanical). These diagrams show the conditions in thermal and mechanical load space that elicit safe elastic and elastoplastic shakedown behaviors. The design maps are typically created numerically using upper and lower bound shakedown theorems or through parametric full cyclic finite element analyses. These shakedown design theorems have yet to be incorporated in modern structural optimization (topology optimization or parametric sizing optimization) protocols to take advantage of lightweighting and durability benefits for aerospace applications. It is very rare to find these Bree Interaction Diagrams being validated or created experimentally. Infact, to date there is a shortage of tests involving cyclic, mechanical or thermo-mechanical loads at the limit between shakedown and ratchetting.

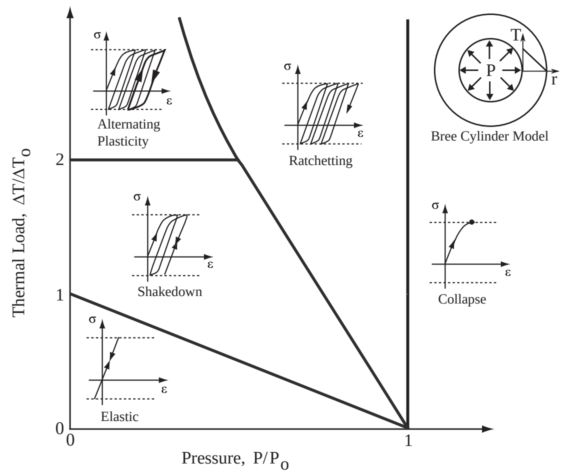

Figure 1: *Bree interaction diagram for the benchmark problem of a thin-walled cylinder and schematics of the resultant cyclic elastoplastic behaviors [1, 2].*

Description of Project Technical Objectives and Outcomes:

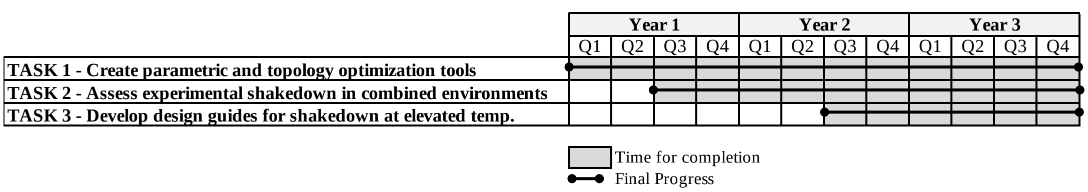

Figure 2: *Project Schedule & Final Progress.*

Tasks & Outcomes:

The overall objective of this project was to develop validated structural design methodologies that exploit shakedown for thermostructural performance. This objective was pursued through three main tasks outlined below. This project has USAF relevance through the development of advanced plastic design tools that will reduce weight, moderate maintenance and repair scheduling, and enhance structural durability/mobility. *See Summary of Accomplishments for a full list of students supported, publications, communications, honors and awards related to this project.*

Task 1: Create parametric and shape/topology optimization protocols for elastoplastic shakedown response. This task includes technical milestones related to (i) identifying and employing efficient mathematical elastoplastic shakedown formulations to be included in topology optimization frameworks, (ii) establishing complementary parametric sizing optimization protocols coupled with commercial finite element codes (ABAQUS) that can handle more detailed structural design. Our group has completed the research for both of these milestones.

We have identified new formulations to incorporate shakedown constraints in topology optimization frameworks that allow for lightweighting (Figure 3). Related to (i) the final editing of a manuscript for publication is being completed. It should be noted that this article in preparation was a collaboration with the PI's AFOSR Summer Faculty Fellowship Program Advisors (Dr. Phil Beran, Dr. Josh Deaton, WPAFB/RQVC). In this way, continued emphasis on USAF relevance was ensured. At the same time, we have established a full cyclic thermomechanical shakedown sizing optimization protocol that leverages ABAQUS finite element solvers [2]. This protocol has been used for a thorough study of 2D beam structures relevant for exhaust-washed structures and other heated components in order to demonstrate shakedown benefits for lightweighting and durability. The study also included sensitivities to material selection, constraint and loading conditions, as well as investigating the influence of thermal buckling on shakedown performance. This study includes case studies with lightweighting benefits up to 33% for shakedown designs compared to traditional elastic ones [2].

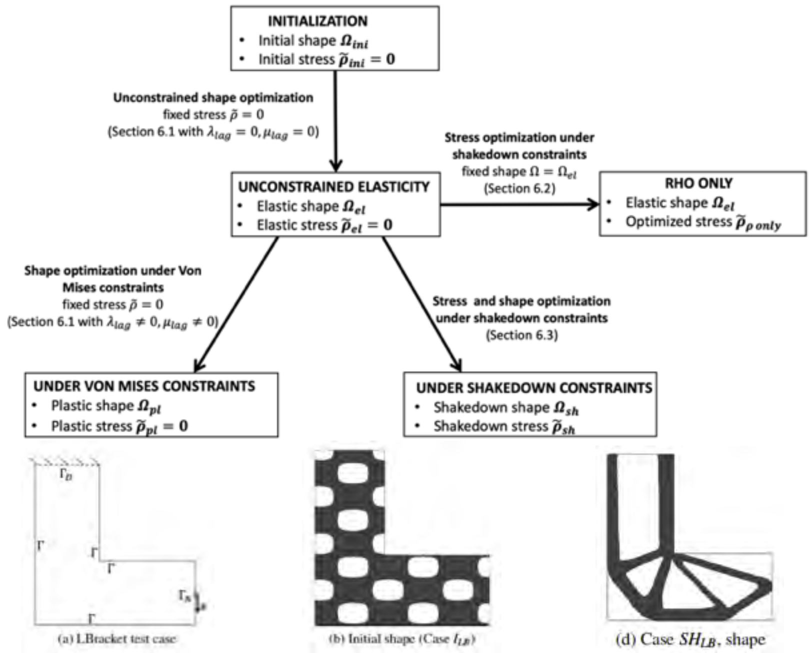

Figure 3: *Optimization strategy and L-Bracket test case results under shakedown constraints (from manuscript in preparation).*

Task 2: Use full-field experimental measurements to assess the shakedown behavior of structures in combined environments. This task includes technical milestones related to (i) benchmarking ambient shakedown experiments (extensometry-based) and expanding measurements with DIC, (ii) modifying and calibrating testing platform to include high-temperature DIC, and (iii) performing novel high-temperature shakedown demonstrations. These milestones have been met and the results from (i) and (ii) are being prepared for publications. For (iii) in aerospace applications, in order to convince designers to employ plastic (shakedown) design rules instead of first-yield design rules, experiments are needed to reliably show shakedown as the stabilization of plastic deformation. The results of this project include the first demonstrations of shakedown at the macroscale for aerospace materials like IN625 [3] and single-crystal Ni-based superalloys [4]. For example in [3], asymmetric cyclic uniaxial testing of cylindrical rods was conducted at

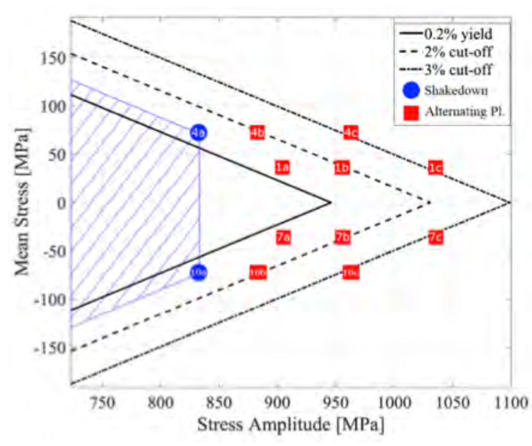

Figure 4: *Experimental Bree Diagram for Inconel 625 at 600 °C under cyclic uniaxial loading [3].*

600 °C over a range of cyclic stress amplitudes that were imposed at non-zero mean stresses while maintaining a constant maximum stress. In addition, the effect of dynamic strain aging (DSA) on the macroscopic shakedown behavior was established under load control. The inelastic work done per cycle was used as a measure of the severity of the cyclic inelastic behavior, and was evaluated by monitoring the evolution of the hysteresis loop width. It was found that shakedown occurred at maximum stress levels up to 1.4 times the linear elastic limit (Figure 4; note that the linear elastic limit is not visible in the figure). In other studies under review, the benefits extend to up to 4 times the elastic limit.

Another highlight from the project and this task was that the PI's leading work on the cyclic inelastic design of materials and structures in complex multi-axial high temperature environments using her thermostructural rig was featured in a case study recently published by MTS Systems Corporation, a provider of testing and sensing solutions. The case study is the first in a series called "Leveraging Non-Contacting Strain Measurement Solutions," produced by MTS in partnership with Trilion Quality Systems, a developer of precision 3D optical measurement and inspection testing devices. `http://www.mts.com/cs/groups/public/documents/library/mts_4036934.pdf`.

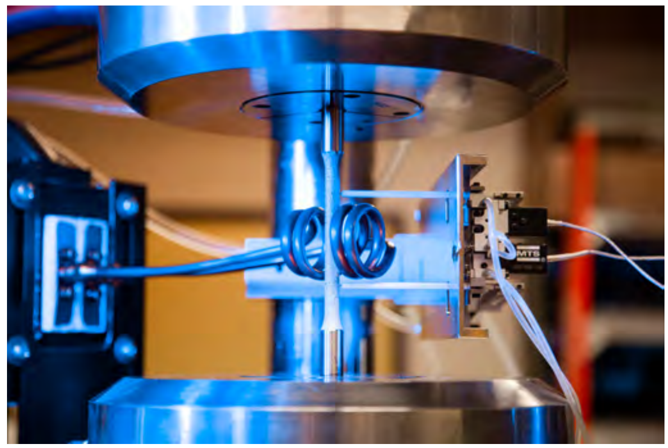

Figure 5: *PI's thermostructural rig.*

Task 3: Investigate the role of material, geometry, and loading on shakedown behavior at elevated temperature (600°C). This task includes a technical milestone related to creating elastoplastic design maps for parametric optimization studies that illustrate performance sensitivities to material, geometry, and loading. We completed this milestone focusing on beam structures as a test-case [2]. In [2], not only are material, geometric, and loading parameters explored as they influence shakedown behavior at elevated temperatures, but interactions between thermal buckling and shakedown are also identified (Figure 6). Figure 6 depicts the elastic, shakedown and buckling limit curves for a fixed pressure level ($P = 0.1$MPa). The limit curves are presented in terms of thermal strain and beam aspect ra-

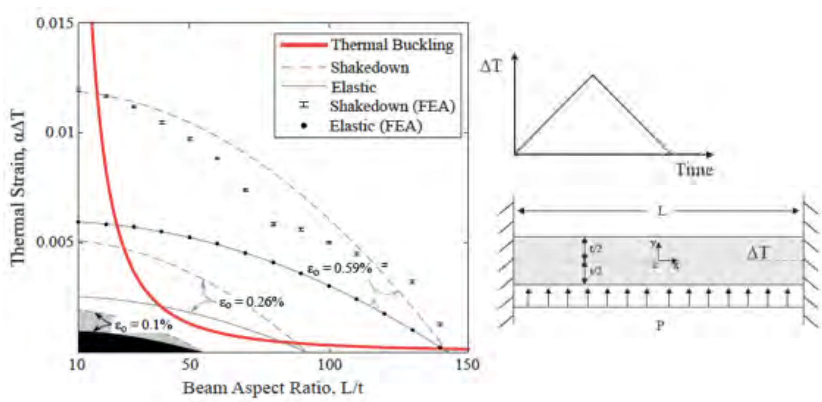

Figure 6: *Idealized aerospace structure and loading used to investigate cyclic plasticity responses. Consideration of elastic thermal buckling, elastic and shakedown limits for several aerospace materials [2].*

tio. Elastic and shakedown limits for different materials are shown with solid and dashed curves, respectively. The elastic thermal buckling constraint depends only on the beam aspect ratio and is shown as a thick solid line. The ratios of Young's modulus and yield strength are representative of nickel-based superalloy Inconel 718 ($\varepsilon_o = 0.59\%$), Inconel 625 ($\varepsilon_o = 0.26\%$), and some other nickel and copper alloys ($\varepsilon_o = 0.1\%$) at an elevated reference temperature of 600C. It is seen that (a) thermal buckling may be initiated before yield or shakedown depending on the material and geometry and (b) shakedown significantly enhances available design space. It should be noted that this article was also a collaboration with the PI's AFOSR Summer Faculty Fellowship Program Advisors (Dr. Phil Beran, Dr. Josh Deaton, WPAFB/RQVC). In this way, continued emphasis on USAF relevance was ensured.

Project Accomplishments Summary:

Personnel: 1.5 Students supported; 1 Postdoc supported

- Partially supported PhD student Dr. Ismail Soner CINOGLU. Dr. CINOGLU successfully defended his PhD Defense in August 2019. In 2018 and 2019, CINOGLU recieved Honorable Mention for the Lehigh University Graduate Life Leadership Award 2018. In 2016, CINOGLU was honored by being named a Lehigh P.C. Rossin Doctoral Fellow. The primary objective of this program is to enhance the preparation of selected Lehigh engineering doctoral students for successful future academic careers. **Dissertation:** *On the Cyclic Inelastic Behavior and Shakedown-Based Design of Metallic Materials and Structures: Analysis and Experiments*.
- Partially supported PhD student Mr. Sirui LI. Mr. LI has passed his General Examination towards the completion of his PhD degree in 2018 and is preparing his PhD Proposal Defense for Spring 2020.
- Supported Postdoc Dr. Ali CHARBAL from the leading Digital Image Correlation (DIC) group in Europe (LMT-ENS-Cachan). Dr. CHARBAL did his PhD with Prof. F. Hild and has expertise in DIC and Infrared Digital Image Correlation (IRIC) that was leveraged for this project.

Publications: 9

- Journal Article: I.S. Cinoglu, A. Charbal, N. Vermaak. *Towards exploiting inelastic design for Inconel 625 under short-term cyclic loading at 600 °C.* Mechanics of Materials, Volume 140, 103219. `https://doi.org/10.1016/j.mechmat.2019.103219` (2020).
- Journal Article: Z. Zhang, I.S. Cinoglu, A. Charbal, N. Vermaak, L. Lou, J. Zhang,. *Cyclic inelastic behavior and shakedown response of a 2nd generation nickel-based single crystal superalloy under tension-torsion loadings: experiments and simulations.* European Journal of Mechanics / A Solids, p. 103895, In Press. `https://doi.org/10.1016/j.euromechsol.2019.103895` (2019).
- Journal Article: S. Quiel, C.H. Irwin, C. Naito, N. Vermaak, *Mechanical characterization of normal and high strength steel bars in reinforced concrete members under fire* Journal of Structural Engineering, In Press, (2019).

- Journal Article: I.S. Cinoglu, M.R. Begley, J.D. Deaton*, P.A. Beran*, R. M. McMeeking, and N. Vermaak. *Elastoplastic design of beam structures subjected to cyclic thermomechanical loads.* Thin-Walled Structures, 136, pp. 175-185, https://doi.org/10.1016/j.tws.2018.12.024 (2019). ****Note that these co-authors are also N. Vermaak's AFOSR Summer Faculty Fellowship Program (SFFP) Advisors and Collaborators from her 2015 and 2016 SFFP participation.***

- Invited Book Chapter: N. Vermaak, M. Boissier, L. Valdevit, R. M. McMeeking, *Some graphical interpretations of Melan's theorem for shakedown design*, Chapter in: Advances in Direct Methods for Materials and Structures, Editors: Olga Barrera, Alan Cocks, Alan R. S. Ponter, Springer, Chap. 11, 179-198, https://doi.org/10.1007/978-3-319-59810-9_11 (2018).

- Journal Article Under Review: I.S. Cinoglu, A. Charbal, N. Vermaak, *Inelastic Design for Type 316L Stainless Steel at Ambient and 600 °C under Uniaxial Loading*, International Journal of Pressure Vessels and Piping (Under Review) (2019).

- Journal Article Under Review: A. Charbal, I. S. Cinoglu , F. Hild, S. Roux, N. Vermaak. *Stereocorrelation Formalism Considering Brightness and Contrast Effects: Application to Torsional Loadings*, Experimental Mechanics (Under Review), (2019).

- Conference Paper: M. J. Zielinski, I. S. Cinoglu, Cross Sectional Area Changes due to Plastic Bending of Prismatic Bars, ASME International Mechanical Engineering Congress and Exposition (IMECE) 2018 Conference Proceedings, Volume 13: Design, Reliability, Safety, and Risk, (2018).

- Conference Paper: I.S. Cinoglu, A. Charbal, N. Vermaak, *Development of Elastoplastic Design Strategies for Reinforced Structures at Elevated Temperatures*, ASCE (American Society of Civil Engineers) Earth and Space 2018 Conference, (2018).

Journal Publications in Preparation (Working Drafts): 4

- Journal Article. M. Boissier, G. Michailidis, J. Deaton*, P. Beran*, G. Allaire, N. Vermaak, *Elastoplastic Topology Optimization of Cyclically Loaded Structures via Direct Methods for Shakedown*, In preparation for Structural and Multidisciplinary Optimization, 2019. ****Note that these co-authors are also N. Vermaak's AFOSR Summer Faculty Fellowship Program (SFFP) Advisors and Collaborators from her 2015 and 2016 SFFP participation.***

- Journal Article. A. Charbal, I.S. Cinoglu, N. Vermaak, *Multiaxial Shakedown Analysis of Structures Using Stereo Digital Image Correlation*, In preparation for Experimental Mechanics, 2019.

- Journal Article. A. Abdulridha, A. Charbal, I. S. Cinoglu, N. Vermaak, S. Quiel. *Creep deformation of a new generation reinforcement bar under fire conditions.* In preparation for the Journal of Constructional Steel Research, 2019.

- Invited Book Chapter: D. Barbera, A. Charbal, I.S. Cinoglu, N. Vermaak, *Investigations of Shakedown in the Presence of Ambient Creep using Direct Methods for High Strength Steel* *under Multiaxial Loadings*, In preparation for Chapter in Direct Methods: Methodological Progress and Engineering Applications, Edited by: Aurora Pisano, Konstantinos Spiliopoulos and Dieter Weichert. Springer 2020.

Dissemination of Research Outcomes: 11

- Industry Feature: Vermaak 's leading work on the cyclic inelastic design of materials and structures in complex multi-axial high temperature environments using her thermostructural rig was featured in a case study recently published by MTS Systems Corporation, a provider of testing and sensing solutions. The case study is the first in a series called *Leveraging Non-Contacting Strain Measurement Solutions*, produced by MTS in partnership with Trilion Quality Systems, a developer of precision 3D optical measurement and inspection testing devices. This feature was further promoted by MTS and Trilion using their social media platforms (LinkedIn, Facebook, Twitter). `http://www.mts.com/cs/groups/public/documents/library/mts_4036934.pdf` (2019).

- Invited Talk: N. Vermaak, *Design and Optimization Strategies for Thermostructural Durability in Aerospace Structures*, NASA Glenn Research Center, Mechanics and Life Prediction, Cleveland, OH May 2019.

- Invited Talk: N. Vermaak, A. Charbal, I.S. Cinoglu, *Numerical and experimental investigations of multi-axial elastoplastic shakedown for Inconel 625 at elevated temperatures*, Air Force Institute of Technology, Department of Aeronautics & Astronautics (AFIT), WPAFB, OH May 2019.

- Invited Talk: I.S. Cinoglu, A. Charbal, N. Vermaak, *Thermomechanical Shakedown Analysis of Structures Using Finite Element Analysis and Non-Contact Measurements*, Department of Civil, Construction, and Environmental Engineering, North Carolina State University (NCSU), NC March 2019.

- Invited Talk: N. Vermaak, *Towards Elastoplastic Optimization of Cyclically Loaded Thermal Structures*, Northeastern University Department of Mechanical & Industrial Engineering, Boston, MA, March, 2017.

- Invited Talk: N. Vermaak, *Towards Elastoplastic Optimization of Cyclically Loaded Thermal Structures*, Brown University Mechanics of Solids & Structures, Providence, RI, March, 2017.

- Conference Presentation: I.S. Cinoglu, A. Charbal, N. Vermaak, *Development of Elastoplastic Design Strategies for Reinforced Structures at Elevated Temperatures*, ASCE (American Society of Civil Engineers) Earth and Space 2018 Conference.

- Conference Presentation: I.S. Cinoglu, A. Charbal, N. Vermaak, *Experimental and Numerical Analyses of the Uniaxial Shakedown Behavior of 316 Stainless Steel*, TMS(The Minerals, Metals & Materials Society) 2019 Annual Meeting & Exhibition, San Antonio, TX, Mar. 2019.

- Conference Presentation: I.S. Cinoglu, A. Charbal, N. Vermaak, *Experimental and Numerical Analyses of Uniaxial Shakedown Behavior of 316 Stainless Steel.* ASME-IMECE (American Society of Mechanical Engineers International Mechanical Engineering Congress & Exposition), Pittsburgh, PA November, 2018.

- Conference Presentation: A. Charbal, I.S. Cinoglu, N. Vermaak, *Numerical and experimental investigations of multiaxial shakedown of Inconel 625 at high temperature.* ASME-IMECE (American Society of Mechanical Engineers International Mechanical Engineering Congress & Exposition), Pittsburgh, PA November, 2018.

- Conference Presentation: I.S. Cinoglu, *Elastoplastic design of aircraft surfaces subjected to cyclic thermomechanical loads.* ASME-IMECE (American Society of Mechanical Engineers International Mechanical Engineering Congress & Exposition), Advances in Aerospace Structures and Materials II Session, Phoenix, AZ, November, 2016.

PI Awards/Honors During Project Period: 6

- 2019: Named TMS Frontiers of Materials Awardee, (The Minerals, Metals & Materials Society)
- 2019: Received Hillman Award for Excellence in Graduate Advising, Lehigh University
- 2019: Promoted to Associate Professor with Tenure, Lehigh University
- 2018: Named Outstanding Reviewer for Acta Materialia, Elsevier and Acta Materialia, Inc.
- 2018: Named Founding Chair of the Design of Engineering Materials Technical Committee, ASME (American Society of Mechanical Engineers)
- 2016: Summer Faculty Fellow, Air Force Office of Scientific Research WPAFB/RQVC; Aerospace Systems Directorate, Multidisciplinary Science & Technology Center

References

[1] J Bree. Elastic-plastic behaviour of thin tubes subjected to internal pressure and intermittent high-heat fluxes with application to fast-nuclear-reactor fuel elements. *The Journal of Strain Analysis for Engineering Design*, 2(3):226–238, 1967.

[2] I.S. Cinoglu, Matthew R. Begley, Joshua D. Deaton, Philip A. Beran, Robert M. McMeeking, and Natasha Vermaak. Elastoplastic design of beam structures subjected to cyclic thermomechanical loads. *Thin-Walled Structures*, 136:175–185, 2019.

[3] I.S. Cinoglu, A. Charbal, and N. Vermaak. Towards exploiting inelastic design for inconel 625 under short-term cyclic loading at 600c. *Mechanics of Materials*, 140, 2020.

[4] Z. Zhang, I.S. Cinoglu, A. Charbal, N. Vermaak, L. Lou, and J. Zhang. Cyclic inelastic behavior and shakedown response of a 2nd generation nickel-based single crystal superalloy under tension-torsion loadings: experiments and simulations. *European Journal of Mechanics / A Solids*, page 103895, 2019.