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MIDWEST STRUCTURAL SCIENCES CENTER 2011 ANNUAL REPORT

William A. Dick

University of Illinois at Urbana-Champaign

OCTOBER 2011
Interim Report

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14. ABSTRACT
The Midwest Structural Sciences Center is a collaboration between the Structural Sciences Center, Air Vehicles Directorate of the Air Force Research Laboratory (AFRL/RBSM SSC), and a team of faculty, graduate students, and professional staff researchers of the University of Illinois at Urbana-Champaign (UI), Wright State University, University of Cincinnati, and the University of Texas at San Antonio. The team works closely to simulate, model and test structures and materials for use in future air-and space-vehicles in a risk quantified design process.

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Midwest Structural Sciences Center

University of Illinois at Urbana-Champaign
University of Cincinnati
Wright State University
Structural Sciences Center, U.S. Air Force Research Laboratory

2011 Annual Report

The Midwest Structural Sciences Center is a collaborative effort between the Structural Sciences Center, Air Vehicles Directorate of the Air Force Research Laboratory (AFRL/RBSM), and a team of faculty, graduate students, and professional staff researchers of the University of Illinois at Urbana-Champaign (UI), Wright State University (WSU), University of Cincinnati, and the University of Texas at San Antonio (UTSA). The team works closely to simulate, model, test, and assess structures and materials for use in future air- and space-frames focusing on structural response and life prediction.

The University of Illinois Midwest Structural Sciences Center (MSSC) was established in February 2006 to expand rapidly the technical manpower available to the Structural Sciences Center at AFRL. The MSSC has the long-term objective of developing the knowledge base required for validated tools for the design and simulation of coupled aero-thermo-mechanical structures. In close collaboration with the scientific and engineering staff of AFRL/RBSM, faculty, staff and students from the universities undertake medium-term research projects (five- to ten-year horizons) in two key areas:

- Structural response prediction
- Structural life forecasting

Supported by parallel technologies:

- Laboratory experiments and validation
- Uncertainty quantification and risk assessment

MSSC Technical Program Features

Structural response prediction
Structural life prediction
Multiscale materials modeling
Generalized finite element methods
Risk analysis and quantification
Sensitivity analysis
Experimental comparison

MSSC Research Program Partners

Air Force Research Laboratory Air Vehicles Directorate, Structural Sciences Center
University of Illinois at Urbana-Champaign
Aerospace Engineering
Civil and Environmental Engineering
Computational Science and Engineering
Mechanical Science and Engineering
University of Cincinnati
Wright State University

The team employs analytical, computational, experimental, personnel and financial resources from several university departments and AFRL organizations, and seeks additional resources as needed from other federal and non-federal sources. Outstanding facilities are available at all sites and are being applied to MSSC projects and programs. Graduate research assistants work with faculty at the universities and their AFRL/RBSM colleagues to evaluate and extend the understanding of structures and materials in aerospace structural components that experience extreme combined environments.

1 Introduction

Future missions of the United States Air Force (USAF), such as prompt global strike and operationally responsive space access, will be performed with air/space vehicles now in conceptual design. However it is clear that the structural concepts needed to make such next-generation vehicles sufficiently durable and lightweight will involve novel structural arrangements and material systems. During typical operating conditions, aircraft are subjected to random loads due to engine noise and other aeroacoustic vibrations. The random aeroacoustic pressure load, combined with other extreme conditions like elevated temperatures, turbulence, etc., may lead to the failure of the aircraft structure. Challenges in predicting the response of structures in extreme environments include aerothermoelastic coupling; computational cost and complexity of large models; material nonlinearity, temperature dependence and degradation; spatial variation of material and structural properties; and uncertainty in loads, material properties, geometry, and boundary conditions.

Modeling/simulation — Used in reliability analysis, design, and for designing effective experiments

Experiments — Data used for parameter identification studies to improve modeling effort and validation of simulations

Risk/reliability — Algorithms used for reliability analysis, parameter identification and design

1.1 Air Force Structural Sciences Mission (Ravi Chona, AFRL/RBSM)

Reaching halfway around the globe in a matter of hours from the continental United States … using air-breathing platforms that fly hypersonically for extended periods of time ... affordably accessing space using operationally-responsive, reusable launch vehicles ... a stealthy, survivable fleet of manned and unmanned vehicles … these are all game-changing capabilities, long-desired by the Air Force.

Instantiating the durable, high-performance aerospace vehicles needed to make these capabilities a reality for tomorrow's war-fighter is no easy task. It demands extraordinary, interdisciplinary, in-depth technical understanding from the scientists and engineers charged with designing and delivering the unique, new aero-structural solutions that hold the keys to success. It is with this in mind that AFRL has long recognized, and worked hard to develop and sustain, unsurpassed excellence in both the fundamental science, and the more applied aspects, of the aero-structures technical competency. Ensuring that the Air Force is always on the leading edge of this core competency demands technical leadership that can:

- Identify and pursue new, fundamental research directions
- Exploit the world-unique capabilities that AFRL has developed over the years, especially those for simulating the combined, extreme environments that are encountered when highly-coupled maneuver, thermal, and aero-acoustic loads occur simultaneously
- Bring together strong teams that partner AFRL, DoD, other government entities, academia and industry
- Lead a research-centric activity in structural sciences that can deliver the capabilities that are needed, and serves as the focal point for ensuring that the in-house technical competency is both unsurpassed in excellence and recognized as such by the technical community at large

From an aero-structures perspective, achieving the desired future capabilities has several critical implications. First, the material-structural systems in use today for extreme-environment applications are not likely to satisfy many of the future fleet's competing demands for higher performance, greater reliability, and lower cost. This will necessitate the development of new structural concepts. Second, it is highly unlikely that the design-build-test methodology currently used for structural verification, which typically culminates with a series of full-scale destructive tests, will be adequately adaptable to meet the challenges of smaller fleet sizes, unfamiliar operating conditions, and compressed design, production, and delivery schedules.

Not only do currently used methods lack some of the essential physics for robust and reliable analysis, design, and simulation of extreme-environment structures, they overwhelmingly rely on component-centric and deterministic assessment methodologies that cannot provide accurate determinations of system-level life and reliability. In addition, with anticipated buy numbers in the tens (rather than in the hundreds or thousands), full-scale destructive testing is not likely to prove cost effective, even if the harsh environmental conditions of full mission trajectories could be satisfactorily replicated over large portions of an airframe. Finally, as history can attest, USAF aerospace vehicles are rarely used exclusively in the manner for which they were designed. As operational requirements change in response to military demands, the ―wear and tear" on the vehicles is likely to differ significantly from pre-deployment predictions. Current assessment methods, which rely heavily on historical engineering practices and fleet-tracking statistics, are unlikely to prove adequate for tomorrow's small fleets of high-performance, advanced concept platforms.

To successfully bridge the gap between today's design, analysis, and certification techniques and the breakthrough methods needed for successful realization of tomorrow's fleet, the AFRL Structural Sciences Center has initiated a research program to enable the development of high-performance aero-structures through combined-extreme-environment, structural-scale simulation within a risk-quantified framework. The goal is to develop a robust framework that can support the structural requirements of game-changing future platforms (Figure Cho-1). This framework rests on two inter-linked technology pillars: structural response simulation and structural life forecasting. The synergistic integration and fusion of these two elements will enable a paradigm shift for designing, certifying, and maintaining the extreme environment structures demanded by future USAF needs.

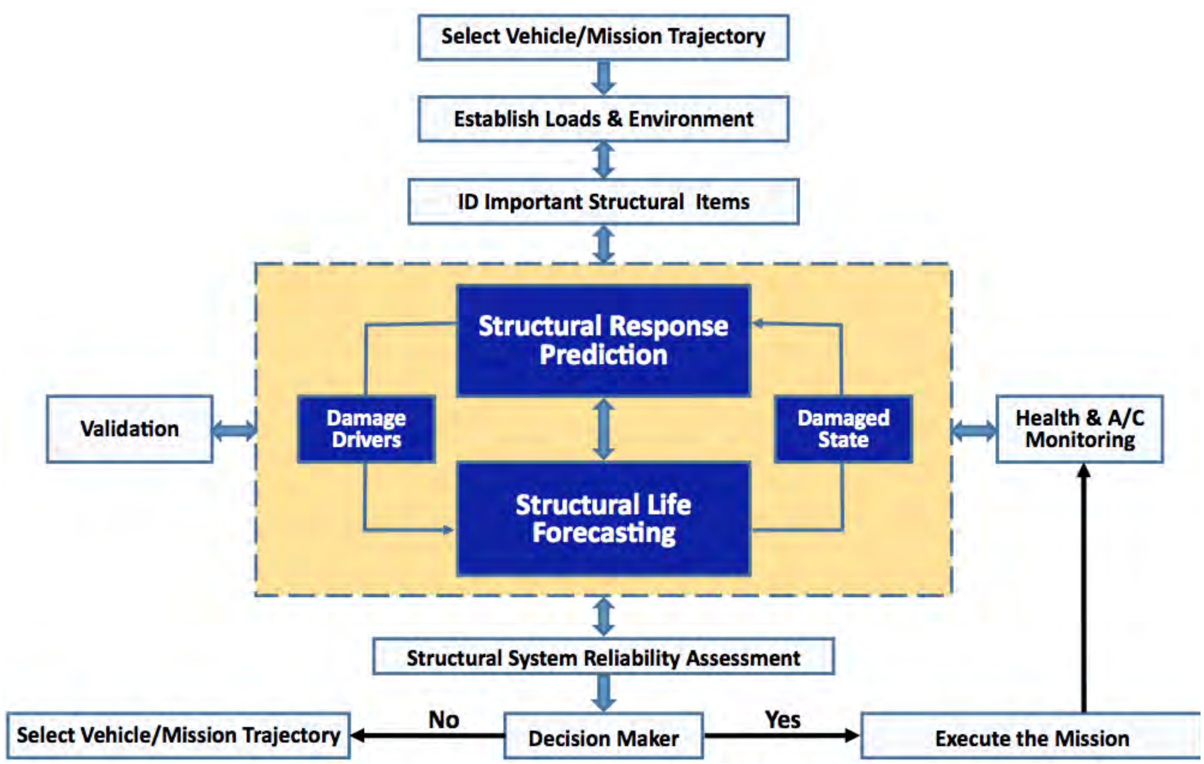

Figure Cho-1: Development of future high-performance aero-structures through combined-extreme-environment, structural-scale simulation within a risk-quantified framework rests on two inter-linked technology pillars — structural response simulation and structural life forecasting.

The primary mission of the Structural Sciences Center is to address critical shortfalls in the capability of today's USAF to exploit state-of-the-art, commercial and non-commercial, modeling and simulation tools for predicting the response, performance, and applicable failure modes and potential failure states, for aerostructures experiencing the intense, coupled, combined thermal-acoustic-mechanical loads associated with high-Mach flight, and do so within a risk-informed/risk-based/risk-quantified structural design, structural assessment and structural evaluation paradigm.

1.2 Midwest Structural Sciences Center

The Midwest Structural Sciences Center is a collaborative effort between the Structural Sciences Center, Air Vehicles Directorate of the Air Force Research Laboratory (AFRL/RBSM), and a team of faculty, graduate students, and professional staff researchers of the University of Illinois at Urbana-Champaign (UI), University of Cincinnati, Wright State University (WSU), and the University of Texas at San Antonio (UTSA). The team works closely to simulate, model, test, and assess structures and materials for use in future air- and space-frames. The MSSC team is viewed as a ―living organization" whose members change over time to meet the needs of the collaborative partnership.

The team employs analytical, computational, experimental, personnel and financial resources from all four organizations, and seeks additional resources as needed from other federal and non-federal sources. Outstanding facilities are available at all sites and are applied to MSSC projects and programs. Graduate research assistants work with faculty at the universities and their colleagues at AFRL/RBSM to evaluate and extend our understanding of materials and structures in aerospace structural components that experience extreme combined environments.

MSSC Team Members

University of Illinois
- Bodony — Acoustic response prediction
- Brandyberry — Uncertainty quantification and risk analysis
- Duarte — GFEA, structural analysis, multiscale analysis
- Geubelle — Multiscale analysis, FEA
- Lambros — Experiments, high strain rates, FGM
- Sehitoglu — Thermomechanical response, experiments
- Song — Risk, reliability, stochastic events, FEA
- Tortorelli — Sensitivity, optimization

University of Cincinnati
- Qian — Multiscale methods

Wright State University
- Huang, Penmetsa — Risk, failure probability assessment

AFRL/RBSM
- Acoustic experiments, aeroframe design, operating environments, large-scale structural testing

Collaboration among the partners is frequent and intense (co-advised research projects and graduate theses, teamed simulation and experiments, co-authored journal articles and project proposal submissions, etc.). Computational resources, graduate assistantships, experimental facilities and AFRL/RB visitor office spaces are earmarked to directly support the MSSC, as have graduate student tuition waivers.

High-performance hypersonic aircraft are expected to have stringent structural requirements, especially in regard to their aero-thermal structural components. These components may include specialty high-performance metal alloys or functionally-graded materials, each specifically designed and manufactured to address the combined thermo-mechanical-aeroacoustic loadings unique to hypersonic applications. Important is the development of efficient methods for quantifying the uncertain responses and the risks of aerostructures.

Existing constitutive materials models are generally phenomenological, i.e., they are based on some empirical formulae (e.g., power law) to be fitted to laboratory tests. Phenomenological models rarely work well for advanced materials subjected to extreme conditions, since they usually fail to account for the significant microstructure changes under the extreme environment. Thus novel, physically-based constitutive models are being developed under the MSSC umbrella.

Successfully modeling fatigue in aerospace structures requires detailed knowledge of the various structural and material failure modes across the wide variety of fatigue loadings possible. In parallel to our simulation and analytical tasks, Center researchers are conducting series of experiments to determine the relative importance of low cycle, high cycle, and fatigue crack growth in materials subjected to thermomechanical and aeroacoustic fatigue. Experiments are being performed to understand the interaction between the high stresses associated with thermal loading, superimposed with ultrahigh frequency-induced stresses from an aeroacoustic-type loading. In each project, university investigators are teamed with RBSM personnel to encourage tight relationships between university and government researchers.

2 MSSC Project Summary — 2010-2011

A — Response Prediction: Coupled Aero-Thermo-Mechanical-Acoustic Analysis and Simulation

A3 Integrated Fluid/Structure Interaction Simulation (Daniel Bodony, Philippe Geubelle, Mahesh Sucheendran, Adam Kuester, Halvorson, Joseph Hollkamp, Robert Gordon)

A5 Multiphysics, Coupled Analysis of Extreme-Environment Structures (Daniel Bodony, Philippe Geubelle, Christopher Ostoich, S. Michael Spottswood)

A7 Multiscale Thermo/Strain Field Coupling (Julia Plews, Thomas Eason, Armando Duarte)

B — Life Prediction: Identification and Definition of Structural Limit States

B2 Imperfections and Defect Tolerance of Aircraft Shells and Structures (Daniel Tortorelli, Seth Watts, Thomas Eason)

B3 3-D Cyclic Plasticity Model for Thermo-mechanical Loading in Large-scale Analyses (James Sobotka, Robert Dodds, Brian Gockel)

B4 Towards a Fatigue Initiation Theory for Multiaxial Thermo-mechanical Fatigue (Alpay Oral, Huseyin Sehitoglu, Ravi Penmetsa)

C — Life Prediction: Framework and Methodologies for Risk-quantified Structural Assessment

C1 Uncertainty/Risk Quantification Methods for STATS (Junho Song, Young Joo Lee, Eric Tuegel) — Completed in 2010

C2 Validation of Simulations Having Uncertainties in Both Simulation and Experiments (Mark Brandyberry, Jason Gruenwald, *Mark Haney*)

C4 System Reliability with Correlated Failure Modes (Harry Millwater, Luciano Smith, Daniel Sparkman, David Wieland, Eric Tuegel) — Completed in 2011

C5 Identifying Structurally Significant Items using Matrix Reanalysis Techniques (Ravi Penmetsa, Bhushan Kable, Vankat Shanmugam, Eric Tuegel) — Completed in 2010

C6 Enriched Space-time Finite Element Method — (Dong Qian, Y. Yang, S. Chirptukar, D. N. Alpert, Thomas Eason, S. Michael Spottswood)

D — Experimental Discovery and Limit State Characterization

D2 Development of Experimental Techniques for Validating a Coupled Thermomechanical Fatigue Simulation Framework (Jay Carroll, John Lambros, Ravi Chona) — Completed in 2010

D3 Thermomechanical Fatigue of Hastelloy X: Role of Combined Loading on Material Response (Wael Abuzaid, Huseyin Sehitoglu, Ravi Chona)

D4 Thermomechanical Fatigue of Hastelloy X: Role of Defects (Mallory Casperson, Ravi Chona, John Lambros)

Italic — Concluded projects

A — Response Prediction: Coupled Aero-Thermo-Mechanical-Acoustic Analysis and Simulation

A3 Integrated Fluid/Structure Interaction Simulation (Mahesh Sucheendran, Phillipe Geubelle, Daniel Bodony, Joseph Hollkamp, Robert Gordon, Timothy Beberniss)

During the past year, the focus was on two activities: (i) Verification of the 3-D, parallel, coupled numerical solver with the analytical theory developed for predicting the acoustic-structure interaction of thin plates flush-mounted in a rectangular duct, and (ii) using the analytical theory to study the effect of plate thickness and presence of uniform mean flow in the duct on the plate response.

The individual fluid and solid solvers were verified with problems for which analytical results were available. The fully coupled, 3-D, parallel numerical solver was verified using the coupled acoustic-structure response of a thin plate mounted in a duct predicted by the analytical theory using a broadband plane wave input spectrum centered around plate modes. For a thin, clamped Al plate mounted in a duct with SEF-like conditions, the plate response predicted using the numerical solver is shown in Figure Geu-1 for an input frequency range of 125-145 Hz at 100 dB amplitude. The spectral response of the plate is then compared with that predicted by the analytical theory, which is shown in Figure Geu-2. The two results match reasonably well. To capture the spectral response more accurately, the coupled code was made more efficient to capture longer time records. During this verification case the numerical coupled code was ported to a new parallel machine with significant performance improvement.

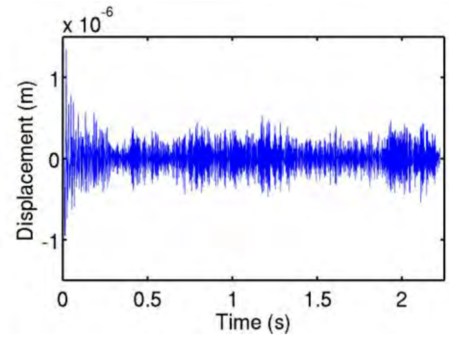

Figure Geu-1. Coupled response of a wall-mounted thin plate in a duct to acoustic plane waves.

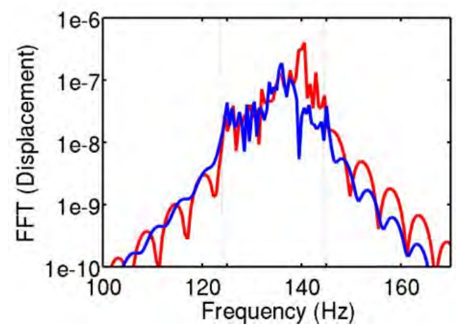

Figure Geu-2. Spectral response of thin plate load from Figure Geu-1.

The analytical theory is useful for conducting parametric studies of the coupled response of thin plates to acoustic loads to investigate variations that are difficult or expensive to do experimentally. Figure Geu-3 shows one such study of the effect of the plate thickness on the coupled response of plate near the first two *in vacuo* bending frequencies of the plate. It can be seen from the figure that as the plate thickness reduces, the acoustic-structural coupling becomes significant and the frequency at which response peaks starts drifting away from the *in vacuo* peaks in a mode-dependent fashion. The effect of uniform flow on the plate response was also studied using the analytical theory.

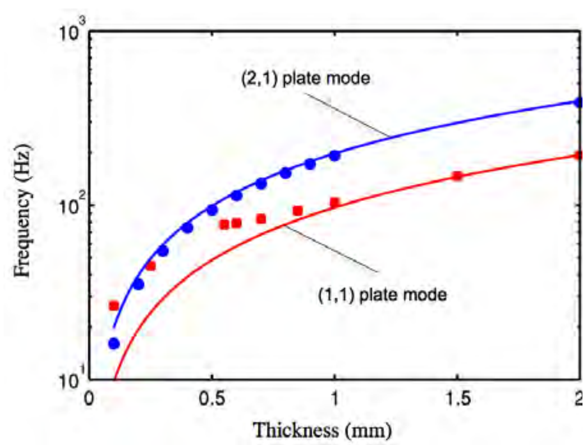

Figure Geu-3. Variation of coupled response peak frequency with plate thickness. Solid lines: *in vacuo* frequencies of plate; symbols: analytical model.

In the future, we plan to use the analytical theory to do more parametric study of the coupled acoustic-structure response of thin plates. Also we plan to use the numerical solver to study the effect of uniform mean flow in the duct on the coupled response of thin plates. The numerical solver can be used to study the nonlinear effects on the plate response. As the amplitude of acoustic loads is increased, the nonlinearity in the fluid equations and the in-plane stresses in the plate become significant. These effects can be studied using the numerical solver.

A5 Multiphysics, Coupled Analysis of Extreme-Environment Structures (Daniel Bodony, Christopher Ostoich)

The goal of Project A5 is to develop a multiphysics fluid-thermal-structural solver capable of providing a detailed and validated prediction of the response of a thermo-mechanically-compliant structure in a realistic hypersonic environment. In contrast to reduced-order models which utilize various assumptions to produce solutions at low cost, the solver sought in Project A5 makes very few assumptions about the physics of the problem to provide accurate information, though at a higher computational cost. Coupling becomes more important as interest progresses further into the hypersonic regime. An accurate multiphysics tool is thus needed to supplement the understanding provided by experiment, to investigate situations that are prohibitive to experimental approaches, and to determine when and how reduced order methods fail to provide accurate predictions. The solver both would provide valuable information about this environment and provide accurate data with which reduced order models could be verified and/or modified.

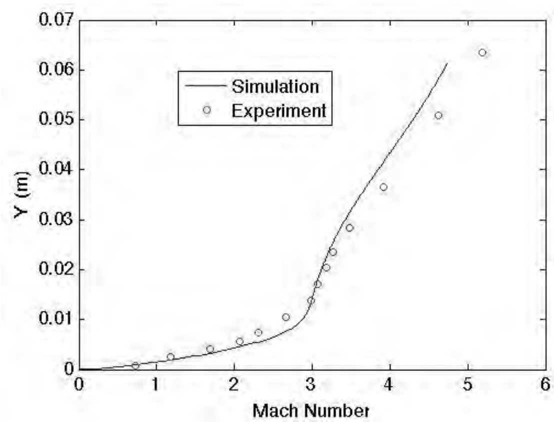

Figure Bod-1: Mach number profile in the vicinity of the flat plate upstream from the dome used in Glass & Hunt (1986) experiments.

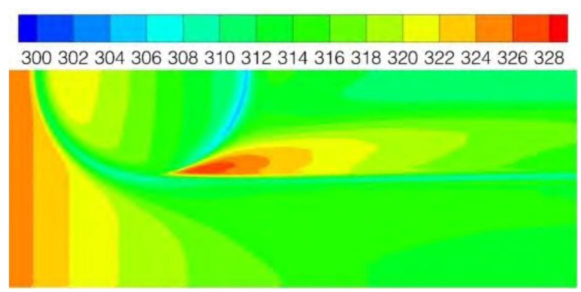

Figure Bod-2: Surface temperature in K, showing the localized heating associated with the vortex

The first benchmark in the development of the coupled fluid-thermal-structural solver, involving the validation of the fluid-thermal coupled code, has been completed on a Mach 6.5 laminar boundary layer flowing past a nominally-rigid spherical dome fitted with pressure and temperature probes tested in the 1980s as part of NASA's NASP program in the NASA Langley 8 Foot High Temperature Tunnel (8' HTT) (Glass & Hunt, 1986). The original study evaluated a thermal protection system designed to mechanically relax into the oncoming flow when exposed to thermally-induced stresses and included a variety of runs taken with different boundary layer states (laminar, turbulent) over flat plates with different leading edges (sharp and blunt). In order to make a fair comparison with the experiment, work was done to understand the flow conditions (not all of which were documented), boundary conditions, and measurement procedures inside the tunnel.

Due to the increased cost of a resolved high-fidelity coupled simulation, the coupled domain included only the portion of the flat plate containing the dome, and was entirely contained downstream of the shock formed by the leading edge of the plate. The fluid-only simulation of the full test article was conducted using a RANS solver to a) improve the understanding of the flow conditions and b) provide boundary conditions for the coupled simulation domain that were consistent with the experiment. Figure Bod-1 shows a comparison between Mach number profiles near the plate from the simulation and experiment. The close match gave confidence in our understanding of the wind tunnel conditions, while the differences highlight the uncertainty in the experimental conditions.

Coupled simulations were run to simulate the thermal response of a rigid structure over 5 seconds in Mach 6.5 flow. Figure Bod-2 shows the surface temperature of the thermal domain at 5 seconds. It was noted that both cold and hot regions were generated due to viscous effects, which are not captured by reduced-order approaches based on inviscid analyses, such as piston theory. A quantitative comparison with experimentally measured values of heat flux validated the ability of the solver to make response predictions in the hypersonic environment. Figure Bod-3 shows the differences between simulation and experiment in the heat flux on the dome. The differences are normalized by a reference heat flux used in the experiment report and do not represent a ―relative error." The work on the coupled fluid-thermal solver will conclude with a simulation employing a more complex thermal model in the fluid. Results will be compared with experiment and will allow the assessment of whether a more complex model is necessary in this regime.

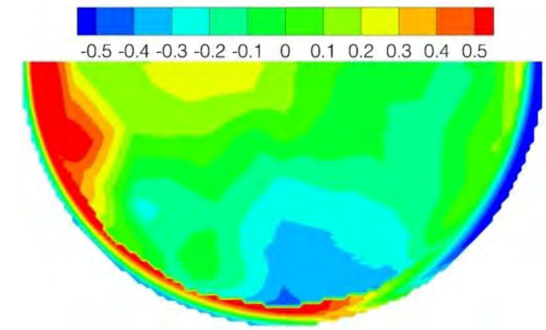

Figure Bod-3: Normalized difference in heat flux between simulation and experiment.

A7: Multi-scale Thermo/Strain Field Coupling (Armando Duarte, Julia Plews, Thomas Eason)

The availability of a computationally efficient technique to solve multiphysics, multiscale thermal strain problems is of great importance in the structural design and response prediction of hypersonic flight vehicles. Generalized finite element methods (GFEMs) provide an especially useful means for simulations of this nature, enabling the generation of specialized enrichment functions tailored to the problem at hand. In this case, multi-scale effects can be characterized by special global-scale enrichments derived from small-scale boundary value problems, leading to the so-called GFEM with global-local enrichments ($GFEM^{gl}$). Building upon a framework for temperature gradients resulting from transient, sharp thermal loads, steps are being taken to develop a GFEM platform to resolve localized thermo-mechanical stresses and strains while maintaining a coarse, structural-scale mesh.

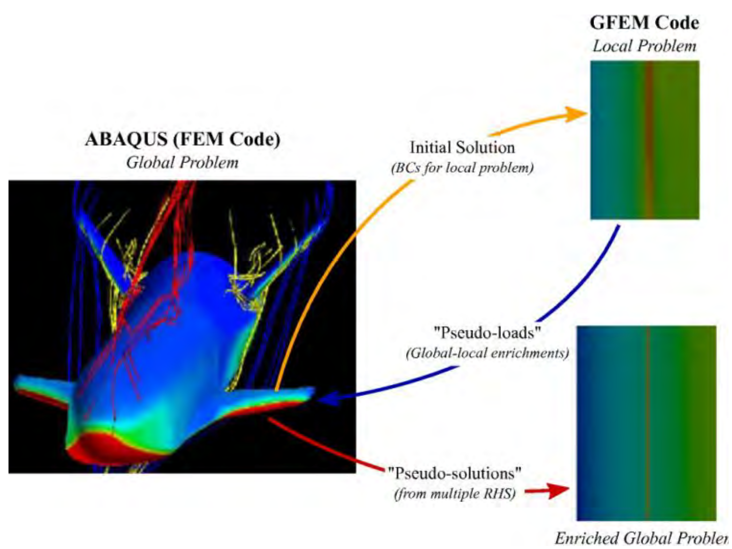

Figure Dua-1: The non-intrusive interface between Abaqus and the GFEM code – exchange of pseudo-loads (global-local enrichment right-hand-sides) and resulting pseudo-solutions.

During the past year, the primary focus of work on Project A7 has been the development of an interface between the $GFEM^{gl}$ for thermal analysis implemented in the scope of Project A2 with a well-known, commercial finite element analysis software package, Abaqus, without any intrusive code modifications, in order to facilitate the transitioning of this technology to the Air Force. In the proposed non-intrusive interface, only loads (or right-hand-sides) and solutions are exchanged between Abaqus and a separate GFEM analysis code, while still enabling the use of the full feature set of the standard $GFEM^{gl}$. Figure Dua-1 shows a schematic illustration of the non-intrusive implementation.

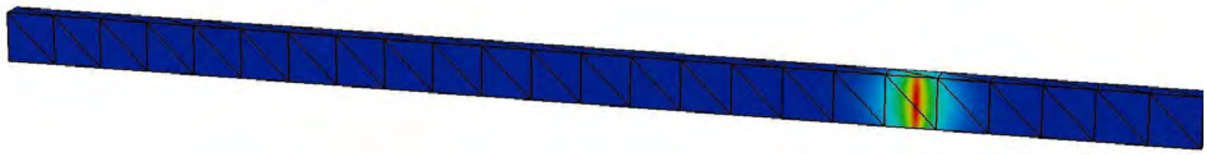

Figure Dua-2: Aluminum beam subjected to laser heating; global domain with localized heating and coarse, global Abaqus mesh is shown.

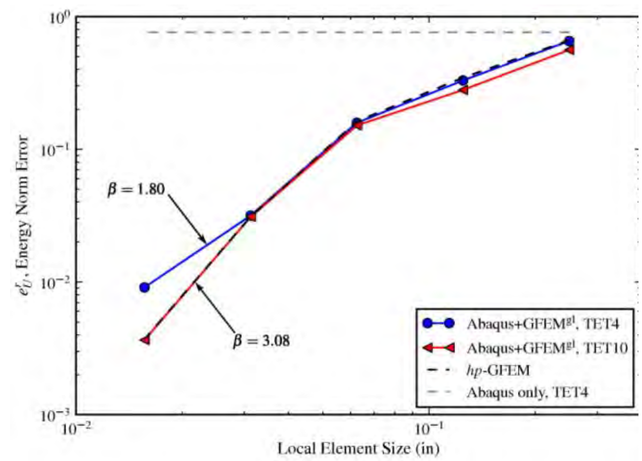

Figure Dua-3: Convergence of GFEM^{gl} implementation in Abaqus with respect to local mesh size. Convergence rates and error levels are competitive with those of the standard, optimal methodology (hp-GFEM).

Figure Dua-2 shows a representative BVP used to verify the Abaqus interface implementation: a three-dimensional aluminum beam subjected to a local laser heating. Here, the benefits of the GFEM^{gl} are twofold – global-local enrichment functions are able to capture sharp solution characteristics on the coarse Abaqus mesh, and also information from highly refined local problem meshes may be used to more accurately calculate the very sharp global loading, which would prove difficult in Abaqus otherwise. Figure Dua-3 shows that the non-intrusive methodology leads to optimal convergence of the global GFEM solution, even when using the standard FEM solver Abaqus in the global problem. Convergence is compared with the methodology that is considered optimal for solving problems of a similar nature, the state-of-the-art *hp*-GFEM. As further demonstration of its promise, the methodology implemented as part of this work was applied to a sample problem in which multiple analysis cases were required. In this instance, the exact same Abaqus global model was reused multiple times, since localized features are handled using the GFEM^{gl} alone in the GFEM code. This non-intrusive implementation in Abaqus provides added functionality and accessibility to the GFEM^{gl}, while streamlining the eventual extension of a two-solver environment to multiscale thermal strain fields.

B — Life Prediction: Identification and Definition of Structural Limit States

B2 Imperfections and Defect Tolerance of Aircraft Shells and Structures (Daniel Tortorelli, Seth Watts, Thomas Eason)

This project aims to develop a methodology to optimize functionally graded materials (FGMs) with applications in Spatially Tailored Aero-thermal Structures (STATs). The approach is to quantitatively characterize the microstructure of FGMs, with the goal of developing a mapping of the microstructure's phase morphology to the composite material properties. In conjunction with other projects, this will enable the ability to predict the properties of novel FGM materials, as well as to optimize FGMs in design applications.

In previous reports we have described the division of this work into sub-tasks, and noted the accomplishment of several of these. In particular, we described the development of a library of SEM images of the microstructure of a candidate FGM material and the development of morphological descriptors (the Minkowski valuations, or MVs) to quantify the microstructure of the FGM.

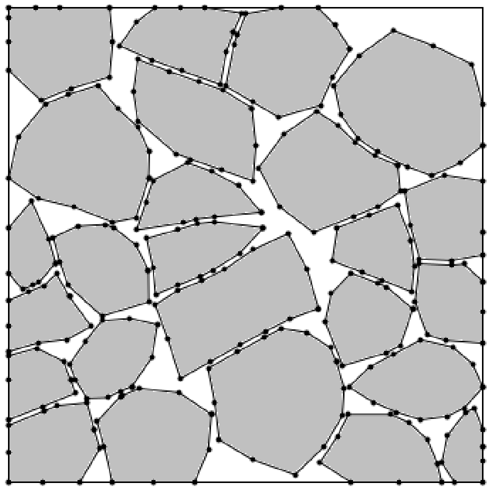

Figure Tor-1. Test of the topological non-overlap constraint. Objective is to fill domain to 80% area fraction while not allowing any particles to overlap or even touch.

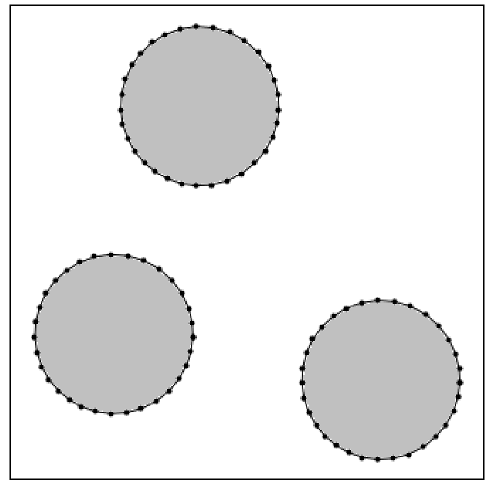

Figure Tor-2. Matching morphological descriptors. Objective is to move and distort three initially very small particles such that the final pattern has area fraction and perimeter of three discs with diameter one third the domain size, with pattern centroids at the center of the domain.

For the past year, we have been focusing on understanding the relationship between the MVs and material properties of interest. We can do this as a forward problem by generating random virtual specimens (with uncontrolled microstructure) and use software we have written to determine the homogenized material properties of the virtual specimens via finite element analysis. To fully understand the relationships between morphology and properties, however, we need to be able to generate specimens with a given target morphology. In this way we can observe directly what changes in the morphology have on material properties (versus coincidental changes caused by generating random images).

We pose this inverse problem as an optimization problem, i.e. we seek the state of parameters (roughly, the microstructure itself) that optimally matches a target morphology. In the previous report we noted that this inverse problem is ill-posed because the map from a microstructure to a finite morphological description is uninvertable. However, by placing a topological constraint on the morphology, we can at least define a pseudoinverse mapping, which makes the inverse problem tractable so long as the topological constraint is satisfied.

Satisfaction of the topological constraint is equivalent to ensuring that distinct pieces of the microstructure (which are controlled by our optimization parameters) do not overlap as we change the microstructure to match the target morphology. It is crucial that this constraint always be satisfied at every intermediate point in the optimization, since evaluation of the objective function is unreliable if it is not. We have written software to perform the optimization under this constraint, using techniques from contact mechanics. Figure Tor-1 shows a test of the constraint. Twenty-five small particles were initialized, and the optimizer was asked to fill the domain to 80% volume fraction, while ensuring the particles remain a finite distance apart. This simulation confirmed our constraint method works. We are now able to match target morphologies, at least for the first few orders of MVs. Figure Tor-2 illustrates satisfaction of area, perimeter, Euler characteristic, and area and perimeter centroid target values.

Our work now focuses on improving the conditioning of the inverse problem to speed solutions and improve matching, and to remove some ad hoc approaches and replace them with methods that have provably good properties.

B3 3-D Cyclic Plasticity Model for Thermo-mechanical Loading in Large-scale Analyses (James Sobotka, Robert Dodds, Brian Gockel)

The coupled interaction of air flow, thermal effects, and the structural response on hypersonic aircraft platforms produces severe, thermo-mechanical loading histories during flight profiles. Combined thermal and mechanical loading alters the elastic-plastic material response of structural alloys. For example, the yield stress of Hastelloy X decreases progressively by 80% over the temperature range from 70°F to 2000°F. Further, cyclic loading induces additional behavior (ratcheting, stress relaxation, Masing) that contributes to fatigue damage and crack nucleation.

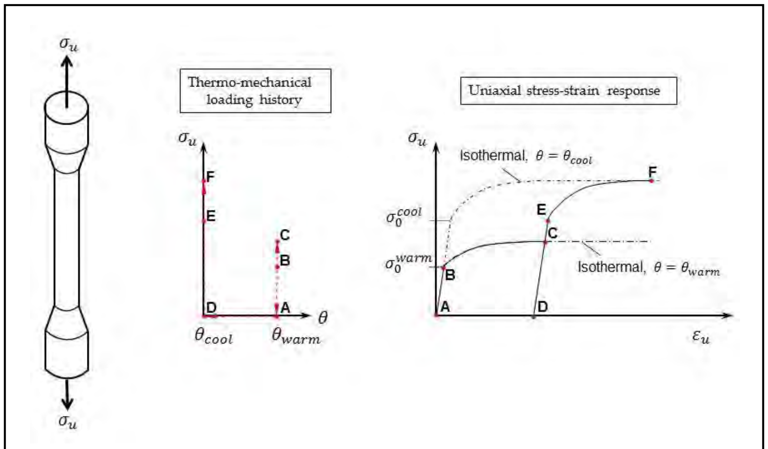

Figure Sob-1: Pre-strain effect on the universal elastic-plastic response under a cyclic, thermo-plastic loading history captured by the GP model with thermal effects.

The Generalized Plasticity (GP) model provides a novel approach to incorporate cyclic loading effects on the material response into 3-D finite element analyses. Auricchio and Taylor (1995, Int. J. Plas.) originally defined the GP model for cyclic mechanical loading of structural alloys. Material parameters

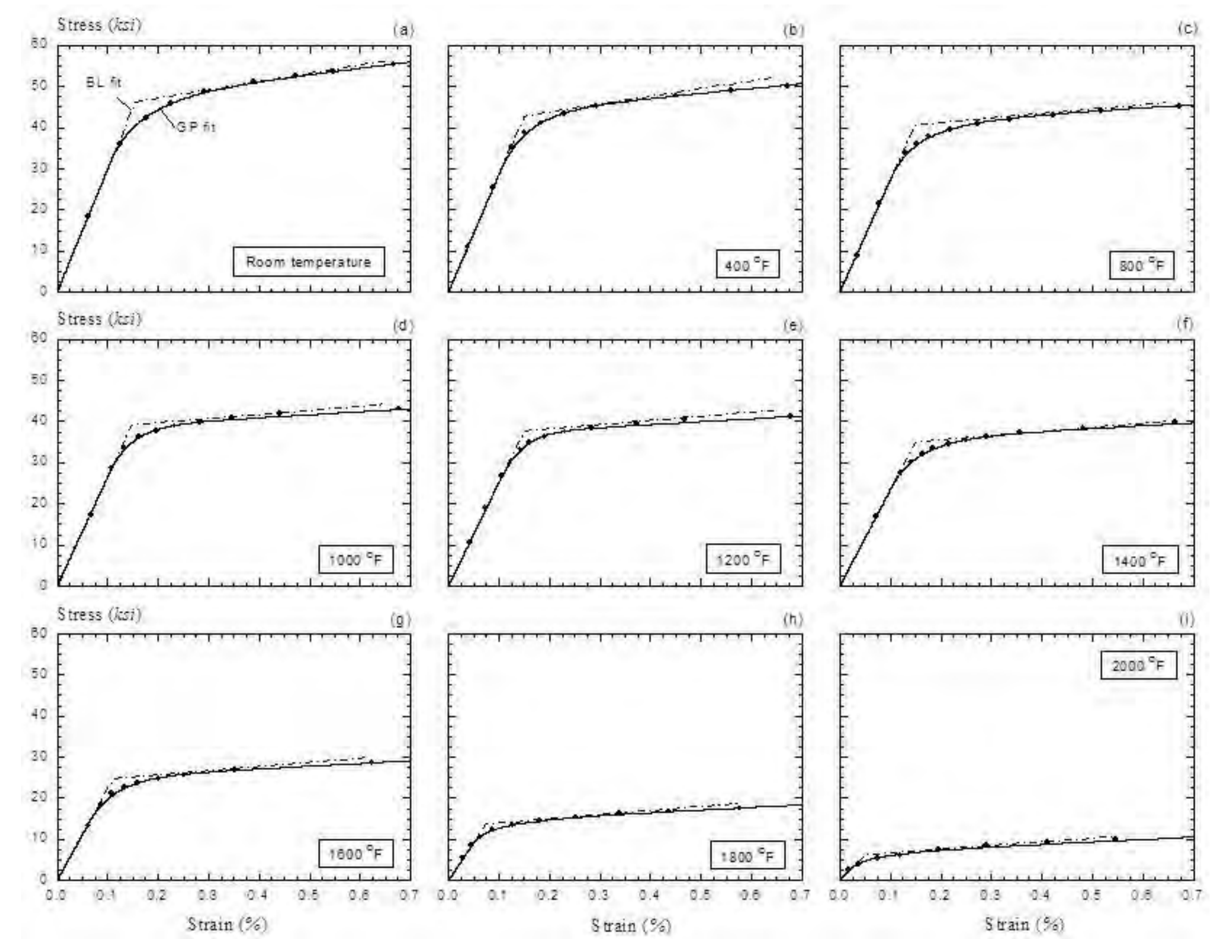

Figure Sob-2: Generalized Plasticity (GP) and BiLinear (BL) fit of Hastelloy X uniaxial stress-strain data.

Approved for public release; distribution unlimited.

within the GP model provide control over ratcheting rates and mean stress relaxation. The GP model introduces renewed plasticity (plastic flow reinitiates during reloading before reaching the previously attained flow stress) into the material rate equations.

Prior to work performed over the past year, the GP model was formulated only for isothermal material properties. Work in Project B3 has focused on the development, implementation, and verification of a modified GP model with temperature-dependent, material properties. A series of technical reports document this work and are available upon request.

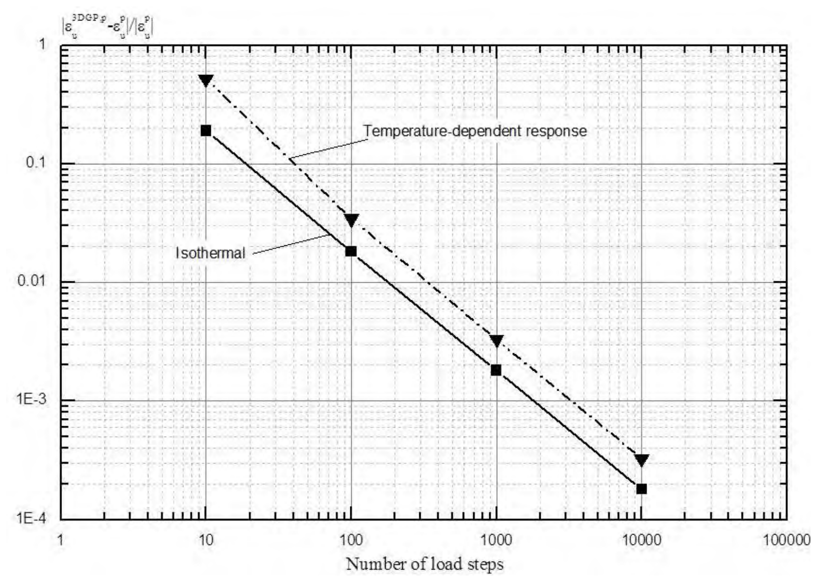

Figure Sob-3: Convergence of the modified GP model to an analytical solution with and without temperature effects.

The modified GP model reflects key features of the elastic-plastic material response, e.g., the pre-strain effect illustrated in Figure Sob-1. Here, a uniaxial specimen is loaded at a warm temperature well into yield, unloaded, cooled, and then reloaded to yield at a cool temperature. An analysis of this loading history with the modified GP model shows a temperature-dependent response that cannot be captured by existing thermo-cyclic material models. Figure Sob-2 shows that the GP model improves fits to uniaxial stress-strain data at nine isothermal temperatures for Hastelloy X compared to the bilinear hardening model that has been employed by previous studies.

Work in Project B3 is incorporating the 3-D GP model with thermal effects into WARP3-D - a highly-parallel, open-source, finite element code for nonlinear solid mechanics problems. The numerical implementation of the GP material model employs a backward Euler integration scheme that remains stable under large load increments. The consistent tangent minimizes the number of global iterations needed to reach an equilibrium configuration during the implicit solution. Figure Sob-3 shows convergence of the GP implementation to an analytical solution derived with and without temperature effects. Adaptive integration of the governing GP rate equations further reduces truncation error and improves the accuracy of the material point calculations.

Ongoing work in Project B3 also integrates high-fidelity, finite element analyses of structural components with the multi-physics/multi-scale approach adopted by the AFRL. Coupled fluid-thermal-structural analyses, performed by Dr. Adam Culler produce thermo-mechanical loading histories for ramp panel geometries. In Project B3, we impose these loadings on representative structural proxies to determine the thermo-plastic material response that drives life prediction estimates of Project B4. Such analyses demonstrate viability of the AFRL framework to improve life prediction estimates.

C — Life Prediction: Framework and Methodologies for Risk-quantified Structural Assessment

C1 Uncertainty/Risk Quantification Methods for STATS (Junho Song, Young Joo Lee, Eric Tuegel)

Aircraft structures are often subjected to the risk of progressive failure caused by fatigue crack growth under repeated loadings. However, due to uncertainties in materials, loadings and mathematical models, and the complex effects of load re-distributions, it is a challenging task to estimate the reliability of aging aircraft pertaining to crack growth. The goals of this research project are: (i) to develop novel system reliability analysis methods for estimating the probability of system-level failure caused by fatigue and for identifying critical failure sequences; (ii) to integrate the developed methods with advanced finite element (FE) simulations of aircraft structural systems; and (iii) to suggest a new framework for updating the estimated failure probability based on inspection results. The outcomes of the research will make crucial contribution to the risk-based life forecasting and condition-based maintenance of aircraft structures.

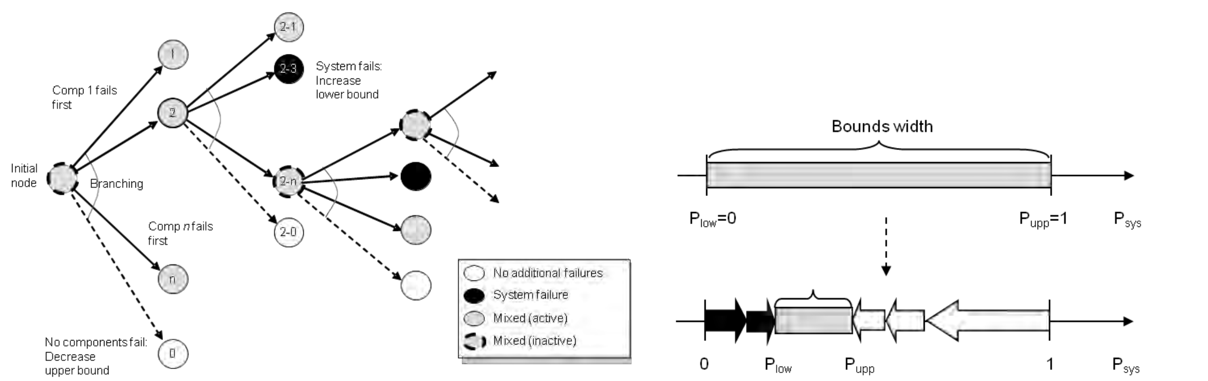

Figure Son-1. Procedure of the B^3 method: searching for critical failure sequences (left) and updating of the bounds on the system failure probability (right).

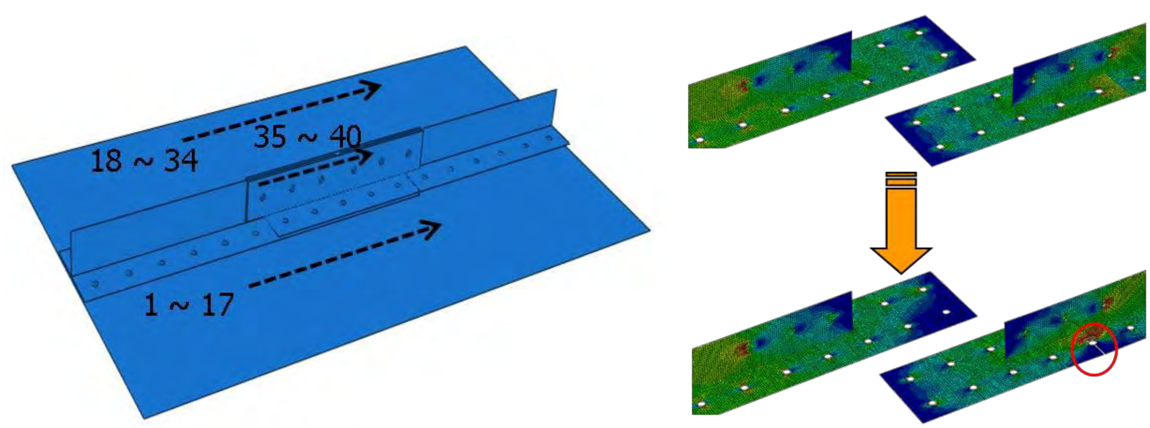

Figure Son-2. Details of the longeron FE model: fastener hole numbers (left) and the stress change caused by a local cracking failure (red circle on the right).

Based on a literature review and discussions with other researchers in MSSC, we developed a new Branch and Bound method employing system reliability Bounds, termed the ―B^3 method.” Figure Son-1 illustrates the procedure of searching for critical failure sequences (left) and the corresponding updating of the bounds on the system failure probability (right). The method enables us to estimate the risk of progressive failure accurately while minimizing the cost of finite element (FE) analysis. In addition, the method can identify most critical failure sequences in the decreasing order of their probabilities. The B^3 method was successfully demonstrated by a three-dimensional truss structure. A journal paper on this study has been accepted in the *Journal of Engineering Mechanics*.

The B^3 method was then generalized for continuum structures. In order to test the applicability of the generalized B^3 method to continuum aircraft structures, an FE model of an aircraft longeron system was developed through collaboration with other MSSC researchers including Prof. Harry Millwater (Univerity of Texas at San Antonio) and Luciano Smith (Southwest Research Institute). A detailed mechanism of fatigue-induced sequential failures of the generic aircraft longeron was formulated through collaborations as well. The developed FE model simulated fatigue-induced local failures so that the load re-distributions caused by sequential failures could be considered during the B^3 analysis. Figure Son-2 shows the details of the developed FE model including locations of the fastener holes (left) and an example of stress re-distribution caused by a local cracking occurred around a fastener hole (right). The generalized B^3 method was successfully applied to the longeron structure, and Table Son-1 shows a variety of critical system-failure modes identified by the B^3 analysis.

Failure sequence	Probability ($\times 10^{-3}$)	Yielding material	Yielding location
11	4.448	aluminum	around #11 hole
28	4.448	aluminum	around #28 hole
22 → 5	0.480	steel	#35 fastener
5 → 22	0.480	steel	#35 fastener
23 → 11	0.282	aluminum	around #11 hole
6 → 28	0.282	aluminum	around #28 hole
6 → 22 → 4	0.109	steel	#35 fastener
23 → 5 → 21	0.109	steel	#35 fastener

Table Son-1. Critical failure sequences in the longeron identified by the generalized B^3 method

Currently, the generalized B^3 method is being integrated with a Bayesian approach to update the reliability estimates by the B^3 method based on the results of inspection on fatigue crack growth. Tests by discrete structural systems showed that the B^3 method enables the Bayesian approach to update the probability of the system-level failure based on various types of inspection results efficiently and accurately. The new updating approach is being tested by the developed longeron FE model under a variety of inspection scenarios. The developed method is expected to provide an effective probabilistic framework for condition-based maintenance of aircraft systems.

C2 Validation of Simulations Having Uncertainties in Both Simulation and Experiments (Jason Gruenwald, Mark Brandyberry, Ben Smarslok)

The goal of this project is the development of a robust methodology for the validation of complex structures simulations under the presence of uncertainty. This methodology will allow the propagation of uncertainties through a computational model for comparison with experimental data, while minimizing the computational expense. A curved beam under harmonic loading was selected as a simple surrogate problem that is similar to the vibration of thin-skinned panels on aircraft. Experiments on curved beams, Figure Gru-1, were conducted at WPAFB to generate data for the methodology.

The process uses the *Reduced Order Clustering Uncertainty Quantification* (*ROCUQ*) methodology developed at Illinois[1]. The ROCUQ method allows for uncertainties in simulation input parameters to be efficiently propagated through computationally expensive simulation models, in order to generate distributions of output parameters of interest (System Response Quantities, or SRQs). These simulation distributions can be created and compared to experimental data (which also has uncertainty associated with it).

The foundation of the ROCUQ method is the use of Reduced Order Models (ROMs) to decrease computational expense and, most importantly, model the trends in SRQs.

Progress has been made in creating a ROM for the vibrating beam. The Implicit Condensation and Expansion (ICE) method was chosen for the ROM[2]. This method satisfies the requirements of ROCUQ – it is fast running and has the ability to model all of the uncertain parameters in the simulation. The ICE method has also been show to model nonlinear displacements accurately for a similar problem[2]. ICE leverages commercial FEA programs to perform a regression analysis of static nonlinear test cases to find nonlinear equations of motion. Direct integration is then used on the equations of motion to determine displacements, strains, and stresses. Using straight and curved beam problems as described in Reference 2, Abaqus simulations were performed and compared to ICE results. Figures Gru-2 and Gru-3 show the comparison for harmonic loading for the straight and curved beams, respectively. The results are nearly exact for the straight beam case, whereas, there are discrepancies in the curved beam. These discrepancies are being investigated and once resolved, the ROM will be considered verified. The uncertain parameters that are going to be modeled in the simulation include: geometric parameters (width, thickness, radius of curvature); material properties (Young's modulus, Poisson's ratio, density); and the loading amplitude and frequency.

Figure Gru-1: The beam fixed in the testing apparatus and mounted on the electromagnetic shaker.

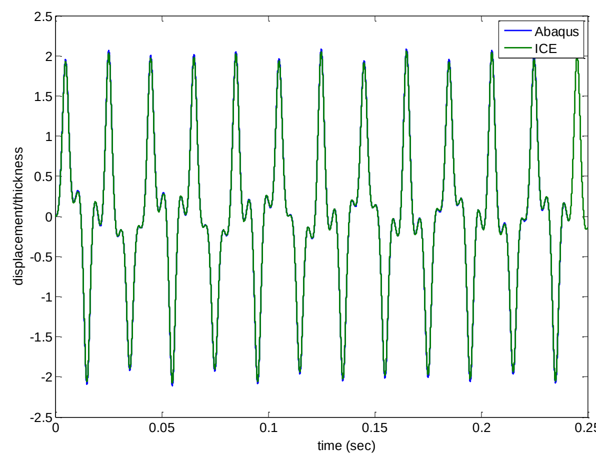

Figure Gru-2: Center displacement/thickness vs time plot for straight beam under 0.2 psi harmonic loading at 50 Hz. Simulations conducted by Abaqus and Matlab ICE program are compared and are nearly identical.

The experimental setup is described in Ehrhardt[3]. A clamped-clamped curved beam was subjected to swept sine tests with a base excitation of 9g's and at a rate of 55 Hz/s over the frequency range of 60-430 Hz. Two high-speed cameras with a resolution of 1024x512 pixels operating at 3000 fps were used to capture the images. Data from these experiments will be used to validate the simulations and ROCUQ methodology.

With the completion of the ROM, the ROCUQ methodology will be used to perform an uncertainty propagation through the simulation, with an SRQ of the RMS value of the beam center displacement. The resulting cumulative distribution function(s) (CDF) for the SRQ(s) will be compared to similar CDF(s) from the

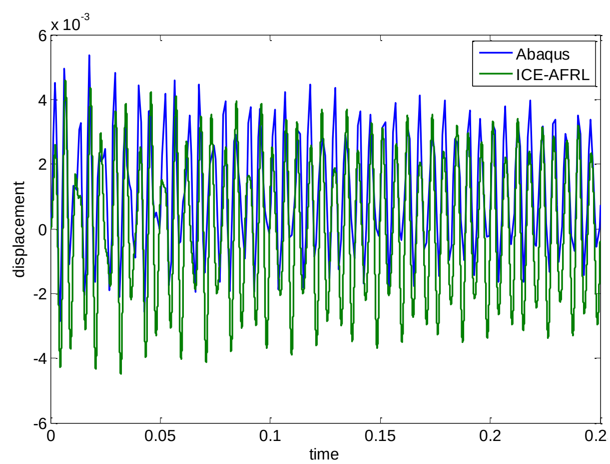

Figure Gru-3: Center displacement vs time plot for curved beam under 0.1 psi harmonic loading at 180 Hz. Simulations conducted by Abaqus and Matlab ICE program are compared.

experimental data, including the uncertainty estimates in both.

1. Brandyberry, M. D., 2008. “Thermal Problem Solution Using a Surrogate Model Clustering Technique,” *Computer Methods in Applied Mechanics and Engineering*, Vol. 197(29-32), pp. 2390-2407.
2. Hollkamp, J. J., Gordon, R. W., 2008. “Reduced-order models for nonlinear response prediction: Implicit condensation and expansion.” Journal of Sound and Vibration. Vol 318.
3. Ehrhardt, David et al., 2011. “Non-Contact Experimental Modal Analysis of a Curved Beam Using a Full Field Optical Technique,” *52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. AIAA, Denver, Colorado.

C2 Tudor Simulation and Force Analysis of a T-38 Performing a Touch-And-Go Maneuver (Andy Tudor, Mark Brandyberry, Eric Tuegel)

This project involves deriving a framework for taking aircraft flight recorder data and simulating aircraft surface loading along a flight path using computational fluid dynamics (CFD), and then developing force information from the CFD surface pressure results for a USAF T-38. The force data is used to simulate forces on the aircraft in a structural mechanics program, ultimately to obtain stress information at several key locations. The CFD simulations are performed in a static sense where the T-38 is simulated at specific “points in the sky” without the inclusion of changing orientation or velocity during each CFD simulation. A series of 10 points were chosen from a 51 second touch-and-go maneuver by observing points along the flight-path where the speed and/or orientation of the aircraft changed significantly. Simulation results are then compared with thin airfoil theory to assess the reasonableness of the simulation.

The flight profile used in the current work was taken from an actual touch-and-go landing performed by a T-38. A suite of sensors on board the aircraft comprise the data collection process. In order to obtain a flight profile the following variables have been examined: translational accelerations, angular rates, angle of attack, time and landing gear up/down. Using these variables the T-38 body frame translational velocities as a function of time may be derived.

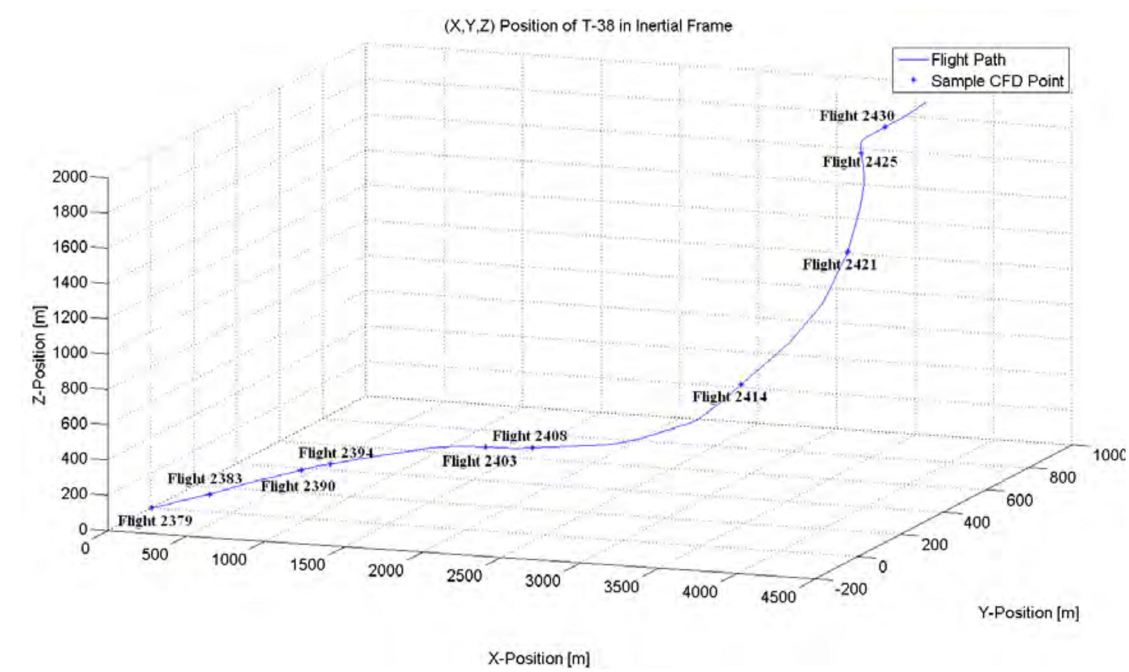

Figure Tud-1: T-38 inertial position.

Figure Tud-1 shows the Cartesian coordinate flight path for the takeoff and initial turn of the aircraft in the touch and go run. The points along the flight path where CFD simulations are performed are noted on the line with the four digit numbers denoting a number of seconds since recording began for the flight. Notice the aircraft begins its flight with a small angle of attack then begins to turn at 2408 seconds (the "Flight 2408" point in Figure Tud-1). The aircraft first performs a roll then begins to pitch causing the aircraft to turn. Using the orientation of the T-38, the translational velocity of the aircraft in its body frame is calculated. The translational velocity is the essential information for performing a CFD simulation at a specific time in the sky. Since the aircraft is not changing orientation or velocity quickly along this flight-path the points chosen along the path will generate a reasonable first-order approximation to the surface pressure loads on the aircraft.

These velocities are input as boundary conditions directly into the CFD solver (The *Rocflu* unstructured mixed-mesh solver in the *Rocstar Simulation Suite)*. At each CFD point-in-the-sky, the T-38 flow field is run to steady-state in order to produce the resulting pressures, and thus surface forces on the aircraft. The CFD grid is composed of 126737 unstructured four-node tetrahedral elements. This generates 49588 elements on the surface of the aircraft. This grid is then enclosed in a cube where the inflow velocity and orientation boundary conditions can be specified. The boundary conditions used are the body frame translational velocities as discussed previously. As a result, the only differences between the 10 simulations are the boundary conditions that control the simulated orientation and velocity of the aircraft. When each simulation of a point in the sky is complete, the tractions are stripped off of the surface of the aircraft and converted to element based forces. These forces are then provided to AFRL analysts for computation of the structural response of the aircraft. Figure Tud-2 shows one simulated pressure distribution on the surface of the aircraft for point-in-the-sky 2408. A variety of drag, lift and force checks are performed on the CFD pressure field results to ensure that reasonable values are being generated by the calculated flowfield. The *Rocstar* CFD results are compared to results from *Aeromatic*, *XFOIL* [1] to grossly verify the CFD simulations. Ongoing work involves simulating further points in the sky to generate a better characterization of the flightpath, performing a grid refinement study, and investigating the use of overset mesh/moving grid CFD technologies in the *Rocstar Simulation Suite* to perform a continuous flightpath simulation of the touch and go maneuver.

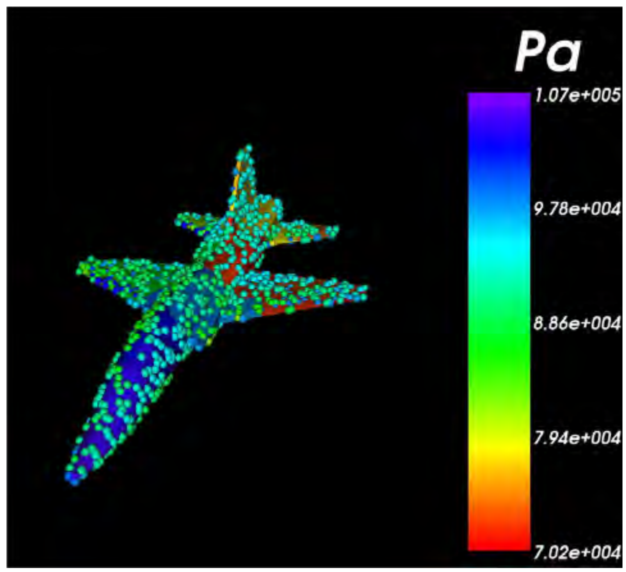

Figure Tud-2: T-38 Flight 2408 at steady state.

1. Fundamentals of Aerodynamics, Fourth Edition, John D. Anderson Jr.

C5 Probabilistic Cohesive Zone Model for Fiber Bridging (Ravi Penmetsa, Bhushan Kable, Vankat Shanmugam, Eric Tuegel) Completed in 2010

The main focus of this research is to validate the probabilistic cohesive zone model calibration process using known material test data. In our previous research, probabilistic cohesive zone model was developed using test results from an unknown aluminum material. Currently AFRL is testing unidirectional composite material (IM7/977-3) using double cantilever beam (DCB) specimens with and without Z-pins. Z-pins are inserted in Z-direction of the laminate to increase the strength of the composite.

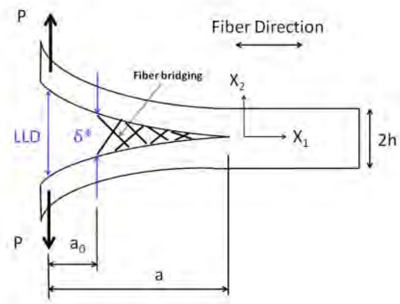

Figure Pen-1: DCB specimen.

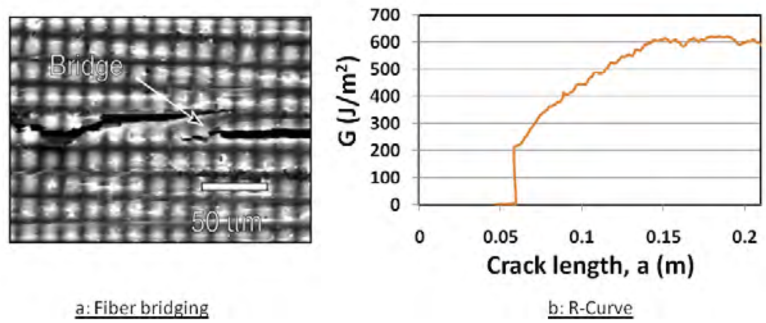

Figure Pen-2: Fiber bridging and R-Curve effect.

Delamination between plies is the most common failure mode one can see in composite laminates and it occurs at the free edges like holes and notches in a laminate. The interply delamination can cause fiber breakage and reduce the life of the composite. Generally Mode-I interlaminar fracture toughness or critical energy release rate of a composite is measured using double cantilever beam (DCB) with unidirectional composites (ASTM D5528). Unlike metals, energy plot of a DCB specimen's shows increase in energy release rate with increase in crack length. This is due to fiber cross-over bridging at the interface between the top and bottom arm of DCB. During fiber bridging, shown in Figure Pen-2a, a crack jumps from one fiber/matrix interface to another without breaking the fiber. This occurs only in unidirectional composites where the fibers migrate during curing process of composite preparation. The increase in energy release rate with respect to crack length is called R-curve effect as shown in Figure Pen-2b. Sorensen and Jacobsen indicated in their research that the behavior of R-curves depends on specimen geometry and therefore R-curve cannot be considered as material property when large-scale bridging phenomenon occurs. Large-scale bridging occurs whenever the length of the crack at fiber bridging is equal to or greater than the geometry size.

Since unidirectional composite DCB specimen test results are available from AFRL, this research uses the known test data to develop a probabilistic cohesive zone model for fiber bridging. First this research will focus on developing probabilistic cohesive zone models for fiber bridging (without Z-pin). Then this research will identify an efficient method to predict load vs load line displacement scatter for different geometries. Finally, the test results are compared with the predicted numerical results to identify any discrepancies. Any discrepancies that are identified in this process will be addressed by performing targeted tests and calibration processes to improve the confidence of the simulation tools. Using the probabilistic cohesive zone models a simulation tool will be developed for predicting the delamination behavior of DCB specimens.

C6 Enriched Space-time Finite Element Method — (Dong Qian, Y. Yang, S. Chirptukar, D. N. Alpert, Thomas Eason, S. Michael Spottswood)

Professor Qian and his colleagues developed a general formulation of the enriched space-time finite element method for solving structural dynamics applications that are of interest to the Air Force. By formulating the multiscale approximation within the context of the extended space-time finite element method, the goal is to integrate the physics that are governed by different characteristic temporal scales. Compared with the implementations without the enrichment, the proposed method provides extended capabilities in multiscaling in both the spatial and temporal domains.

For the analysis of structural dynamics problem, the use of enriched space-time method not only inherits some of the basic features of space-time FEM in reducing the oscillations and producing stable results that are high-order accurate, it also provides extended capabilities in capturing multiscale temporal responses. In particular, it alleviates the need for temporal mesh refinement, which can be tedious in implementation without the enrichments.

We have developed a set of benchmark problems in both one-dimension and two-dimension (example problem shown next page, Figure Qia-1 and Qia-2) to evaluate the robustness of the proposed approach. The accuracy is measured in terms of the error estimates, i.e., the difference between the analytical and numerical solution. It is shown that multiscale space-time FEM enjoys superior convergence properties over the traditional space-time FEM (Figure Qia-3) and the proposed method represent a new paradigm towards resolving structural and solid mechanics problems with strong temporal nonlinearity.

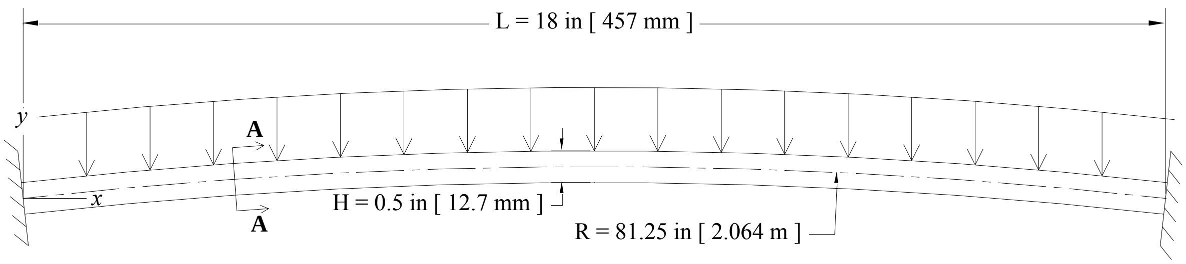

Figure Qia-1: Slender curved beam subjected to dynamic transverse pressure.

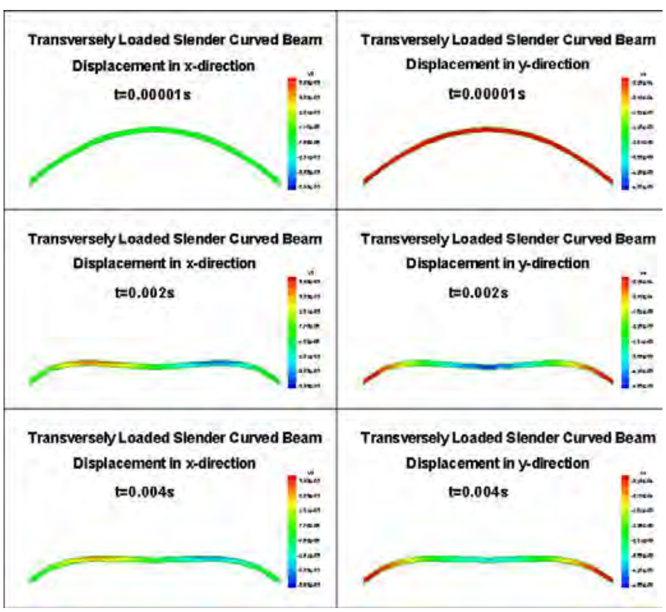

Figure Qia-2: Simulation of transversely loaded slender curved beam subjected to pressure load.

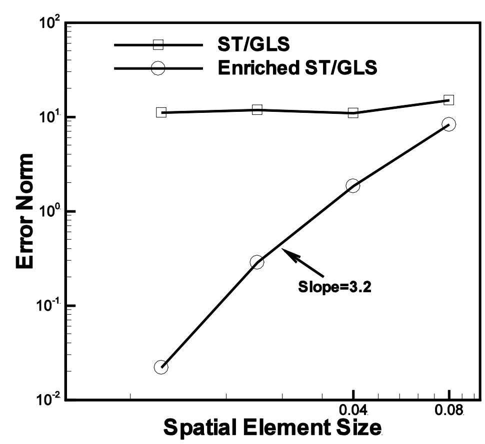

Figure Qia-3: Error norm vs. spatial element size between regular and enriched space-time solutions.

D — Experimental Discovery and Limit State Characterization

D2 Development of Novel Experimental Techniques for Validating a Coupled Thermomechanical Fatigue Simulation Framework (Jay Carroll, John Lambros, Ravi Chona, Mallory Casperson, Wael Abuzaid, Huseyin Sehitoglu, James Sobotka, Robert Dodds) Completed May 2011

Microstructural variability, even for globally similar microstructures can make a significant difference when it comes to fatigue lifetimes. In this project, multiscale experiments were performed to study of the relationship between fatigue crack growth, local strain fields, and microstructure. Using experimental techniques developed for this project in previous years, fatigue crack growth in a nickel-based superalloy, Hastelloy X, was studied at the microstructural scale.

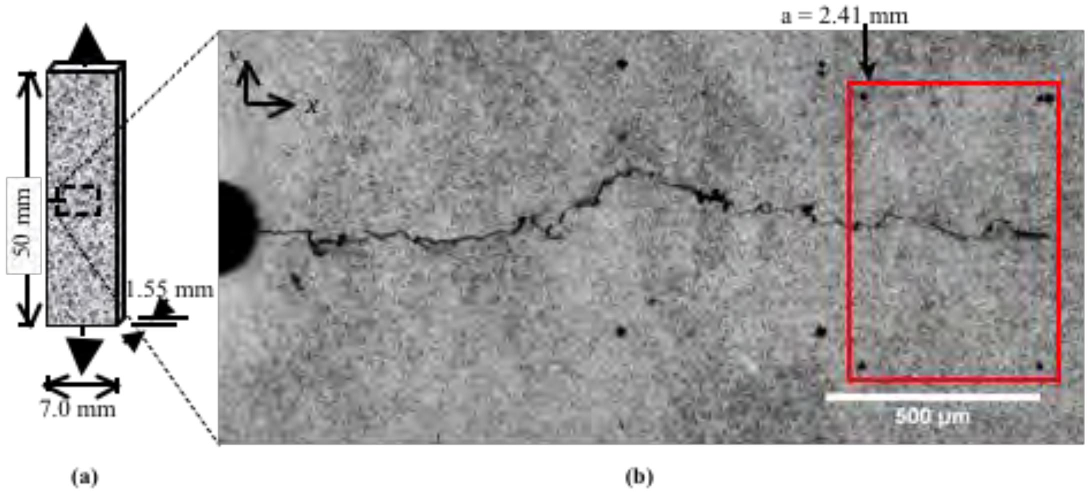

Figure Car-1: (a) Specimen dimensions. The notch length is 1 mm. (b) Macroscale region of interest showing the crack path through the specimen. The microscale region of interest is outlined in red (412 μm x 629 μm).

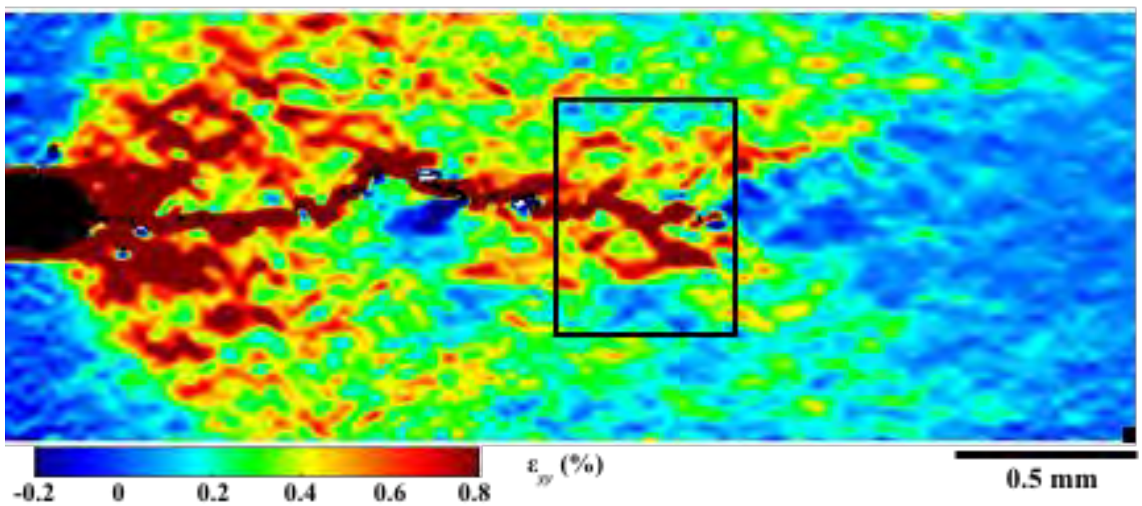

Figure Car-2: Ex situ strain field, εyy, over the macroscale field of view at 5x magnification. The micro-scale region of interest is outlined in black.

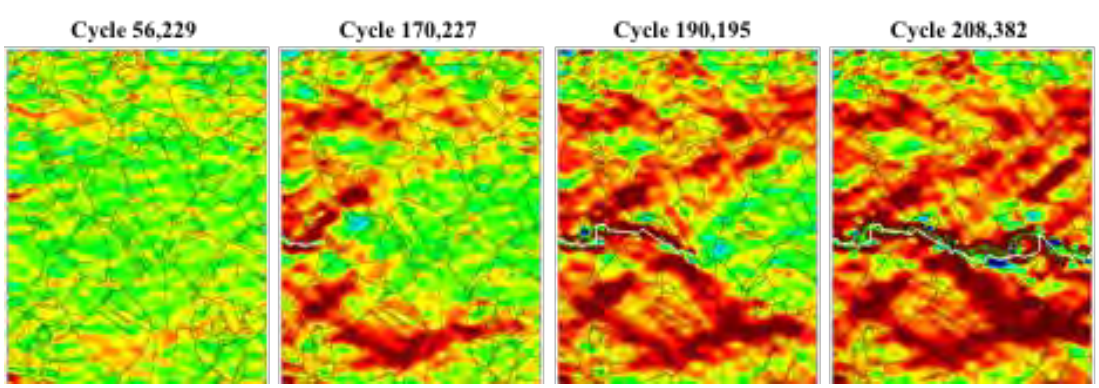

Figure Car-3: In situ development of the strain field with crack propagation. Cycle number is shown below each strain field, and grain boundaries obtained from EBSD are overlaid onto the strain field for comparison to microstructure.

A single edge notched tension specimen was fatigue loaded ($\Delta K \approx 18$ MPa$\sqrt{m}$, $R \approx 0.1$) to propagate a crack from the notch tip. Specimen dimensions and the crack path are shown in Figure Car-1. Before fatigue loading, electron backscatter diffraction (EBSD) was used to gather microstructural information (grain geometry and orientation) throughout the microscale region of interest outlined in red in Figure Car-1b. Additionally, image arrays of the macroscale (entire Figure Car-1b) and microscale regions of interest were captured as reference images for digital image correlation (DIC). The macroscale region was imaged using three partially overlapping images at 5x magnification (0.87 µm/pix), and the microscale region was imaged with 36 partially overlapping images at 50x magnification (0.087 µm/pix).

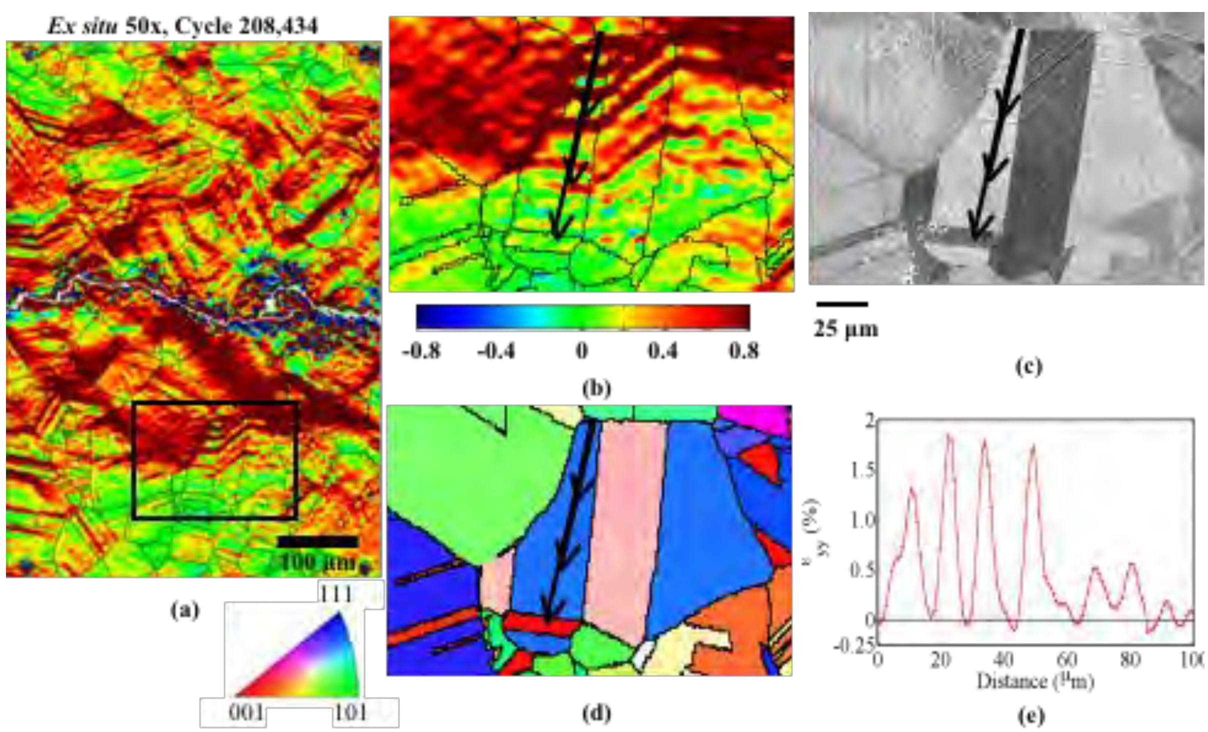

Figure Car-4: (a) Ex situ strain field, εyy, throughout microscale region after 208,434 cycles. (b) A portion of the strain field shown in (a) enlarged to show strains associated with slip bands. (c) The same region imaged with backscatter electron imaging (d) Grain orientation throughout the magnified region (e) Plot of ε_{yy} (vertical) strain along the line indicated in (b-d). Strain within slip bands is around 2% with unstrained regions between bands.

Crack initiation from the notch took approximately 9,000 cycles. As the crack grew across the specimen, images of the microscale region were captured every 16 cycles using an in situ optical microscope at 10x magnification (0.44 µm/pix). The crack tip entered the microscale region of interest around cycle 166,000 and grew through the region for 42,000 cycles until the fatigue loading ceased at 208,434 cycles. The specimen was then removed from the load frame and the ex situ microscope was used to capture image arrays of both regions corresponding to the image arrays before loading.

DIC was used to calculate strain fields in both regions of interest. The residual vertical strain, ε_{yy}, throughout the macroscale region from 5x DIC results after 208,434 cycles of loading is shown in Figure Car-2. Although globally a mode I loading, the plastic wake left behind the growing fatigue crack demonstrates a considerable amount of inhomogeneity primarily due to microstructural effects.

Additionally, the 10x magnification in situ images of the microscale region were correlated and aligned with EBSD measurements of microstructure to study the progression of crack growth with respect to the microstructure. Figure Car-3 shows ε_{yy} strain fields at certain cycles obtained from the real time imaging with grain boundaries drawn in black and the crack path in white. The plastic wake associated with fatigue crack growth is seen to grow by two lobes emanating forward and moving along with the crack tip. Strain localizations are observed at angles ahead of the crack tip, but little strain is observed directly ahead of the crack tip. Furthermore, strain localizations appear to accumulate within collections of grains.

The in situ DIC measurements shown in Figure Car-3 are grain level measurements, but the ex situ image arrays of the microscale region at 50x magnification allows DIC measurements with sub-grain level resolution. An example of this is shown in Figure Car-4. The ε_{yy} strain field throughout the microscale region is shown in part (a). A portion of this field, outlined by a black rectangle, is magnified in part (b) to show details of strains associated with slip bands that traverse twin boundaries. For comparison, a backscatter electron image of the magnified region and the grain orientation throughout this region are shown in Figure Car-4(c-d), respectively. A line scan along the arrows shown in these figures reveals strains near 2% within the slip bands and relatively strain-free regions between bands (Figure Car-4e).

The techniques developed in this project provide quantitative measurements of fatigue crack growth at the microstructural level. In addition to elucidating the relationships between microstructure, fatigue crack path, and strain localizations, this information will prove valuable for researchers developing microstructurally-informed fatigue models to improve fatigue life predictions.

D3 Thermomechanical Fatigue of Hastelloy X: Role of Combined Loading on Material Response (Wael Abuzaid, Huseyin Sehitoglu, Ravi Chona, Jay Carroll, Mallory Casperson, John Lambros, Robert Dodds, James Sobotka, Alpay Oral)

The scope of this project is twofold: first, to experimentally investigate the response of Hastelloy X under thermo-mechanical fatigue loading conditions utilizing multiscale full field measurements techniques; second, to develop a deeper perspective of grain level damage evolution during cyclic loading and how it affects macroscale fatigue response. Throughout the past year, the focus was on studying the role of microstructure in the development of local plastic strain heterogeneities in the material. We have particularly emphasized on analyzing the differences in grain boundary (GB) resistance to slip transmission and the impact it has on plastic strain magnitudes and incompatibilities in the vicinity of GBs. A better understanding of these strain incompatibilities is important as it relates to damage nucleation during fatigue loading. This part of the work aids the current modeling efforts in Project B4 that aims to develop a fatigue initiation theory for multiaxial fatigue loading.

To this end, we use a combination of high-resolution ex-situ digital image correlation (DIC) and electron backscatter diffraction (EBSD) to measure deformation heterogeneities in the uniaxial plastic response of polycrystalline Hastelloy-X. Figure Abu-1a shows a grain orientation map of a selected region investigated in this work. The specimen was deformed in uniaxial tension and the total residual strain was 2% nominal strain. Reference and deformed images for DIC were captured using an optical microscope at 31x magnification (0.14 μm/pix). The three in-plane components of the plastic strain tensor were measured spatially in the region of interest. Figure Abu-1b shows the contour plot of ε_{yy} (the largest strain component, i.e., along loading direction). The full field DIC measurements reveal a high level of heterogeneity in the plastic response with local residual strain magnitudes ranging from 0 to 6%. This experimental and analysis procedure provides pointwise comparisons between strain fields (from DIC) and microstructure (from EBSD), and thus, it enables quantitative analysis of local deformation in the vicinity of each and every GB within the field of view of the polycrystalline aggregate.

Traces of the activated slip systems can be seen on the sample's surface as shown in Figure Abu-2a. Observing and identifying the slip systems associated with the slip traces is an approach typically used to determine the activated slip systems (12 possible for fcc materials). For example, grain G3 in Figure Abu-2a shows clear activation of the slip plane (blue line) and the plane (red line). An alternative method for determining the active slip systems, *quantitatively*, utilizes the measured macroscopic plastic strains and crystal orientation to solve for the crystallographic shear strains on individual slip systems. Solving for these scalar quantities at each spatial point yields local information about slip system activation across the selected region. Contour plots of the 12 possible slip systems were generated for the entire region of interest. For the sake of brevity, in Figures Abu-2b-2e, we only show the ones with the highest shear strains in same region shown in Figure Abu-2a. Different slip systems were activated in various spatial regions of each of the grains, e.g., certain slip systems show activity in the vicinity of some GBs but not others. This information regarding slip system activity across GBs is important for the study of slip transmission and how it relates to the development of strain incompatibilities that eventually initiate fatigue cracks.

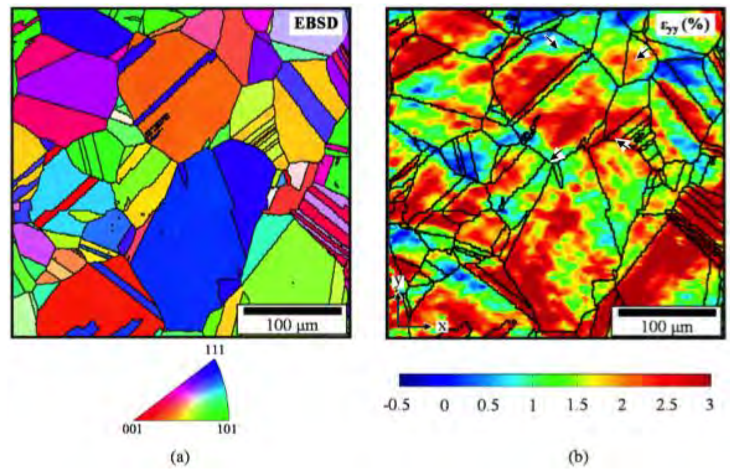

Figure Abu-1: (a) EBSD grain orientation map of a select region; (b) Contour plot of the vertical strain field (ε_{yy}). High strains above 3% are detected in the vicinity of grain boundaries (indicated with arrows).

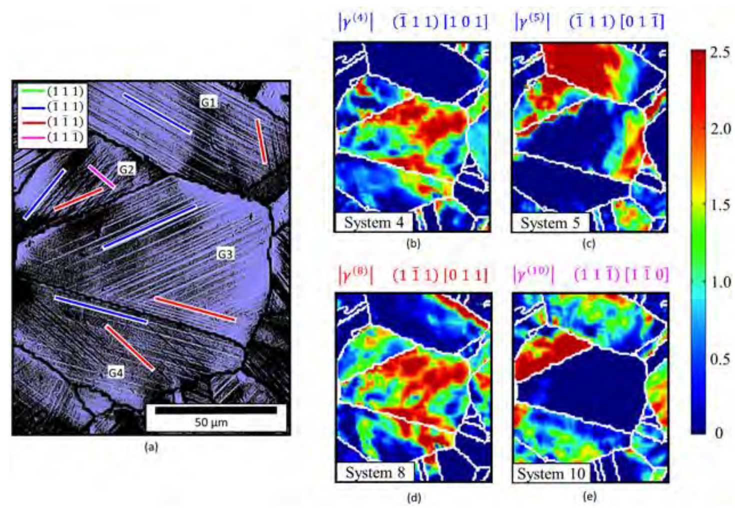

Figure Abu-2: (a) SEM micrograph of the deformed sample; (b-e) Contour plots of the crystallographic shear strains of the same region shown in (a). Different slip system activity in different regions is clearly seen. Some systems are only activated in the vicinity of some grain boundaries.

One of the possible outcomes of dislocation-grain boundary interaction is partial slip transmission of the incoming slip across the GB. This process leaves a residual dislocation, with Burgers vector $\boldsymbol{b}_r$, in the GB plane. The experimental results available from our current efforts enable us to investigate the relationship between $|\boldsymbol{b}_r|$ and the magnitude of strains across GBs due to slip transmission. Figure Abu-3 shows an example of transmission through a selected GB. From the SEM micrograph (Figure Abu-3a), we see continuous slip traces across the GB. Figure Abu-3b shows contour plots of the shear strains for the incident and transmitted slip. The continuity of slip traces and the high shear strains across the interface is associated with slip transmission across this GB. This reaction results in $|\boldsymbol{b}_r| = 0$, i.e., cross slip of the incident dislocation across the GB with no residual dislocation at the GB plane. We note that for this magnitude of $\boldsymbol{b}_r$, high shear strains were measured across the interface. Other observed slip transmission reactions result in higher magnitudes of $\boldsymbol{b}_r$ (not shown in this report), and exhibit high strains in the incident dislocation side and relatively lower strains in the transmitted dislocation side across the GB. At low $|\boldsymbol{b}_r|$, the higher shear strains on both sides across the GB are attributed to lower GB resistance to slip transmission. On the other hand, at high $|\boldsymbol{b}_r|$, the lower strains in the transmitted slip side indicate higher GB resistance to slip transmission. These observations point out that the magnitude of the residual Burgers vector is essential for describing the local strain magnitudes and heterogeneities in the vicinity of GBs.

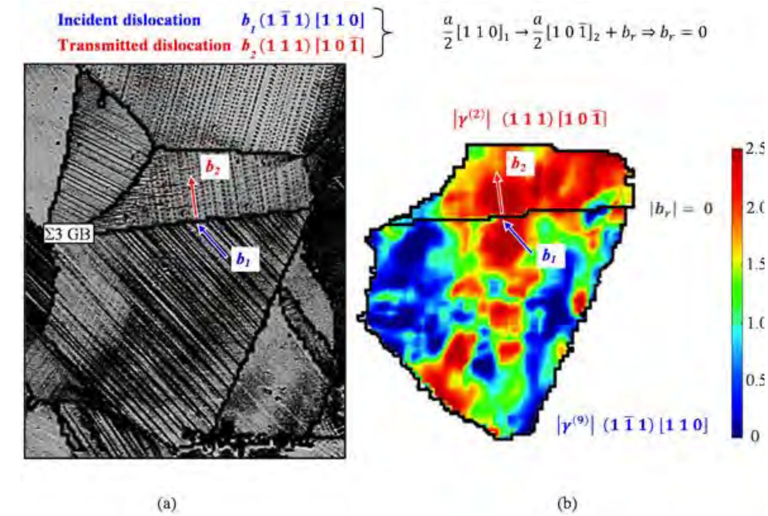

Figure Abu-3: Slip transmission through a GB. (a) SEM micrograph showing continuity of slip traces across the GB. The shear strains associated with the observed traces are shown in (b). The directions and magnitudes of both systems across the interface indicates slip transmission through the GB with $|\boldsymbol{b_r}| = 0$. *a* represents the lattice spacing of the material.

D4 Thermomechanical Fatigue of Hastelloy X: Role of Defects (Mallory Casperson, John Lambros, Ravi Chona, Jay Carroll, Wael Abuzaid, Huseyin Sehitoglu, James Sobotka, Robert Dodds)

The objective of this project, which forms a direct continuation of project D2, centers on extending the techniques and measurements made in D2 at room temperature to higher temperatures – up to about 1,000°C. In particular, the current focus is on studying the effects of elevated temperature on fatigue crack closure loads, knowledge of which is critically important in accurately determining fatigue crack growth rates. For this work we use a Hastelloy X single edge notch tension specimen, shown in Figure Cas-1, that is imaged using digital image correlation (DIC) at two length scales: Microscale – 10x magnification, 400 nm/pixel, and Macroscale – 2x magnification, 2 microns/pixel. In the previous year's efforts, outlined in the 2010 annual report, we had observed by 2x experiments that the effects of crack closure were diminished as temperature was increased from a steady state value. Figure Cas-2 illustrates this effect in Hastelloy X through measurements of the stress intensity factor with load at room temperature (RT), where closure is visible by the discrepancy from the theoretical solution (compensated for modulus thermal softening in each case) and subsequent cycling at elevated temperature of 250°C and 450°C, where no closure is observed.

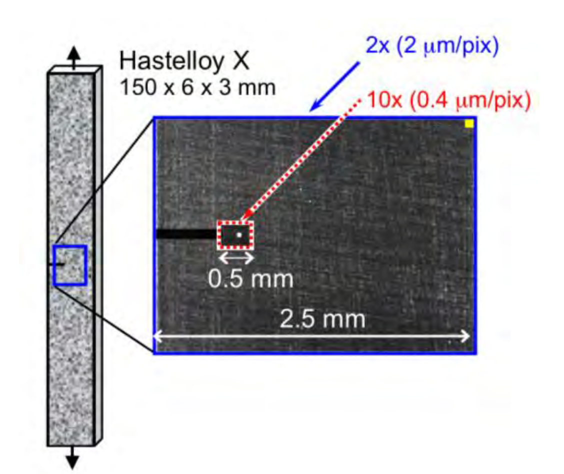

Figure Cas-1: Specimen geometry and fields of view for DIC experiments.

During the current year (2011) we continued investigating this effect at different interrogation scales, and for different thermal histories. Using the methods developed earlier in project D2, we repeated the testing protocol associated with the experiment above – i.e., precracking at RT until crack closure becomes significant, and then increasing temperature above RT – but now preforming the measurements at the microscale (10x magnification). The 10x experiments provide local crack opening vs. load measurements at multiple locations behind the crack tip, thus giving a local indication of the level of crack closure load. Figure Cas-3 shows the crack opening vs. load for a location approximately 300 microns behind the crack tip in RT steady state fatigue crack growth followed by a single 300°C thermal cycle, i.e. the same protocol used in Figure Cas-2. Crack closure is clearly visible in the RT measurements, but has again diminished in the high temperature measurements. Thus a single thermal overload suppresses closure and may have significant impact in terms of increasing crack growth rates.

Subsequently, a new testing protocol was used in which the precracking was done at elevated temperature, specifically 300°C. Then additional thermal ―overloads,” specifically to 400°C, were applied. These experiments were again conducted at 2x to monitor the global value of applied stress intensity factor. Results from the last 300°C cycle and the first 400°C cycle are shown in Figure Cas-4. As seen here, when the precracking is done at a constant elevated temperature closure *is* present, and at comparable amounts to RT closure. Upon an additional thermal overload closure does *not* noticeably diminish in this case, in contrast to the results of Figure Cas-2. The reason for this is believed to be because the thermal overload in this case is far less than in the case of Figure Cas-2. The reasoning is that upon the first elevated temperature cycle, crack blunting occurs because of decreased material yield stress. The difference between RT yield and 300°C yield is much more significant than between 300°C and 400°C. Thus, the blunting effect that eliminates closure does not occur in the second case. An elimination of closure upon a high temperature ―overload” will increase crack growth rate. However, at the same time, the reduced yield

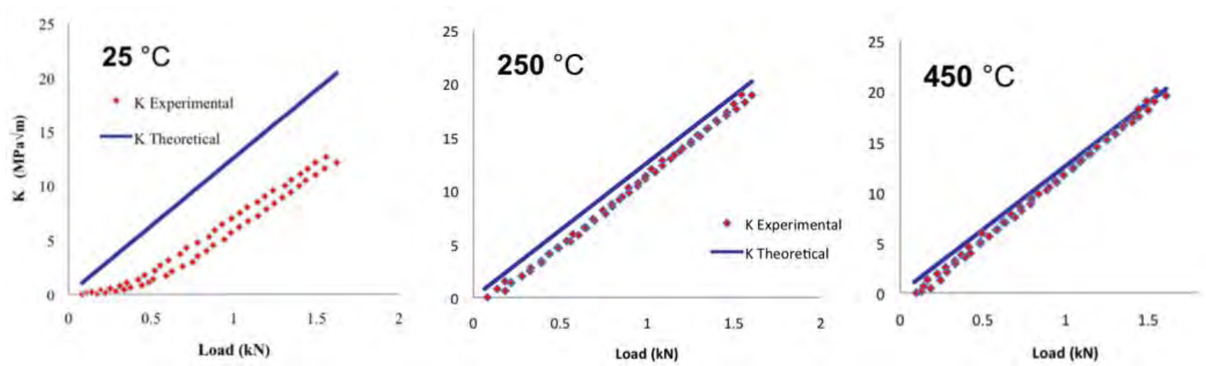

Figure Cas-2: Comparison of experimentally measured SIF from 2x DIC experiments with theoretical (i.e., applied) value for measurement cycles corresponding to temperatures of (a) 25°C, (b) 250°C, and (c) 450°C.

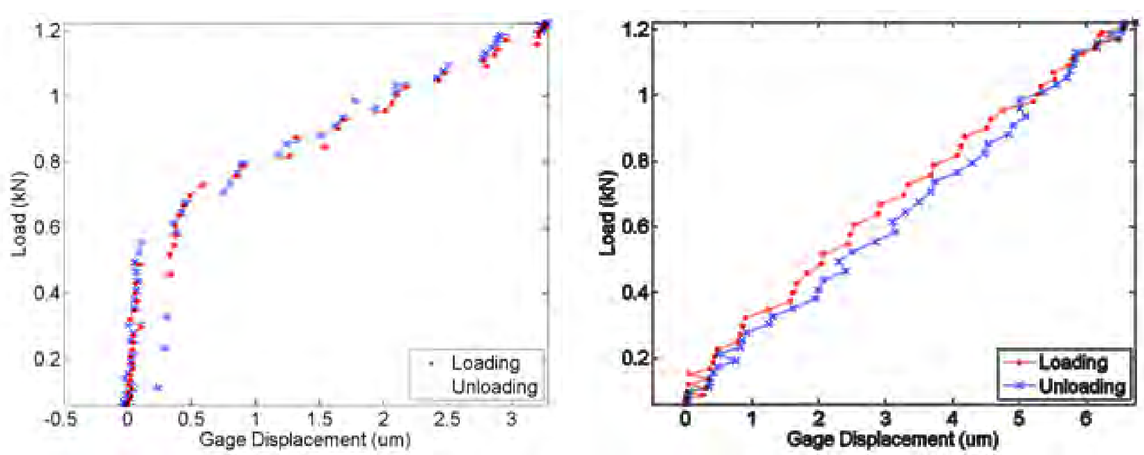

Figure Cas-3: Applied loads vs. local opening displacement 300 microns behind the crack tip for RT cycling (left) followed by a single cycle at 300°C (right). Little opening until about 60% of peak load illustrates the significant amount of crack closure observed in Hastelloy X at RT (left). Right, virtually no closure is observed after the single 300°C cycle (in agreement with the far field results of Figure Cas-2.

stress will increase plasticity effects that should decrease crack growth rate. The next effort of this work will be to experimentally investigate the competition between these two effects.

3 Management

Executive Director William Dick administrates the Center, and along with two UI co-Technical Directors — John Lambros and Robert Dodds — work with their research counterparts at AFRL/RBSM. A Science Steering Committee of program participants (UI and AFRL/RBSM) convenes bi-weekly to guide program execution. Collaboration among the partners is frequent and intense (co-advised research projects and graduate theses, teamed simulation and experiments, co-authored journal articles and project proposal submissions, etc.). Computational resources, graduate assistantships, experimental facilities and visitor office spaces exist at UI to directly support the MSSC. The Directors and Science Steering Committee members are responsible for nurturing the research program, administering the Center, and maintaining and expanding relationships with AFRL/RBSM. This directorate provides the leadership necessary to ensure that the Center identifies the most important research areas, attracts the most qualified researchers, and pursues and completes the work effectively over the long term. A small administrative staff works to execute Center activities.

The MSSC is housed within the University of Illinois Computational Science and Engineering (CSE) Program. CSE is inherently interdisciplinary, drawing faculty, staff and students from 17 departments and requiring expertise in advanced computing technology, as well as in one or more applied disciplines. The purpose of the academic CSE Degree Option is a perfect complement to the goals of the AFRL/RBSM program — to foster interdisciplinary, computationally oriented structural sciences research among all fields of science and engineering, and to prepare students to work effectively in such environments. This academic structure lends itself naturally to the requirements of the MSSC: a free flow of students and ideas across academic departmental, college, and governmental unit lines. A far-reaching Visitors Program has been implemented to encourage close collaboration among the team members. Research offices and computational facilities in CSE space are available for this purpose.

4 Publications

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