Extreme Environment Structures Modeling and Simulation, Verification and Validation

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Abstract: Modern tactical aircraft require structures to survive extreme environments. This creates challenges that are multi-faceted. The behavior of extreme environment structure (EES) is governed by complex multidisciplinary and nonlinear physics that have proved difficult to capture in analysis and design. The same multidisciplinary and nonlinear effects that complicate the computational simulation of EES also leads to non-intuitive structural responses and competing design requirements. Mechanical and acoustic loads are generally dealt with by stiffening or constraining a structure; however, the ideal design prescription for reducing thermal stress is to accommodate thermal expansion. Thus, it is obvious that these constraints are diametrically opposed. Previously, components have failed due to thermally-induced localized stresses. The question is then how to best stiffen the structure or alleviate mechanical loads without increasing the rate of damage and without increasing the load into sub- and surrounding structure. To best address this during a component redesign, or in the development of a new EES, the analysis techniques to be employed must capture the underlying physics of the problem. The conflicting design requirements of the entire exhaust system must then be simultaneously satisfied to deliver a robust and high performing solution.

Introduction: The creation of modeling, simulation, design and analysis capabilities for EES requires topologically optimized, time-accurate, thermoelastic coupled design and analysis capability incorporating thermal expansion; temperature-dependent material properties; spatial and temporal load variations must be created and put through a rigorous verification and validation (V&V) process. A multi-year research program to V&V modeling and simulation tools for EES is being pursued. This fundamental research program is broken into three phases. The first of which is the creation of test panels to use as a pathfinders. It entailed the fabrication and testing of three 'mock' panels to do preliminary V&V of acoustic response models that are required for EES. The next phase will use the exhaust impinged metal structure (EXIMS) that was designed in the 1990s to V&V USAF design and analysis capabilities to ensure the complex, nonlinear physics in the design domain are properly captured by simulation tools. The V&Ved analysis will then be used to design a state-of-art (SoA) EES that leverages the advances made in optimization techniques and materials after EXIMS was developed. This will redefine the SoA.

United States Air Force's Combined Environment Acoustic Chamber (CEAC): The test section of the CEAC (Figure 1) is 4 ft by 9 ft. and both sides are accessible. This progressive wave facility produces a grazing incidence acoustic load to simulate aeroacoustic excitation over the panel surface with overall sound pressure levels (OASPL) up to 170 decibels over a typical controlled frequency range of 50-500 Hz 1/3 octave bands. Low pressure, high volume air compressors are used to produce moving air to carry the acoustic wave through the test section. The test article side of the CEAC test section has been filled with an array of 316 stainless steel closeout panels Figure 2, to enclose the progressive wave tube (PWT). The close-outs provide a warm wall boundary condition for the test article during thermal testing. A gap will remain between the test article and the close-outs to keep the article isolated from any vibrational response of the chamber. In order to provide a smooth transition from the rectangular duct to the curvature of the test article, the closeout array was designed to minimize steps in the duct. This should help reduce turbulence in the duct. A quartz lamp array opposite of the test specimen provides a radiant heat source to simulate aerothermal effects and engine exhaust impingement type environments. The lamp array consists of 8 banks, each with eighty-eight (88) 6000 Watt bulbs. The array has the ability to output an even heat flux across a flat test article of approximately 72 BTU/ft^2-sec.

Figure 1 United States Air Force's Combined Environment Acoustic Chamber

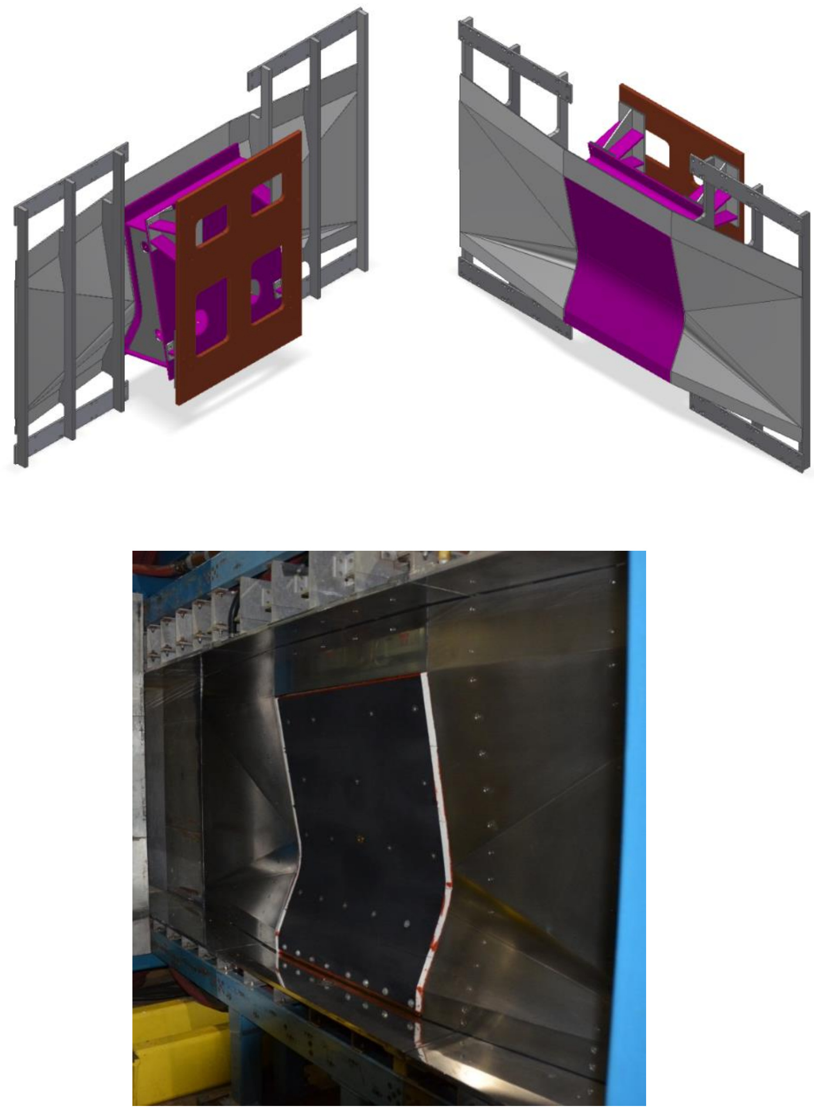

Figure 2: Test Section Close-out Arrangement (pictured with mock panel)

Mock Panels: Three ‘mock panels’ (MP) were designed and fabricated. The MPs were a flux survey panel, a thin panel (3/16” thick) and a thick panel (3/8” thick). The flux survey panel was used to characterize the heat transfer within the CEAC. The thin and thick panels were used to characterize the boundary conditions associated with test fixture and baseline our analytical capabilities. To perform this baseline, a series of experiments were performed. First, modal tests were performed to enable determination of the boundary conditions. Then, a flow velocity survey, a thermal response experiment, an acoustic response experiment and combine thermal acoustic response experiment were conducted. All of which have been completed.

The modal response data was collected using a 3-D scanning laser Doppler vibrometer. The results and preliminary model comparisons are shown in Figure 3.

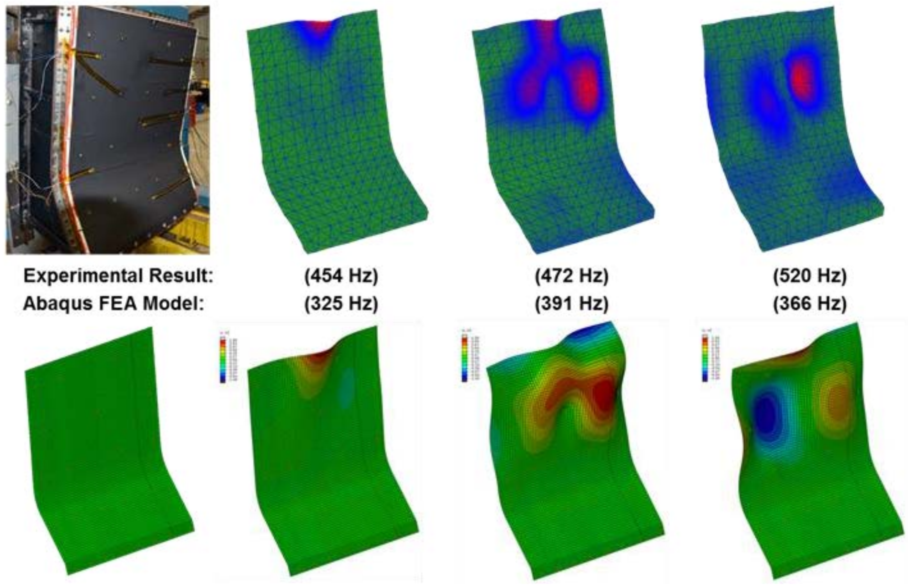

Figure 3 MP modal response and prediction

The flux panel was well instrumented. The data produced allowed us to determine the spatial variations in the radiative flux over the entire MP. We also collaborated with the USAF Computational Science Center (CSC) to perform a CFD study of test flow conditions. It created a prediction of the approximate convection conditions on front face of test article shown in Figure 4 and used the flow velocity survey data to anchor their analysis.

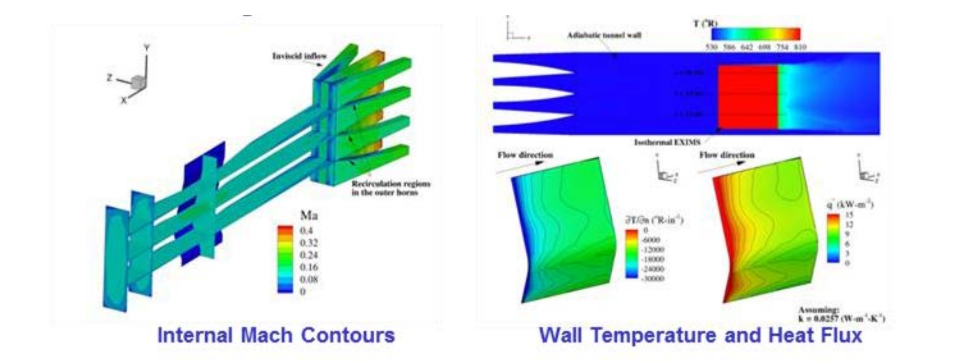

Figure 4 Results of CFD study

The data produced from the all other experiments was used to correlate our design and analysis tools. The modal data is all that is included in this paper.

Exhaust impinged metal structure (EXIMS): The main difference between the mock panel and the EXIMS panel (Figure 5) and the mock panels is that the mock panel was hard mounted to a load deck while the EXIMS panel is a floating deck system which allows the deck to expand and contract with thermal load. The EXIMS article consists of three overlapping pieces, or shingles, manufactured from titanium, TIMETAL-1100. The EXIMS fixture is attached to an adapter plate using tapered standoff members.

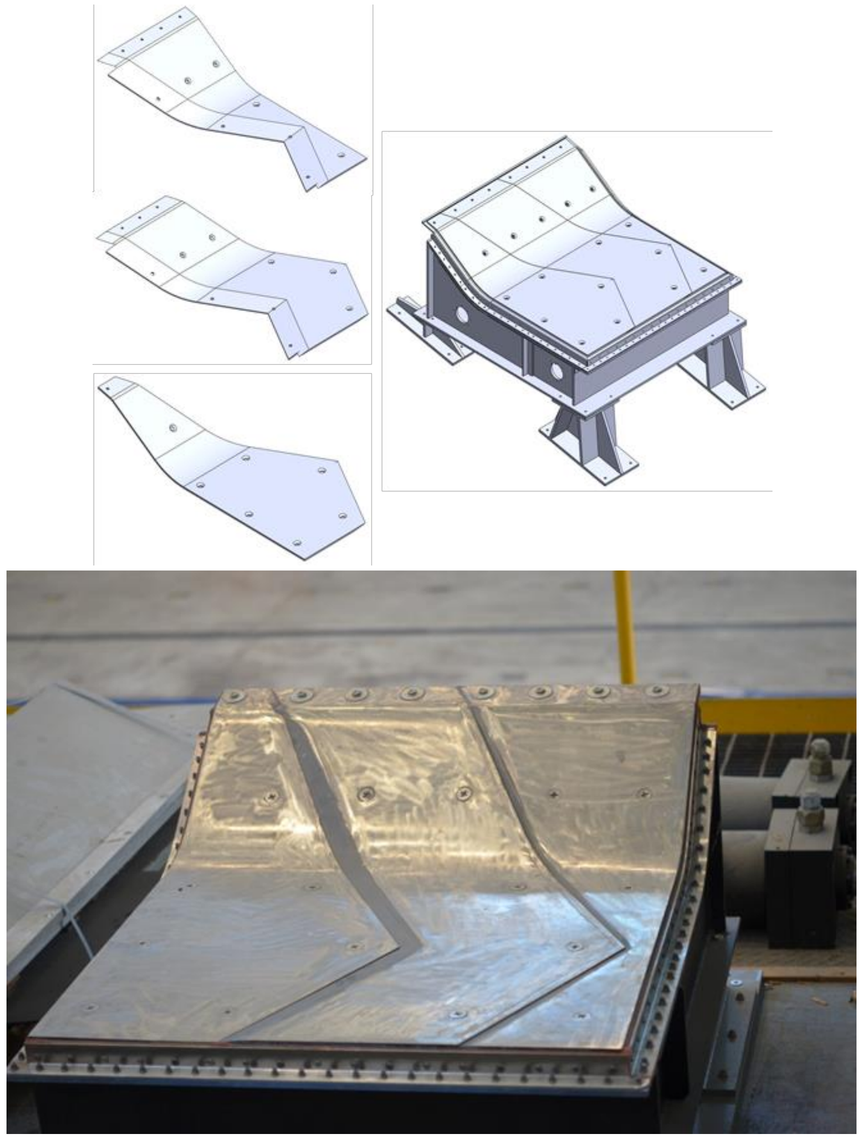

Figure 5 Exhaust impinged metal structure

EXIMS Experiment: Table 1 shows the experiments that were conducted in the CEAC. The modal testing was performed prior to the impingement of any extreme environment loads. The flux survey measured the heat flux distribution generated by the quartz lamp array. The thermal only test of each test article was used to measure the thermal response of the test article when a designated even radiation load is applied to the article. The response measurements will include temperature and thermal strains on both the floating deck and the load deck. Each tests was completed allow the test article reach steady state or until a limit temperature of 527°C (980°F) on the OML was reached. The acoustic only testing was used to measure the dynamic response of the panels when a known fluctuating pressure is applied to the article. The response measurements were acceleration and dynamic response of the titanium test panel.

The combined environment loading was applied in the same manner as the thermal only testing, as well as the same dynamic loading as the acoustic only testing.

Table 1: Test Matrix

Test Sequence	Description
1	Modal Survey - Load deck
2	Flux Survey
3	Acoustic Only Test
4	Thermal Only Test
5	Combined Load Test

Results/Conclusions: The modal data correlation is shown in Figure 6. Good correlation was obtained.

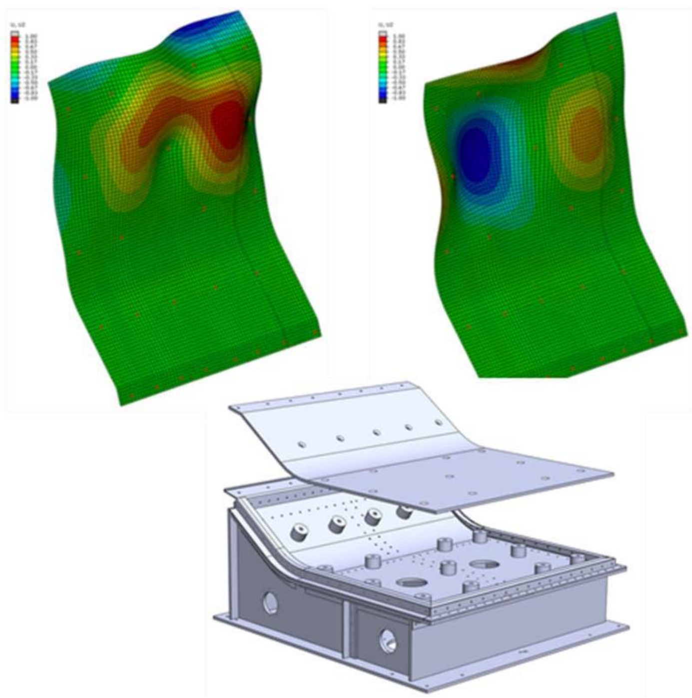

Figure 6 EXIMS Modal Correlation

While good correlation was obtained for the modal data, that is not the case for thermal data when the requisite flow to induce the acoustics on the specimen were applied. Temperature response as a function of time for no flow and a flow cases are shown in Figure 7. In the legend O stands for outer mold line (OML), I stands for inner mold line (IML), and TC stands for thermocouple. Heat was applied via the quartz lamps are to the OML. Figure 7 a) shows the expected response with the OML being at a higher temperature than the IML. However; once flow is applied the response measured shows a physically unrealistic result, the IML is hotter than the OML (Figure 7 b)). This anomaly occurred for every test run. Because of this, all of the thermal data is questionable.

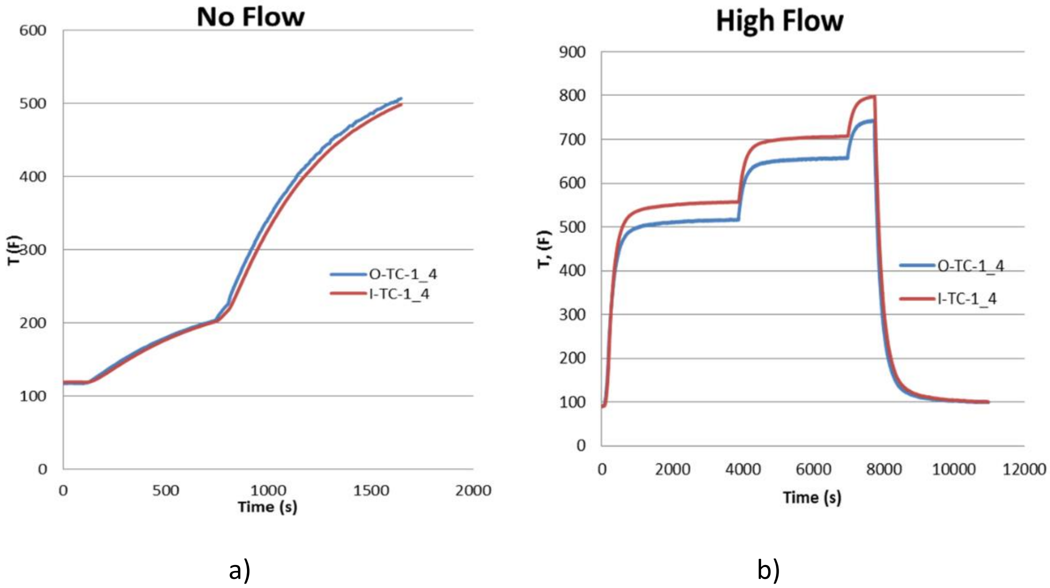

Figure 7 a and b: Thermal Response

To determine the cause of the 'anomaly' and whether or not a correlation from the obtained data to reality could be created, a simple instrumentation experiment was designed. It uses a titanium (Ti-6-2-4-2) plate measuring 30.5 x 30.5 x 0.71 cm (12"x 12"x 0.28") shown in Figure 8.

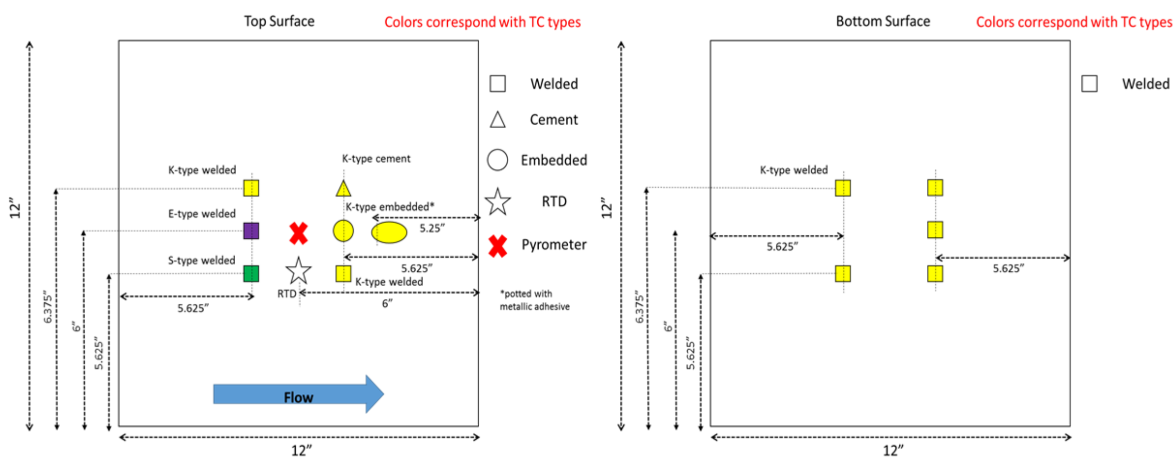

Figure 8 Instrumentation Experiment

This experiment is still being performed but preliminary data (Figure 10) shows that we can replicate the anomaly. In this figure, K-Weld2 is on the OML, K-Weld BK is on the IML and K-Embed is thought to be the true OML temperature.

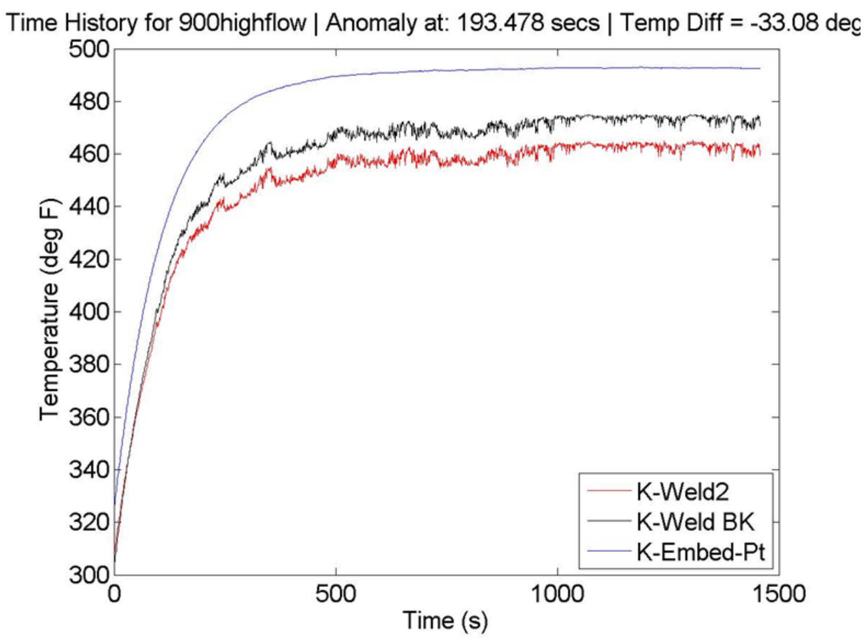

Figure 10 Instrumentation Experiment Preliminary Results

Figure 11 plots the difference between the ‘truth’ and OML thermocouples for two different flow cases. It provides hope that correlations between the ‘truth’ and the OML thermocouples may be obtainable.

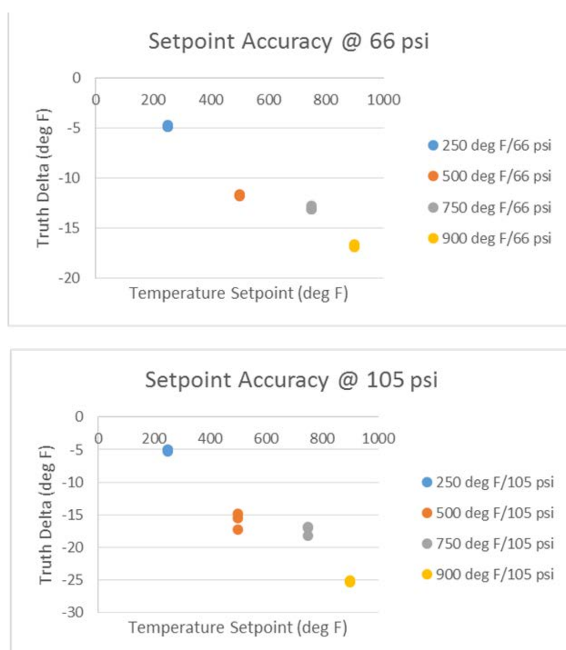

Figure 11 Truth versus OML Thermocouple Reading.

This work was conducted by the United States Air Force Research Laboratory and has been cleared for public release, 88ABW-2016-3870.