Advanced Technologies for Hypersonic, Propulsive, Energetic and Reusable Platforms
REU-HYPER 2019
28 May – 2 August 2019, Orlando, United States

REU-HYPER 2019

Numerical Analysis of Thermo-mechanical Buckling in Combined Extreme Environments

Hugh Leonard, Navindra Wijeyeratne, Firat Irmak, Michael Cabada, Ali P. Gordon

Department of Mechanical and Aerospace Engineering,
College of Engineering and Computer Science, Orlando, Florida, USA

ABSTRACT

This paper covers the analysis of Thermo-mechanical Buckling effects on a computer simulation. It looks over a previous experiment and repeats its process through a Finite Element Analysis (FEA) Simulation on ANSYS Workbench. Unlike the previous experiment with similar specimen, the FEA analysis examines a constant thermal load. With an applied variable temperature, the specimen deforms farther the hotter the thermal load.

NOMENCLATURE

$\delta(t)$	= displacement from initial position
δ_0	= Initial perturbation
$P(t)$	= Force Reaction
t_d	= Dwell Period
I	= Area Moment of Inertia
$T(t)$	= Temperature
σ	= stress
ε	= strain
A	= area

1. INTRODUCTION

Fuselage panels on Hypersonic Aircraft play an important role in providing aerodynamic movement while protecting its interior vessel. However, a common issue that arises is Thermo-Mechanical Buckling, in which a panel is subject to buckle due to thermal effects such as thermal strain, creep and temperature-dependent elasticity and plasticity.

A key challenge for designers is to identify the least resource-intensive path to characterization a structure under service conditions. The current research focuses on developing a framework that identifies the minimum set of experiments needed to allow Thermo-Mechanical Buckling to be simulated.

2. BACKGROUND

Hypersonic vehicles rely on fuselage panels to withstand combined extreme environments, yet the number of these combined environments can vary. One candidate vehicle, the DARPA Falcon HTV-3x, used fuselage panels of Inconel 617 and/or Ti-6353S, which were subjected to conditions applicable to hypersonic flight.[1] This includes elevated temperature, acoustic vibration, oxidation, and high stress. [1] However, such conditions can lead various methods of failure, most notably buckling. [1] It results from many factors such as low cycle fatigue, very high cycle fatigue, creep, coupled environmental fatigue.[1]

Sedlack performed a hardware analysis of using a Buckling test frame and a lamp furnace to analyze the thermomechanical buckling behavior, before modeling the procedure on ANSYS FEA simulation. However, Sedlack's study may have multiple options of analyzing this failure, but the ANSYS models ran into limitations of uniform thermal loads at the time of the study.[1]

It is important to analyze a uniform thermal lead as constant high temperatures result from constant engine operations over long periods of time.

3. MATERIALS AND METHODS

3.1 FEA Setup

An ANSYS Workbench FEA simulation is used to model the effects of Thermal-Mechanical Buckling. A Transient Structural model is used in this case.

The specimen is a long, rectangular 20" x 1" x 0.1" flat plate made of material Inconel 617. Its properties include isotropic, temperature-dependent elasticity and Multilinear Isotropic Hardening

The two ends are in a fixed position and the upper and its upper and lower edges are constrained such that they do not displace or deform in the vertical Y-direction.

A small, ramped initial perturbation of 2.54 mm is applied at the center of the specimen for the first second of the simulation. An applied temperature rises from room temperature, 22°C, to a variable maximum temperature, where it is held constant for a "dwell period" before cooling down back to room temperature.

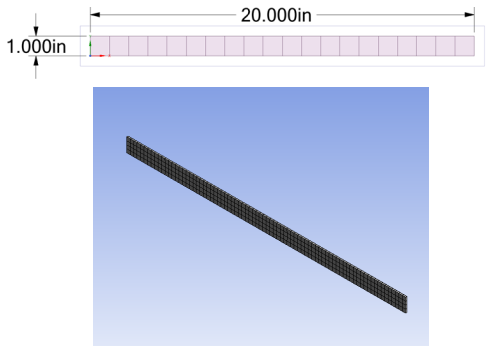


Figure 1. Specimen used for Thermomechanical Buckling simulations

Results of the FEA simulation measure the displacement of the center of the specimen, where it is assumed that the maximum deflection occurs, and a force reaction at one of the fixed specimen terminals.

3.2 Theoretical Equations

Thermal strain produces thermo-mechanical buckling through equations 1-3. However, the initial perturbation is added to the specimen to prevent any data nullification.

$$\delta(x) = \frac{M}{P}\left[1 - \cos\left(\frac{2\pi}{L}x\right)\right] \quad (1)$$

$$\Delta T = \frac{\pi^2 h^2}{3\alpha L^2} \quad (2)$$

$$P = \frac{\pi^2 EI}{L_e^2} \quad (3)$$

The creep effects utilized are based of the Norton model. In which:

$$\dot{\varepsilon}_{norton} = C_1 \sigma^{C_2} e^{-\frac{C_3}{T}} \quad (4)$$

However, the model assumes that $C_3 = 0$ for all temperatures, therefore:

$$\dot{\varepsilon} = C_1(T)\sigma^{C_2(T)} \quad (5)$$

Where, $C_1(T)$ and $C_2(T)$ are functions dependent on temperature.

4. RESULTS AND DISCUSSION

4.1 Findings

The FEA simulations reveal that the applied maximum temperature has a more significant impact on the displacement. There is direct relationship between this applied temperature and the specimen's deflection. However, there is a slight variation in the Force vs time curve, such that the initial compressive force and the final tensile force are larger in magnitude the higher the temperature.

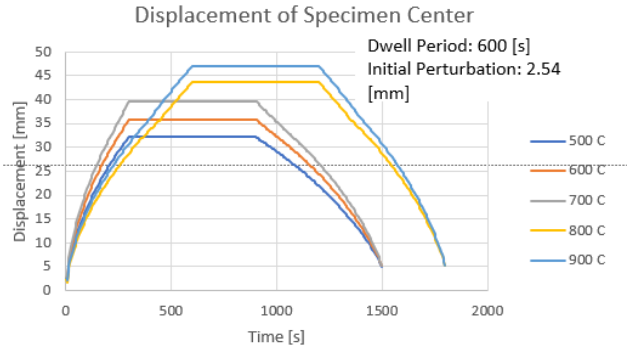


Figure 2: Sample displacement vs time results for a 600 second dwell period.

Regarding the dwell period, there is no significant change in the displacement, although results such as the 500°C trials show an increase by about 1 μm. However, the force reaction decreases in magnitude, and it is in compression during the dwell periods. This shows that creep effects are functional within ANSYS FEA simulations, but they are only more noticeable in lower temperatures. The creep effects were minimal because the specimen relaxed in stress before the dwell period occurs.

4.2 Limitations

Although it is expected that compression occurs before the dwell and tension afterwards, the creep effects were minimal during the dwell period. The displacement could have changed by smaller margins than the data recorded.

Software issues were also encountered in the making of the FEA simulations. Most notably, a 1000°C case was planned to be run, but failed to converge with the given mesh. Attempts to fine the mesh with more nodes and elements were carried out but lead to Exceeded GPU time errors or Pivot errors, which usually imply that the model was under constrained or the material properties were insufficient, although the data used had temperatures from 22°C to 1100°C. This may be because the temperatures inputted are in Fahrenheit and then converted into Celsius. This issue may also stem from fast temperature rates, which is why the heating and cooling periods are different for 800°C and 900°C.

5. CONCLUSION

5.1 Summary

While uniform thermal loads have been analyzed successfully, they yield very marginal if not negligible results. However, this does not impede maximum buckling deformations that are consistent with the applied thermal loads. Although forces do occur during heating and cooling, the specimen attempts to yield no force as dwelling occurs.

5.2 Further Suggestions

Further study should analyze the creep effects during the dwell period with more precise measurements. While the findings in the paper conclude that they are small, it should be worth noting how deformation occurs at small levels.

In addition, if fine meshing is necessary, it is strongly recommended to have the appropriate number and type of CPU units. Attempting to yield a converged solution, on the other hand, requires this method along with an appropriate and consistently used heating and cooling rate.

ACKNOWLEDGEMENTS

The author acknowledges the helpful support of PSM representatives such as, National Science Foundation, Department of Defense, and Alex Torkaan.

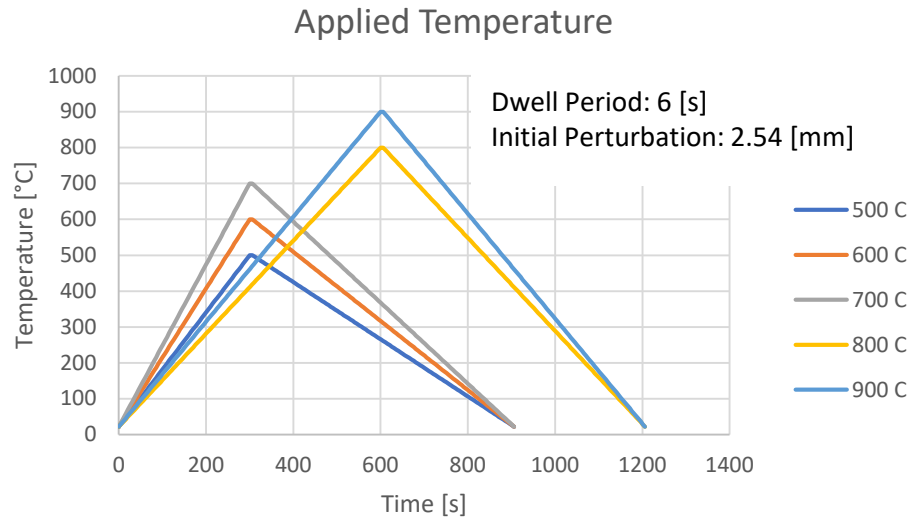
In addition, the author gives much thanks to ANSYS representatives such as Joe Ricci, Ryan Gordon, and Luca Masi.

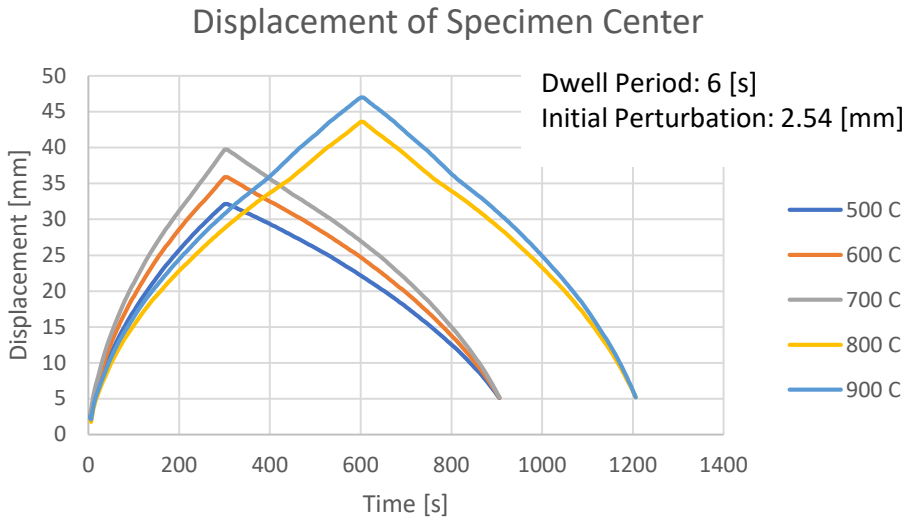
REFERENCES

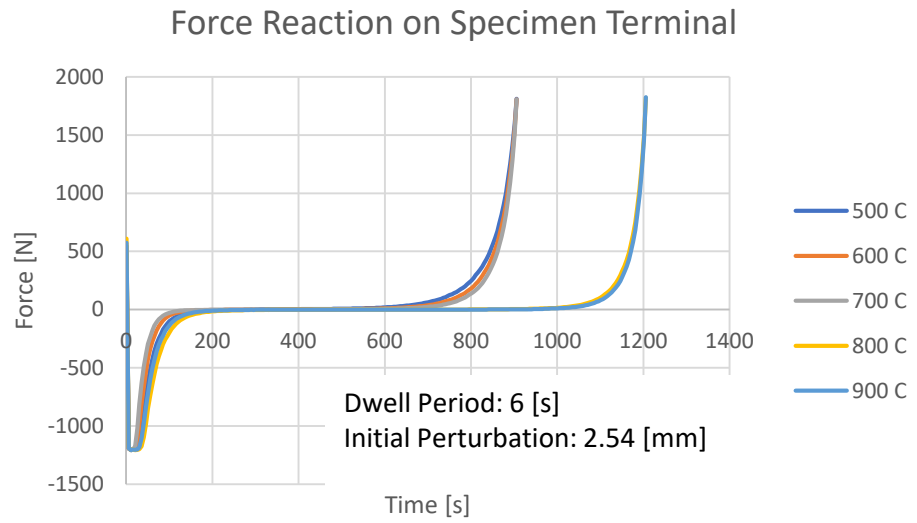
[1] Sedlack M., Deane S., et al. Testing and Modeling of Thermomechanical Buckling Fatigue in Combined Extreme Environments. University of Central Florida, Orlando, FL, 2018.

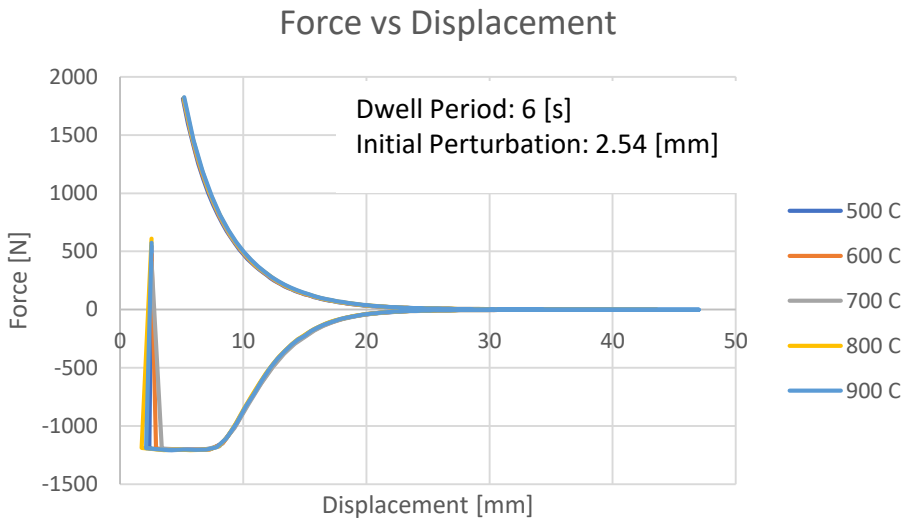
[2] Deane, S., Sedlack, M., Stoll N., Bouchenot T., Dr. Gordon, A.P., "Platform for Combined Extreme Environments," Showcase of Undergraduate Research Excellence at University of Central Florida, Orlando, Fl, 2016-17

Appendix A: Results for 6-second dwell

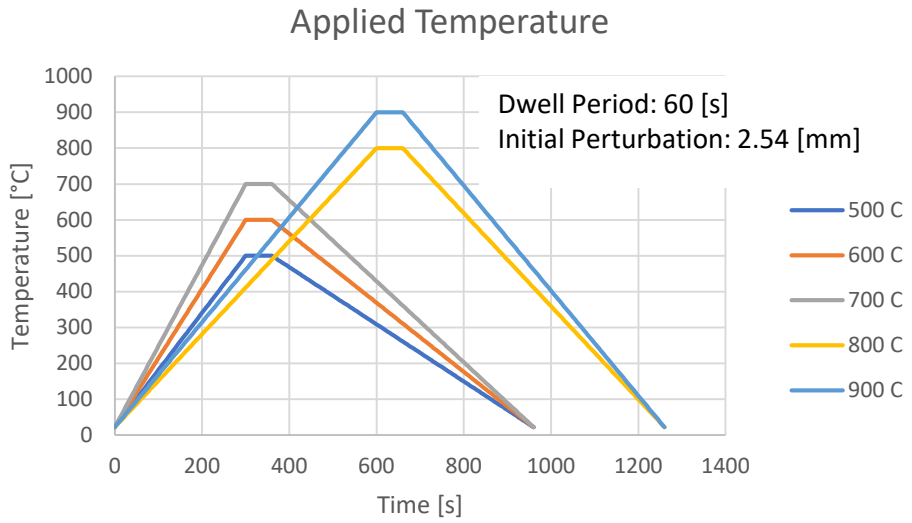


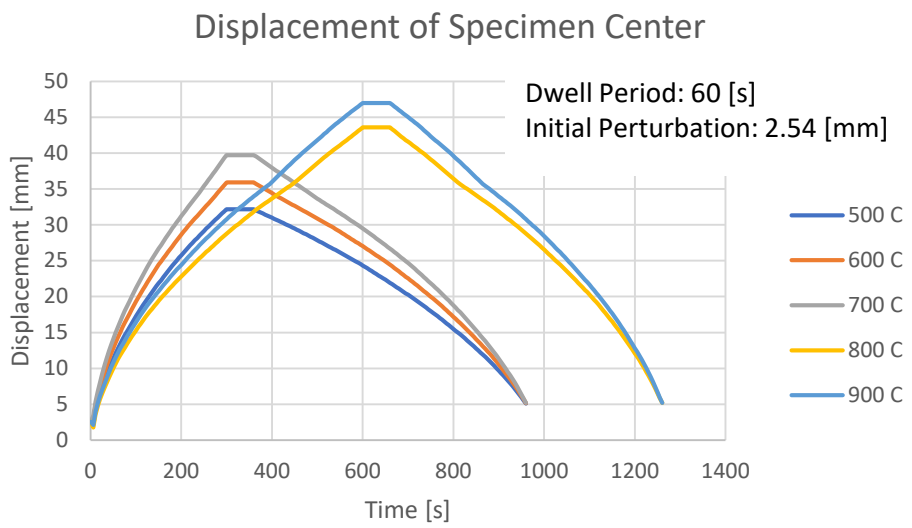


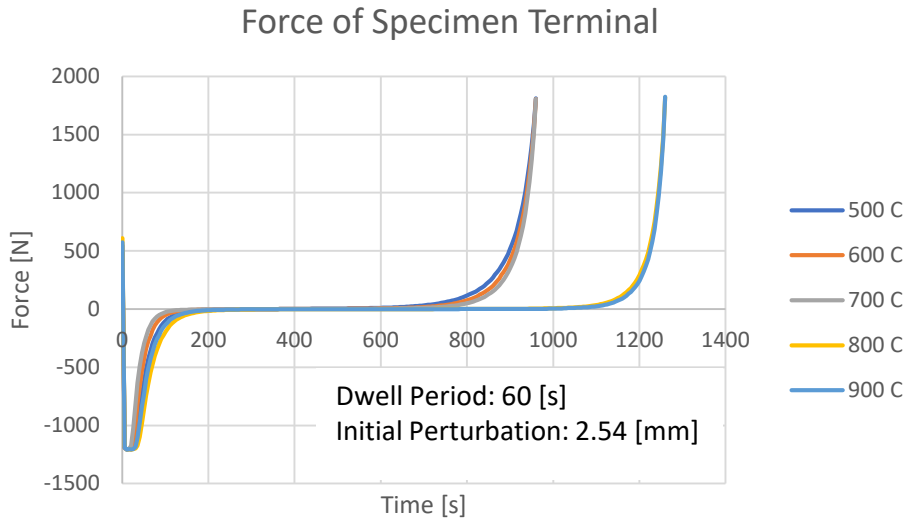


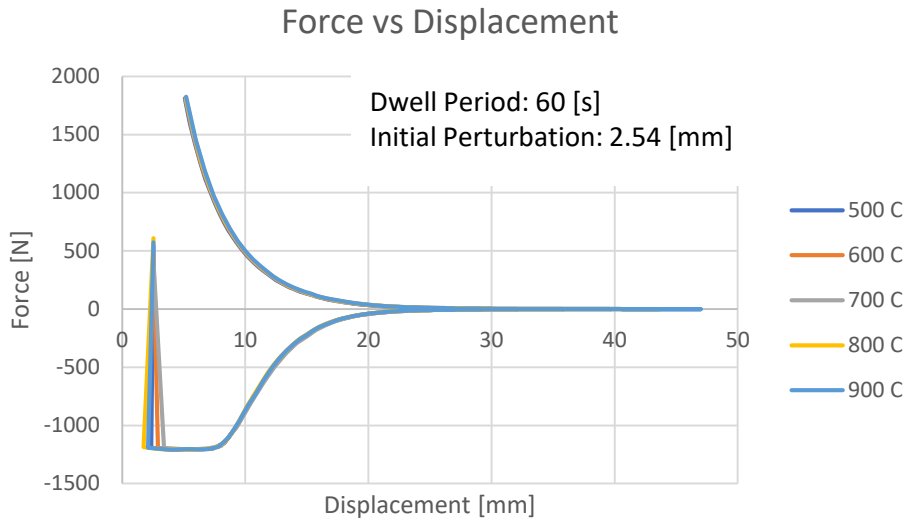
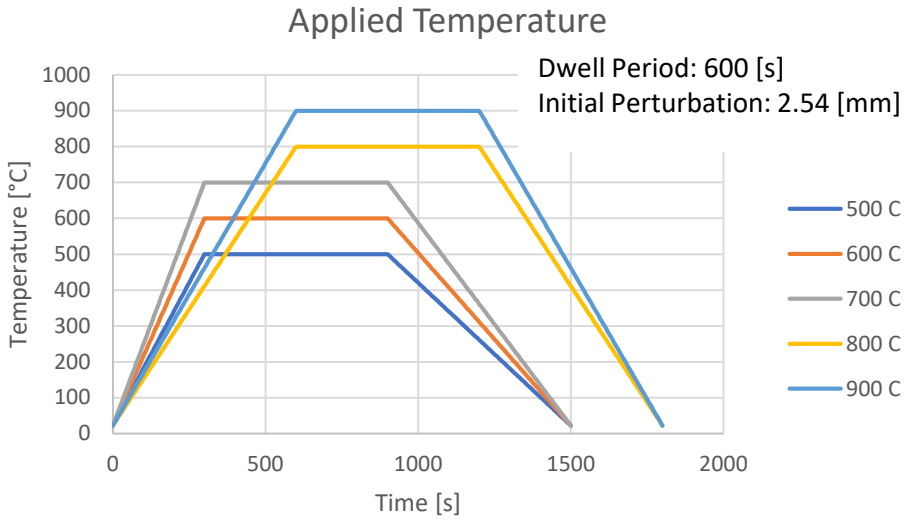
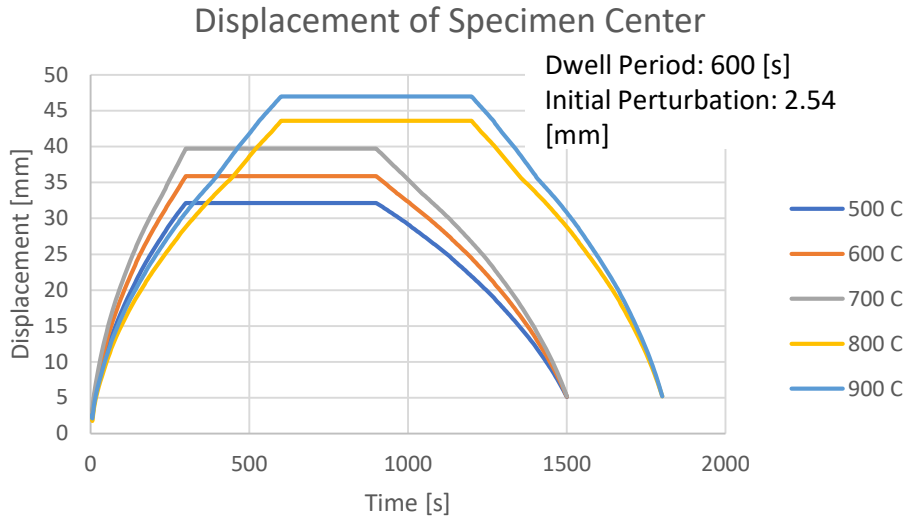
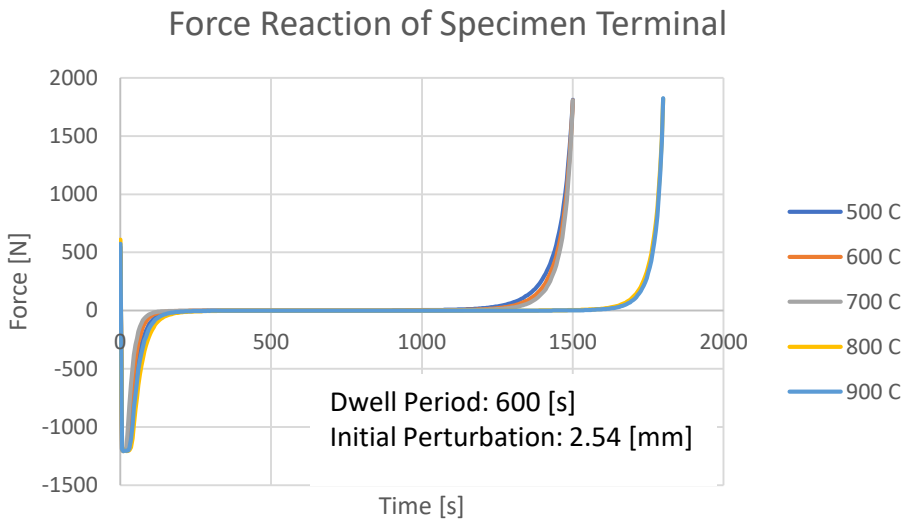
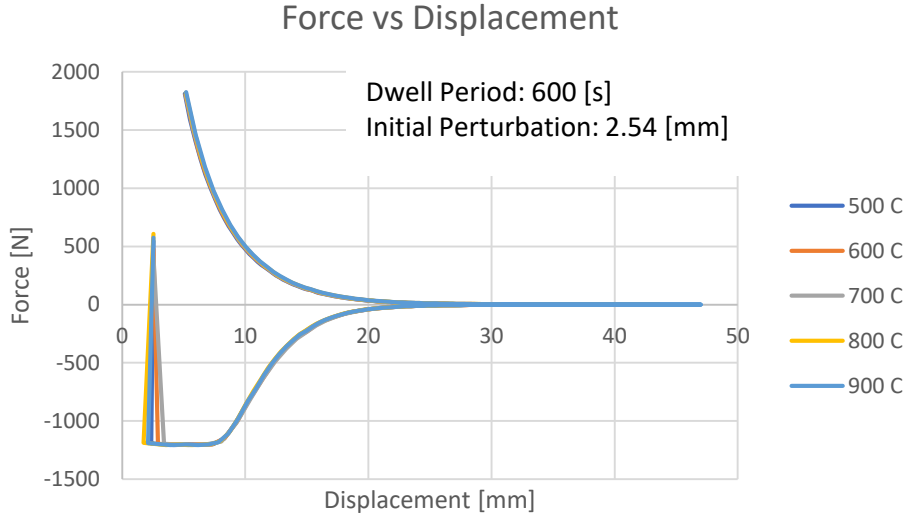


Appendix B: Results for 60-second dwell









Appendix C: Results for 600-second dwell