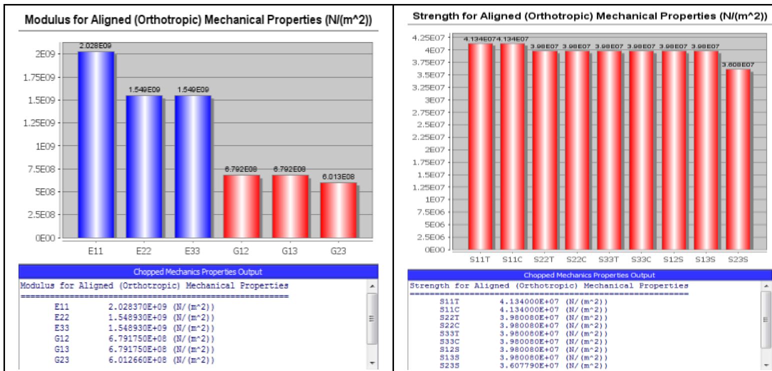
Thermo-mechanical Analysis and Experiment Validation of Fused Deposition Modleing

Application Study

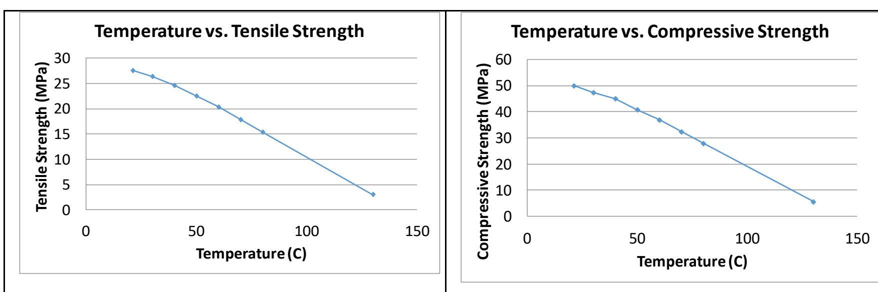
In a proof of concept collaboration between Robert Bosch GmbH and AlphaSTAR Corporation, GENOA 3DP was utilized to simulate Additive Manufacturing (AM) fabrication and service loading of an unfilled Acrylonitrile Butadiene Styrene (ABS) polymer panel with circular and rectangular holes. The build utilized Fused Deposition Modeling (FDM) technology and posed unique challenges related to material modeling and process simulation. The exercise provided an opportunity to highlight the capabilities of the software product.

As a first step, AlphaSTAR's material characterization and qualification module, MCQ, was used to validate a virtual material model for unfilled ABS (**Figure 1**). It should be noted that ABS exhibits different behaviors at varying temperatures. During the print process, temperature gradient between two layers led to contraction of the hot layer and compression of the cold layer until equilibrium was achieved. In addition, thermal stresses generated during the solidification process induced warping/distortion in the part. MCQ analytically captured mechanical properties of ABS in terms of orientation and effect of defects. The analysis was built on the assumption that voids compromised 22% of the polymer, were cylindrical in shape, and maintained an aspect ratio 4. Cure Kinetics and multi-factor analysis were used to predict modulus and strength as a function of temperature. The process accounted



a) Aligned Modulus | b) Aligned Strength

***Figure 1**. RT Mech properties versus print orientation*



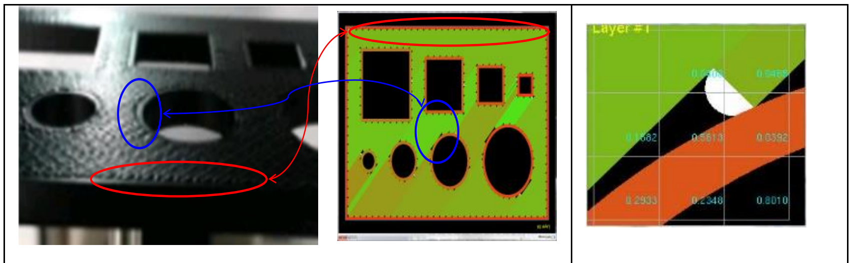
a) Tensile Strength vs. Temp. | b) Comp. Strength vs. Temp.

***Figure 2**. Temperature dependent strength properties validation*

for transient heat transfer and temperature distribution through part of the material by incremental time-steps associated with curing model (**Figure 2**).

GENOA 3DP PathCoverage

The next step entailed evaluation of the G-code in terms of material deposition. Here, GENOA 3DP's PathCoverage module was called upon to detect voids and defects in the layer by layer build in relation to print parameters and non-conforming mesh at the boundary. After detecting voids (**Figure 3**), the software adjusted material properties for limited coverage areas.

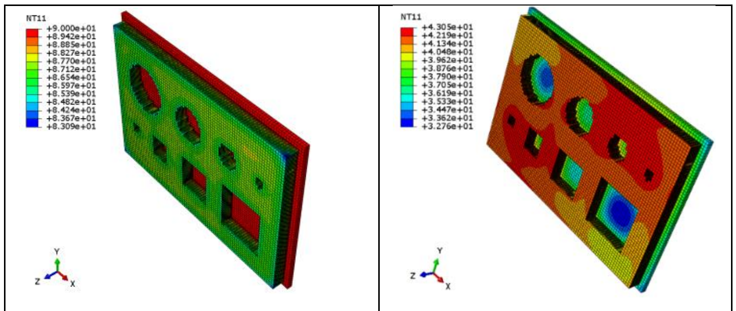


a) Anomalies (L) As-Built, (R) model — b) Finding voids

Figure 3. *Printing Defects Changes Material Response.*

Sequentially Coupled Thermal-Structural Analysis

Abaqus Standard with GENOA 3DP was used to undertake an "uncoupled thermal analysis" of the Hole Plate for XY ±45 build direction. The temperature distribution field was found without the effect of stress deformation. Accordingly, heat transfer analysis was performed to determine the temperature distribution field, which would provide input to the critical coupled thermal-structural analysis. **Figure 4** shows (a) temperature distribution in the part after printing and (b) temperature distribution in the part while cooling. Next, the team employed GENOA 3DP to perform the sequentially coupled structural-thermal analysis to predict residual stress, deformation, and damage-delamination, while considering conduction, convection, and radiation. It should be noted, the Base Plate acted as a heat sink during AM 3D printing process.



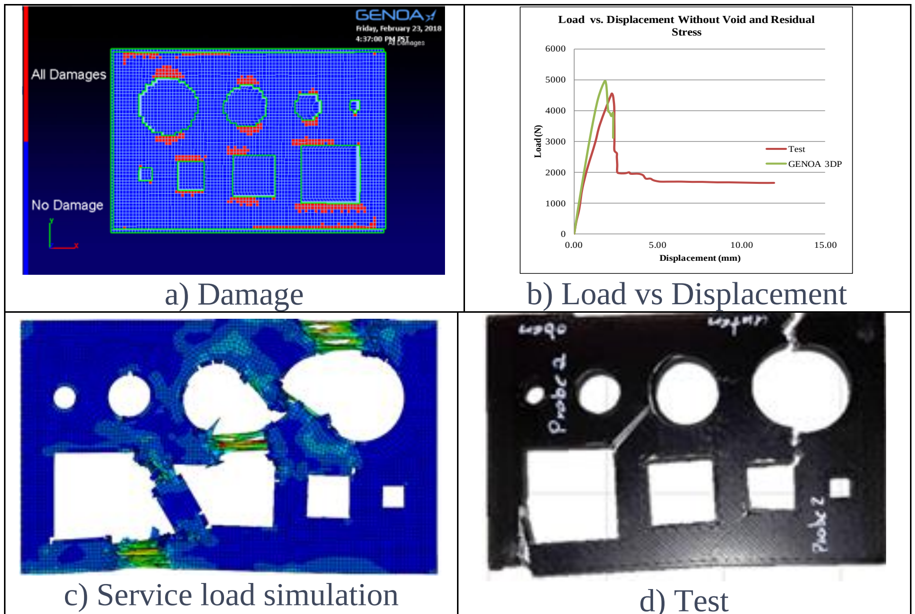
a) After Print in Chamber — b) Cooling at Chamber

Figure 4*. Uncoupled Thermal Analysis*

Service Load / Performance

Following material modeling and process modeling, an accurate understanding of material behavior as well as damage initiation and damage propagation was established. As a final exercise, the team explored part qualification in terms of service loading. Accordingly, the as-built virtual AM panel was subjected to virtual tensile loading and compared to real world test results. **Figure 5** shows the resulting failure process, load displacement, and damage. The simulation was performed running GENOA Multi-Scale Progressive Failure Analysis as a subroutine within the Abaqus solver. After performing 3D printing coupled structural thermal analysis, the base plate from the specimen was removed, and the service load simulation was undertaken with the following assumptions: part service loading (static), displacement control, max stress-based failure criteria, no residual stress from 3D printing, and applied progressive failure analysis (PFA). The results showed good agreement with test.

In conclusion, GENOA 3DP is an essential tool for maximization of AM fabrication technology. The powerful features and user-friendly controls support optimization and qualification of AM parts. The current study simulated service loading of the as-built AM fabricated part which showed good agreement with test and provided another avenue for qualification.



a) Damage | b) Load vs Displacement | c) Service load simulation | d) Test

***Figure 5**. Qualification and Service Loading*