Composite Overwrapped Pressure Vessel Modeling and Analysis

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The use of lightweight composite overwrapped pressure vessels (COPVs) in applications requiring high performance at minimal weight has led to widespread use of COPVs in aerospace, aeronautics, vehicles, mining, and firefighting. However, the complex nature of COPVs makes analysis inherently difficult.

White Sands Test Facility (WSTF) maintains an ongoing effort to improve the capability of accurately modeling COPVs with the use of numerical techniques to simulate their behavior. Over the past 4 decades, NASA has developed advanced numerical modeling tools that allow for complex analysis of composite structures. Technology transfer from the government to the private sector has allowed the development of these analytical tools for the composite industry.

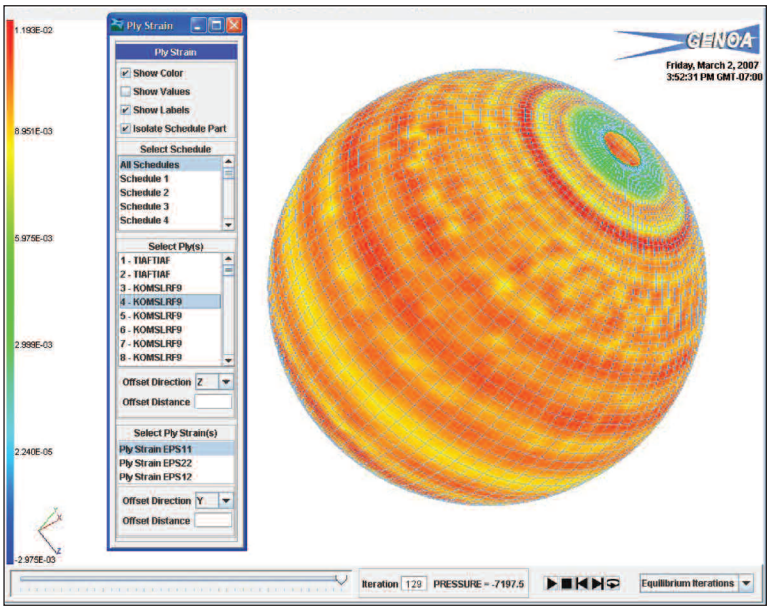

Fig. 1. Typical stress pattern.

Numerical Tools

WSTF partnered with AlphaSTAR Corporation (Long Beach, Calif.) to develop tools to address COPV-specific modeling issues and integrate these tools into their flagship software suite known as General Optimization and Analysis with Progressive Failure Analysis (GENOA PFA). This effort has spanned nearly a decade and spawned the following capabilities specific to COPVs:

- Direct automated composite ply pattern assignment based on manufacturer's filament winding patterns
- Numerical simulation of manufacturing curing processes to model residual stress as boundary conditions of more advanced analysis
- Numerical simulation of COPV sizing processes (autofrettage)
- Extensive fiber, matrix, and ply database of material properties used in construction of COPVs

GENOA PFA is a hybrid code that successfully integrates the use of micromechanics analysis of the three-dimensional ply structure of the composite and global finite element analysis (FEA) coupled with damage tracking. This allows the researcher to not only determine the standard stresses and strains in a composite structure, but also to perform detailed analysis on the composite itself.

The micromechanics capability allows detailed information to the level of each individual ply, including fiber and matrix properties at every ply layer in the structure. The micromechanics model can determine all principle stresses, shear forces, and bending moments, thus allowing a stepwise analysis of the structure as loads are applied. The micromechanics model also allows the calculation of aggregate material properties at each node in the model. This means a specific set of real parameters is developed, per node, including thickness, modulus, and thermal properties, which are of particular benefit when ply lay-up patterns have different angles at different depths as found in the complex winding patterns used in COPVs. Each node can be assigned an accurate set of properties specific to the location of interest.

Damage Tracking

The onset and progression of damage is of vital importance to the health of any composite structure. The use of the micromechanics model allows for examination of limits within every ply at the fiber and matrix level of the structure for comparison to an established set of failure criteria including, but not limited to: tensile; compressive; transverse; rotation; modified distortion energy; and strain invariant failure theory. Coupled with user-defined failure

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continued

criteria based on empirical data for specific composites, this ability allows for dynamic updates of the structural properties based on the failure mode(s). For example, a fiber breaking in a particular ply layer changes the ply lay-up, and stress redistributes around the broken fiber. The fiber can be numerically "removed" from the model to update the material properties at that point, providing a means to account for identifying, tracking, and updating the model that is dynamically based on the damage effects. The matrix material is simultaneously analyzed and can be evaluated in the same manner as the fiber. For example, matrix cracking effects can be tracked and accounted for within the ply lay-up and the properties adjusted accordingly. This process of step-by-step analysis of the micromechanics while updating the global model FEA from changes at the ply level is known as progressive failure analysis. The advantage to the researcher is the ability to not only determine where the structure fails, but also how the structure fails as greater loads are applied, or as damage accumulates under cyclical loading.

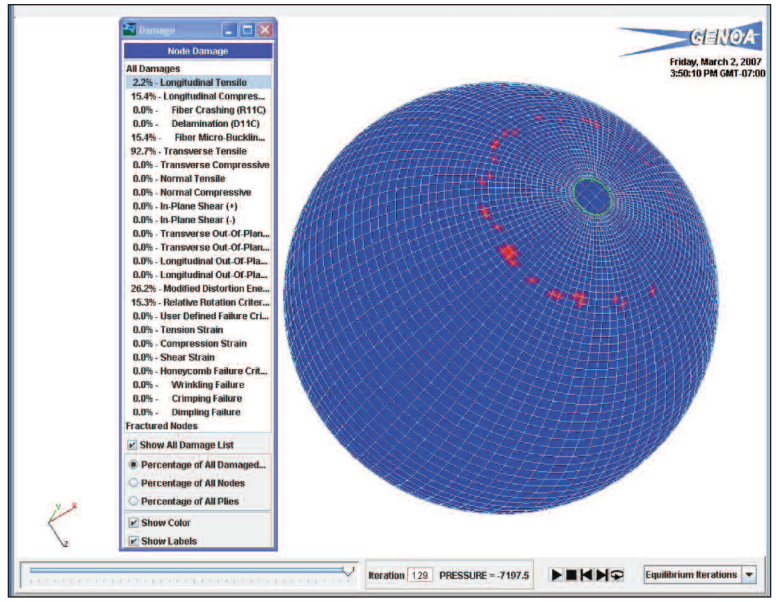

Fig. 2. Longitudinal tensile fiber failures.

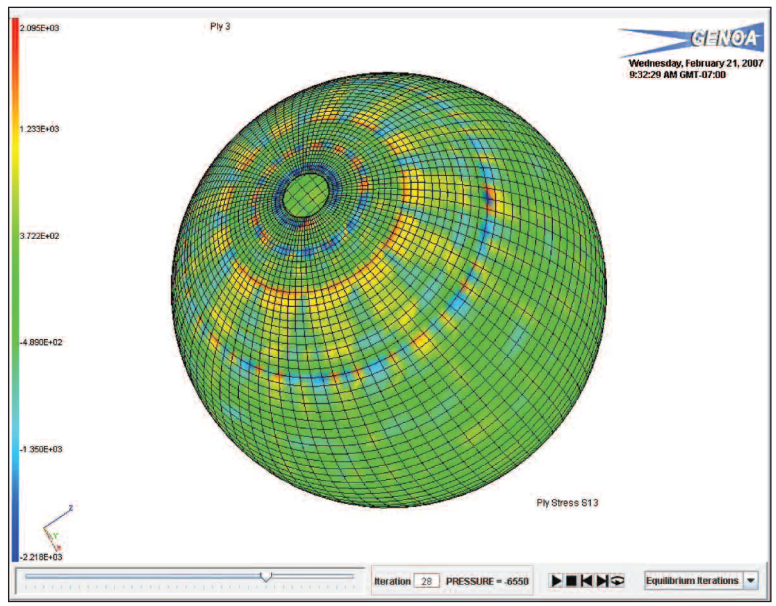

Fig. 3. Shear stress field.

Example Models

Different graphical outputs from a polyamide/epoxy overwrapped Ti-6Al-4V metal liner COPV model are shown. Figure 1 illustrates a typical stress pattern found in a ply layer near the metal liner while under internal pressurization. This stress pattern is given in the local ply coordinate system and is in the direction of the fiber. The low-stress region around the equator is due to the weld buildup area, making this vessel stiffer around the equator as compared to the membrane region. The lower stress field around the boss areas is typical of this type of COPV structure, since it is usually dominated by the metal liner in the thicker boss regions. Figure 2 shows the onset of longitudinal tensile fiber failures (shown in red) in this particular COPV. Figure 3 illustrates a transverse (normal to the fiber direction) shear stress field in a ply layer near the metal liner surface.

Summary

WSTF continues to develop and improve analysis of COPVs using advanced composite simulation software to further the understanding of these complex structures. Continued cooperation between government and private sectors is critical as COPV use expands toward new horizons such as hydrogen gas storage for terrestrial vehicles and the ever-increasing use of different types of fibers and matrix materials in more advanced COPV designs in aerospace and other industries.