Digital Engineering Advances in the Design and Analysis of Composite Overwrap Vessels (COPV)

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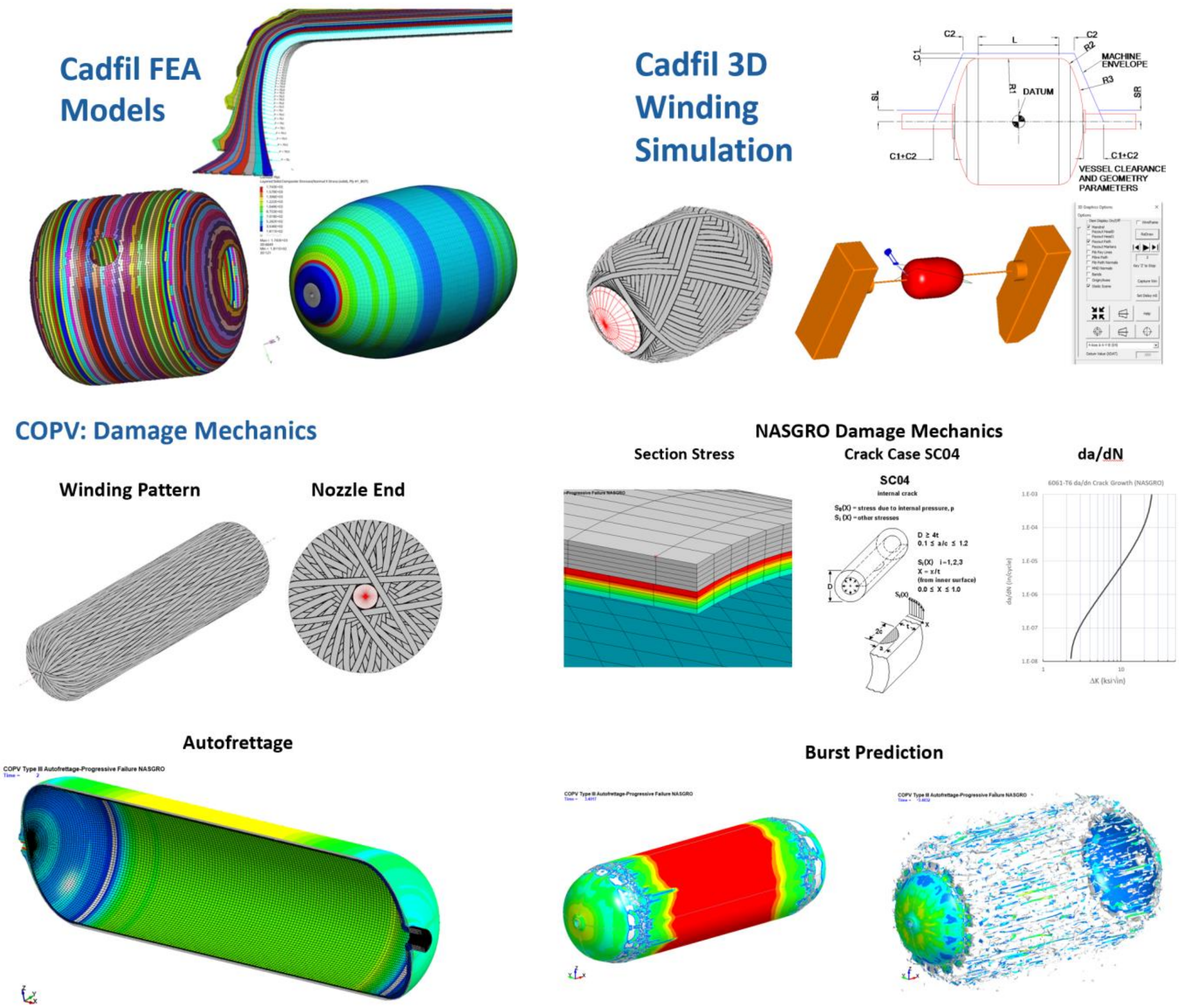


1. INTRODUCTION

There is currently huge commercial interest in the development of high-performance Composite Pressure Vessels (COPVs). A significant driver of this is in the field of low emission and renewable energy technologies for transportation. In transportation applications vessel weight/volume ratios are key which means that high performance composites are the only commercially viable solution. The filament winding process is highly suited to the manufacture of COPVs. The winding process can be fully automated, is highly repeatable and allows the placement of continuous high strength fibres in an efficient manner to meet the demanding structural requirements.

For Compressed natural gas (CNG) is typical filled at around 250Bar, Hydrogen in the 450-700Bar range but for maximum capacity minimum size 700 bar is the target. Because of the potential risks of such high pressures, rigorous design and analysis of COPVs is required. A thick wall COPV is built up of a large number of filament-wound layers, and particularly in the dome areas, the fibre direction and layer thickness is continuously varying. This creates a problem for making detailed and representative finite element models of the fibre architecture. The solution to this problem is to employ software tools that understand the physics, materials, geometry and manufacturing considerations that can allow a designer to simulate feasible winding structures and create a seamless data flow into FEA analysis tools. Established in 1984, Cadfil is a leading solution for creating winding programs for CNC and Robot systems. Cadfil has many direct interfaces into many FEA tools and has recently added support for LS-DYNA (ANSYS).

LS-DYNA is a general-purpose FEA program capable of simulating complex real-world problems. It is extensively used by the automobile, aerospace, construction, military, manufacturing, and bioengineering industries. Its particular strength for the analysis of COPVs is its ability to simulate highly-nonlinear physics from plastic deformation of the liner to progressive fiber failure in the composite and to dynamically simulating the burst test.

Although the material in this article is based on a real-world COPV, Type III design and analysis project, we have created a generic COPV to illustrate the workflow from winding to autofrettage to damage mechanics to burst.

2. WORKFLOW

2.1 DESIGN

The starting point is the geometry of the liner. Figure 1 shows an aluminum 6061 liner with a closed base and a single neck. The liner has an external diameter of 310mm with an overall length of 1100mm. Its capacity is 70 liters. Seamless thin wall liners of this type can be made by well-established metal forming processes. The geometry consists of a planer surface which can be used to establish the liner mesh. The external curves are exported into Cadfil as a base for the filament winding process.

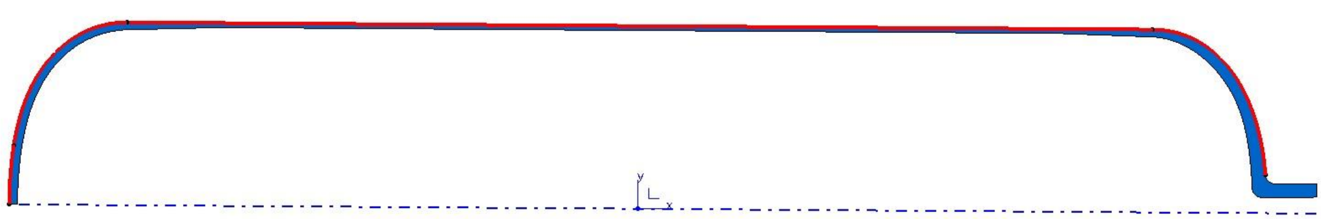


Figure 1: Geometric surface 70L liner 300mm diameter x 1100mm

A pressure vessel rule-of-thumb, is that the hoop stresses are twice the axial stresses. A wound composite is very strong and stiff in the fibre direction as the fibre property is dominant, the transverse direction at 90 degrees to the fibres is relatively weak as this property is dominated by the resin. As is normal with COPVs, you need to create low angle windings to cover the domes and provide axial strength and hoop (circumferential) windings on the cylinder to provide hoop strength. This is one of the beauties of the winding process because the fibre structure can be optimised efficiently to meet the structural requirements. Figure 2 shows the vessel with a low-angle wind and a hoop wind.

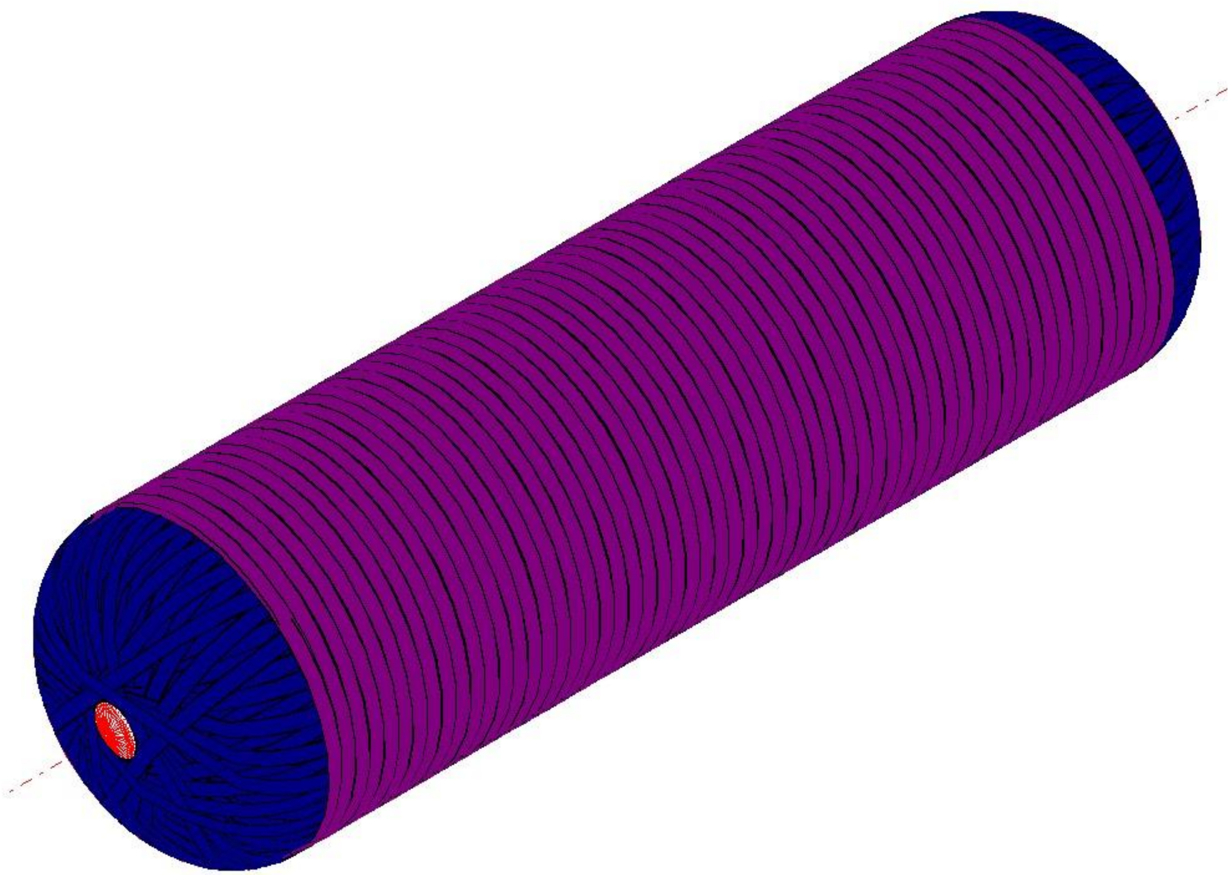


Figure 2: Helical (low-angle) and hoop layers as created by Cadfil

For the purposes of this demonstration, we generated a couple of low-angle winds. The first has a nominal wind angle on the cylinder of +/-7 degrees but the path has non-geodesic adjustments such that the fibre band touches the neck of the boss at one end and touches the extremity of the dome at the other. This ensures the liner is fully covered. This can be seen in Figure 3. A second low-angle winding was created with the end opening increased at the closed dome end. The reason being that the build-up of thickness in this area is very large due to the concentrated overlapping bands.

Low-Angle Wind with Band Closing to Neck	Low-Angle Wind with Band Closing Apex of Base Dome

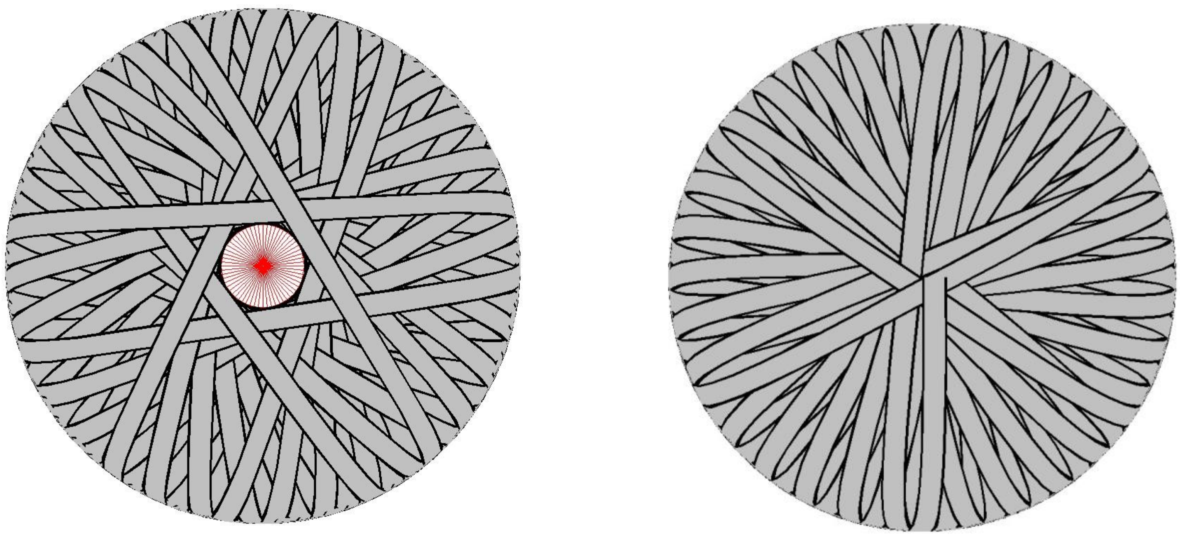


Figure 3: Low-angle winding patterns for neck and base dome regions

The hoop winding is made up of circumferential bands that advance along the cylinder by one band width for each rotation of the mandrel. In this example, the hoop winding has a double pass advancing from one end of the cylinder to the other and then back to the start. Because the start and finish position, this layer can be simply repeated a number of times as required with each repeat adding two band thicknesses. It is not possible to hoop wind on the dome, the fibres will simply just slip off, but it is possible to encroach a very small amount onto the start of the dome where the slope is small. In this example, we created four different hoop layers where the start and end positions are different by a few mm each. This is required to avoid a step thickness change. Such a step is not desirable for design and analysis considerations.

In Figure 4 below you can see a 3D FEA axisymmetric mesh near the dome/cylinder interface. In this figure, one can see that the thickness change is blended over a distance via wedge elements. These elements are automatically created by Cadfil to prevent a step discontinuity in the mesh. We give these elements the same mechanical properties as that of the resin. This is quite realistic, since as in practice, where plies drop off, small pockets form which are then filled by resin.

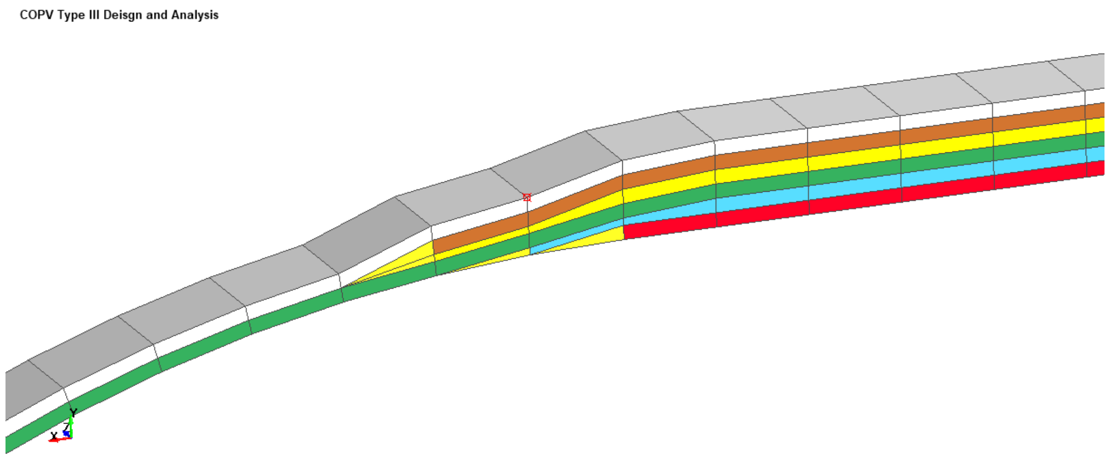


Figure 4: Tapered drop-off of hoop plies at cylinder ends

The material selected for the winding programs was Hexcel HexTow® IM7 carbon fibre and intermediate modulus high-strength PAN-based fibre, available with a 12,000 (12K) filament count. The fibre data came direct from the Cadfil database of commercial materials. The selected material assumed a 65% fibre volume fraction and 3 rovings of 5mm width with a standard resin. This gives a 15mm wide fibre band that has a thickness of around 0.08mm. The helical and hoop windings were included in a winding sequence as shown in Table 1. Each of the program elements shown in Table 1 give a double (2-ply) layer of the cylinder and in each case, you can note that the layer is being repeated 5 times. For each component in the winding sequence, Cadfil generates thickness and direction data and then calculates the FEA composite mesh. For quick design iterations it is very easy just to edit the winding sequence to add, delete or repeat winding elements and then automatically regenerate the FEA mesh using previously defined settings with a single click.

Table 1: Winding Sequence

Combine Programs

Item	.PAY file	Repeat	Cycle/la...	BandWidth	.MND File	Start Pos	End pos	TypeID	FeedR	FeedMode
1	h70A01H00.PAY	5	1	15.00	h70A01H00.MND	431.0	431.0	30	5000.0	2
2	h70A01H01.PAY	5	1	15.00	h70A01H01.MND	435.5	425.5	30	5000.0	2
3	H70L01.PAY	5	64	15.00	M70L01.mnd	-533.9	-533.9	15	5000.0	2
4	h70A01H02.PAY	5	1	15.00	h70A01H02.MND	439.5	429.5	30	5000.0	2
5	h70A01H04.PAY	5	1	15.00	h70A01H04.MND	442.5	442.5	30	5000.0	2
6	H70L03.PAY	5	65	15.00	M70L01.mnd	-533.5	-533.5	15	5000.0	2

Having established the winding sequence a user can go the Cadfil Numerical control (NC) menus and generate complete control programs for the target filament winding machine. As an example, it could be a CNC system such as a Siemens Sinumerik , a general G-code controller or Robot winders such as Kuka and ABB. Another option is to go to the FEA menu and process the winding data to create complete FEA models. Cadfil supports several model types from axisymmetric to full shell and solid meshes. There are a wide range of FEA options such as boundary conditions, materials, pressure loads and so on. Currently Cadfil has direct support for MSC Nastran, Simcenter Nastran, Altair Optistruct (& HyperWorks), ESAComp, Abaqus, ANSYS and LS-DYNA.

Figure 5 shows an example of the FEA mesh generated from Cadfil. This type of mesh is used for an axisymmetric analysis of the COPV. The Cadfil program can apply internal pressure loads and boundary conditions for the analysis creating a run-ready *KEYWORD deck for LS-DYNA.

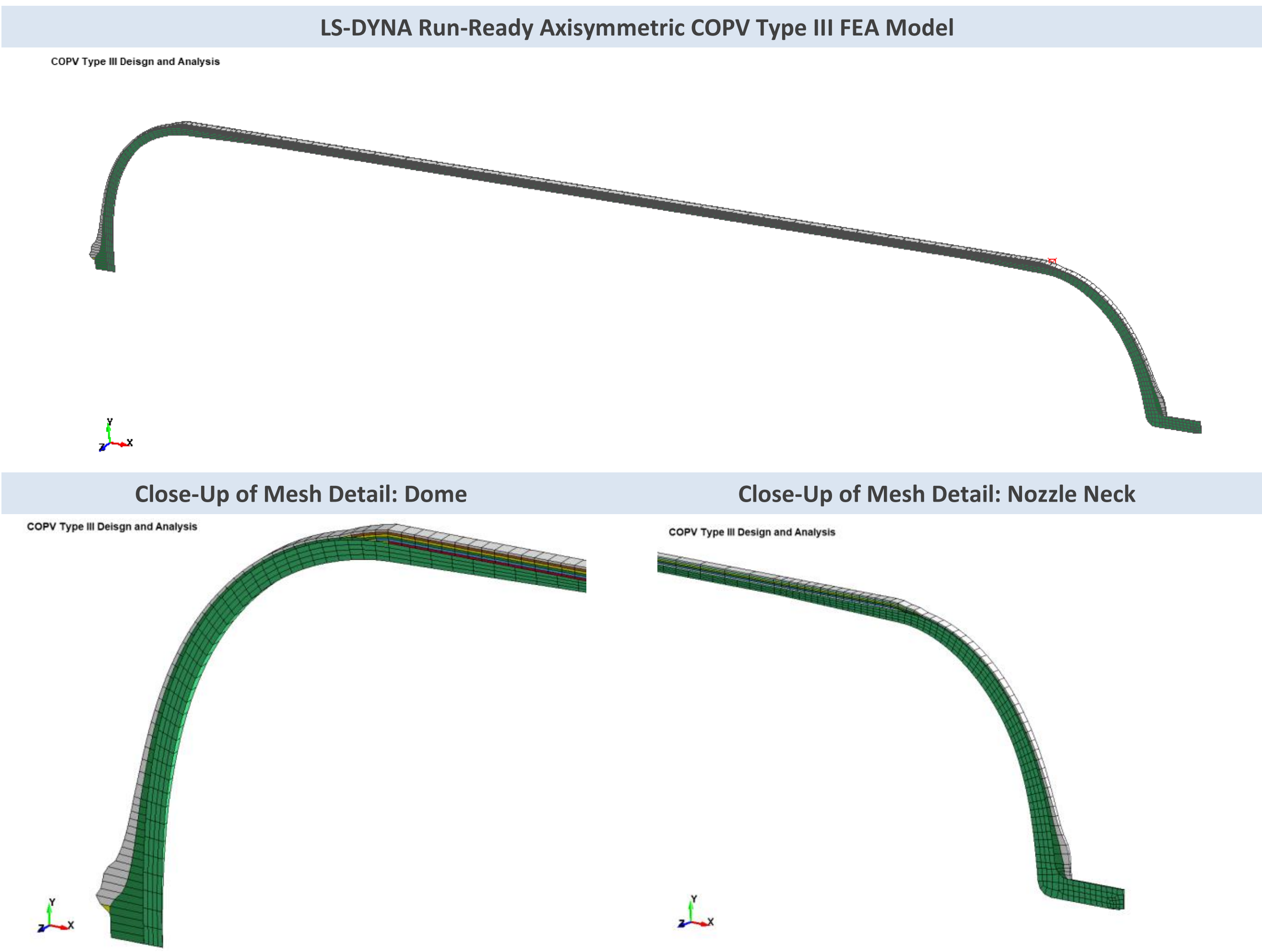


Figure 5: Axisymmetric LS-DYNA FEA model

2.2 Analysis

2.2.1 Fatigue Life Improvement

To extend the service life of COPV Type III vessels, many manufacturers employ the autofrettage process. Figure 6 provides a graphical explanation of this Napoleonic era gun-barrel enhancement technique. Once the liner has been plastically deformed under internal pressure, a compressive stress will then form in the inside of the liner once the pressure is removed. Under operating pressure, the liner's hoop stress is a fraction of that without autofrettage. Although the stress in the composite overwrap does increase, it is not a fatigue concern since the liner is the limiting factor.

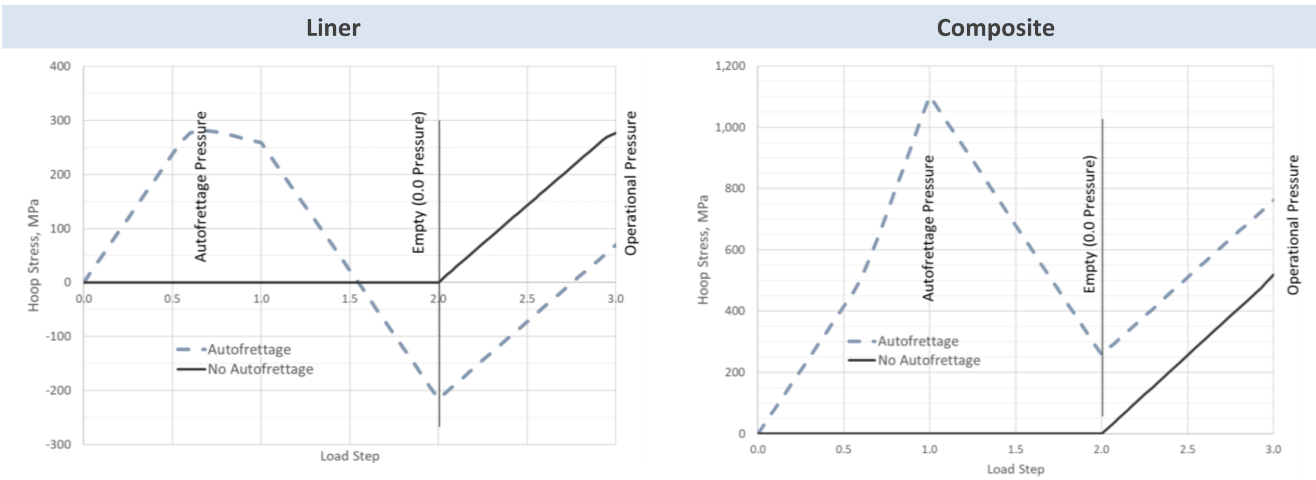


Figure 6: Benefits of autofrettage in COPV Type III vessels to significantly lower operating stress in the liner

2.2.2 Burst Analysis Prediction

A standard requirement for COPV certification is the burst test. Given the complexity of simulating such an event, most manufacturers add additional composite layers as insurance. With today's modern analysis tools, accurate burst pressure predictions can be made virtually allowing the manufacturer to optimize the weight versus performance of the COPV prior to fabrication. Figure 7 shows the full COPV model as it is pressurized from its design pressure to its predicted burst pressure. The complete 360° FEA model is easily generated and then virtually tested using LS-DYNA.

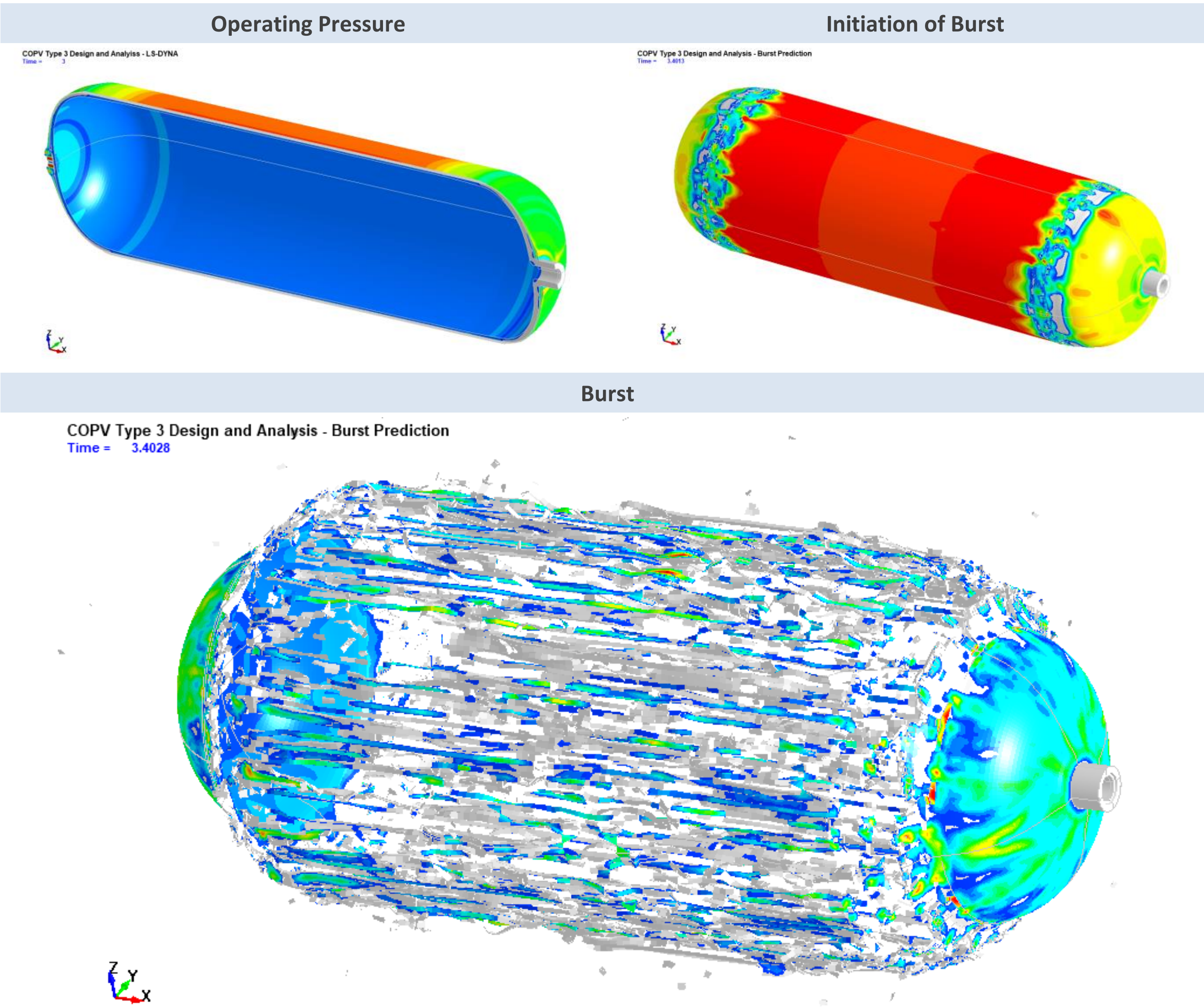
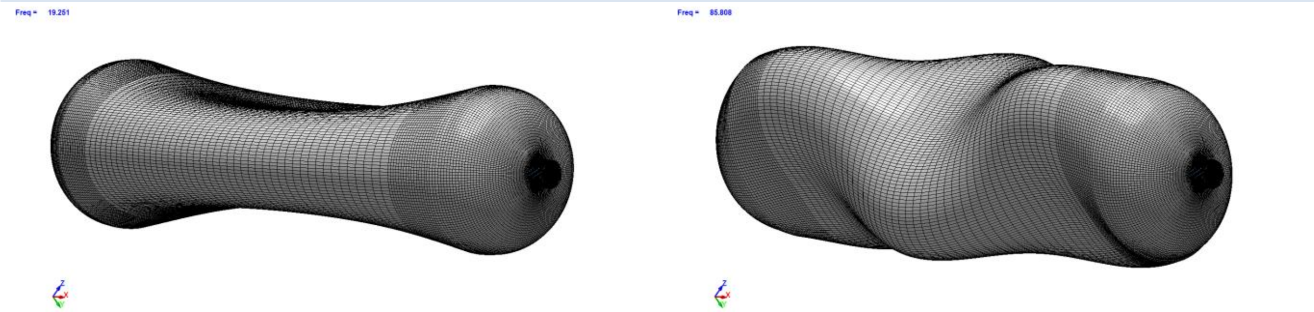


Figure 7: LS-DYNA COPV burst prediction

2.2.3 Vibration Analysis

With a full 360° model, one can also perform a vibration analysis from normal modes, sine-sweep, or a multi-axis PSD analysis. Figure 8 shows results generated from the Cadfil model using LS-DYNA.

Normal Modes (Eigenvalue) Vibration Analysis



PSD Analysis

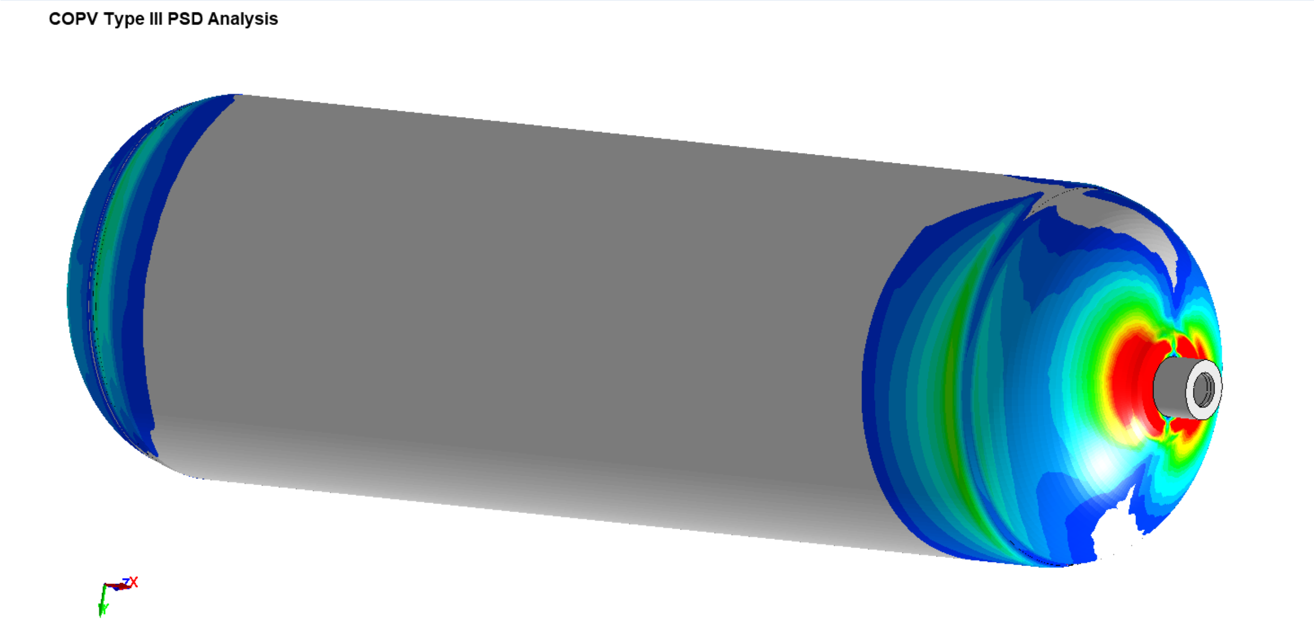


Figure 8: LS-DYNA COPV Type III vibration analysis from normal modes to PSD

3. WHAT HOLDS FOR THE FUTURE?

Historically, the design and analysis of COPVs has been done by using custom codes and dedicated algorithms developed by embedded engineers. Such cobbled together systems had their days of glory when there was no other way forward. These systems were also dependent on the engineers that developed the scripts. We propose a much simpler design and analysis path using "off-the-shelf" industry standard software programs (Cadfil and LS-DYNA) that are easy to learn and offer unparalleled optimization possibilities. Data centric design processes that are integrated with manufacturing data realise more reliable products faster. Such open-door accessibility allows the COPV manufacturer to focus on production goals knowing that their design will pass client review and burst testing without leaving any money on the table.