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FILAMENT WINDING SIMULATION OF A COMPOSITE OVERWRAPPED PRESSURE VESSEL

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ABSTRACT

Filament winding has proven to be a viable manufacturing technique to produce composite overwrapped pressure vessels (COPV) for use in space applications. This technique incorporates winding of composite pre-pregs tapes over a thin metal shell followed by curing. Simulation of this manufacturing process and subsequent assessment of vessel durability and damage tolerance (D & DT) is a computationally challenging task, which requires progressive failure analysis (PFA). This demanding task can be accomplished using GENOA Progressive Failure Analysis (GENOA-PFA), a tested virtual design/analysis software capable of simulating progressive failure of composite structures in a variety of situations. A GENOA-PFA module simulating the manufacturing process for COPVS has resulted in integration of manufacturing, progressive failure, and probabilistic analysis into a robust software package, GENOA-COBSTRAN. GENOA-COBSTRAN has been used to simulate the manufacture and pressurization of a filament wound cylinder consisting of an aluminum 6061-T6 liner overwrapped with graphite-epoxy composite. The result of the simulation are presented and show 1) the failure pressure, 2) damage progression and 4) locations and failure modes of failure.

KEY WORDS: Composite Materials , Finite Element Analysis (FEM), Filament Winding.

1.INTRODUCTION

Fiber reinforced Composite overwrapped pressure vessels (COPVs) achieve significant weight reduction by utilizing the high strength and stiffness of composite materials. The GENOA-COBSTRAN code is designed to carry out analyses required to efficiently design and analyze these filament wound pressure vessels, fabricated by over-wrapping thin metal liners with continuous high strength fibers embedded in resins. Typically the metal liners are made of lightweight aluminum alloys (tempered to T6) and the composite tape wrappings are made of high stiffness fibers (eg., carbon, glass and Kevlar) embedded in epoxy resins. The manufacturing process involves wrapping pre-tensed pre-preg composite tapes of the over a pressurized metal liner. HOOP, HELICAL and POLAR are the three main wrapping techniques used. After wrapping, the cylindrical vessels are cured in furnaces at the recommended cure temperature and then tested for service. The operating pressures of most tanks are of the order of 14-30 MPa, with the burst pressure 1.5 to 3 times the operating pressure.

2. COPV AND MATERIAL DESCRIPTION

The aluminum liner used is generally manufactured by impact extrusion or deep drawing and spinning. A seamless liner without welds or joints is desirable to minimize potential failures from fatigue or mishandling. The liner material should have sufficiently high strength and plasticity. Aluminum 6061-T6 is a typical liner material.

High Specific strength and moduli are important considerations in choosing the fibers. Graphite and Kevlar are the fibers of choice in critical aerospace applications. Most strength critical aerospace structures are wound with epoxy-based resin systems. The choice of the resin system depends on its processing characteristics, curing requirements and physical properties of the resin which affect composite properties. Viscosity and pot life are important processing considerations. A low viscosity is required for complete wet-out of the strands and removal of the entrapped air.

3. ANALYSES OF COMPOSITE CYLINDERS

3.1 GENOA-COBSTRAN Analysis The detailed structural analysis of these composite cylinders involves understanding the proper material properties and using verified structural composite analyses. The *GENOA-COBSTRAN* module undertakes this task using advanced NASA composite mechanics codes combined with a special module for filament winding. The filament-winding module duplicates the manufacturing process to generate the correct tape schedule at each location on the cylinder. The flow-chart is given in fig.1.

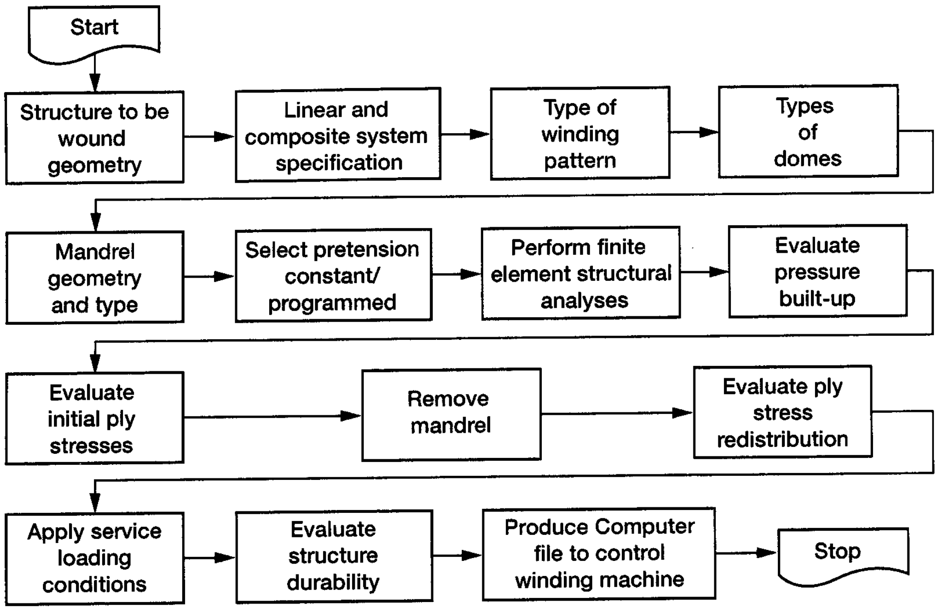


Fig.1 GENOA-COBSTRAN algorithm flow chart [1]

3.2 Coordinate Systems For input GENOA-COBSTRAN utilizes a right hand rectangular coordinate system in which the pressure vessel lies along the x-axis.(fig.2) The input coordinates are assumed to be on the internal surface of the cylindrical liner initially. The code then automatically translates these coordinates to the mid-thickness section in accordance with the thickness of the liner and the number of wrap plies generated by GENOA-COBSTRAN.

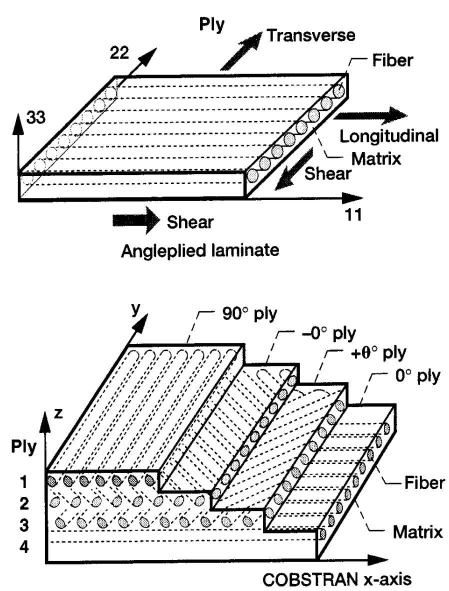
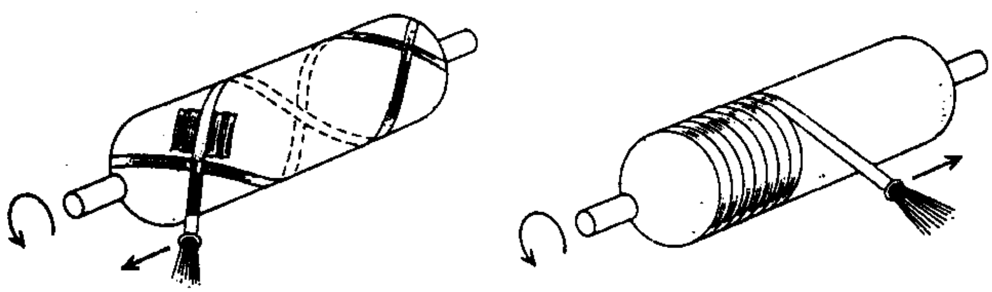


Fig.2 Fiber composite geometry and GENOA-COBSTRAN coordinate system [1]

3.3 Mesh Generation The mesh generation capability in *GENOA-COBSTRAN* is designed to create 2-D plate type meshes. All meshes are created with 2-D NASTRAN QUAD4 elements. Only quadrilateral elements can be generated. The user controls the mesh density by specifying the number of sections along the x-axis and the number of segments along the circumferential direction. *GENOA-COBSTRAN* calculates the surface geometry and generates a mesh based on this input. The coordinates of the mesh are first generated on the radii specified by the user-input parameters. These dimensions must be the internal dimensions of the pressure vessel, since the final thickness of the vessel is not initially known. Following the ply generation and designation of which plies exist at each node, the position of the node is transformed half of the ply stack thickness and normal to the internal surface.

3.4 Liner and Wrapping Descriptions Once the mesh is generated, a wrapping schedule can be specified for input to *GENOA-COBSTRAN.* simulates the manufacturing process to generate the correct ply schedule at each point on the cylinder (or equivalently each node). The inputs are the wrapping angles of the tapes and the number of circuits of each tape, which are used in the manufacturing process. Fig. 3 gives examples of hoop and helical winding. Fig.4 shows how a multi-circuit filament winding manufacturing process is undertaken. The input to the code then is the kind of winding, whether hoop, helical or polar. The liner and its properties are input first. For helical and polar winding the number of windings and the angles of winding are specified. Filament wound tanks are usually wound with a certain amount of tape tension in the tapes. To counter this tape tension the cylinder is internally pressurized so that there is no collapse or damage to the liner. This initial pressurization and tape tension is simulated by the code. This process gives rise to residual stresses in the tape winding which is calculated by the code.[3]



a) Helical winding b) Hoop winding

Fig.3 Filament winding patterns [2]

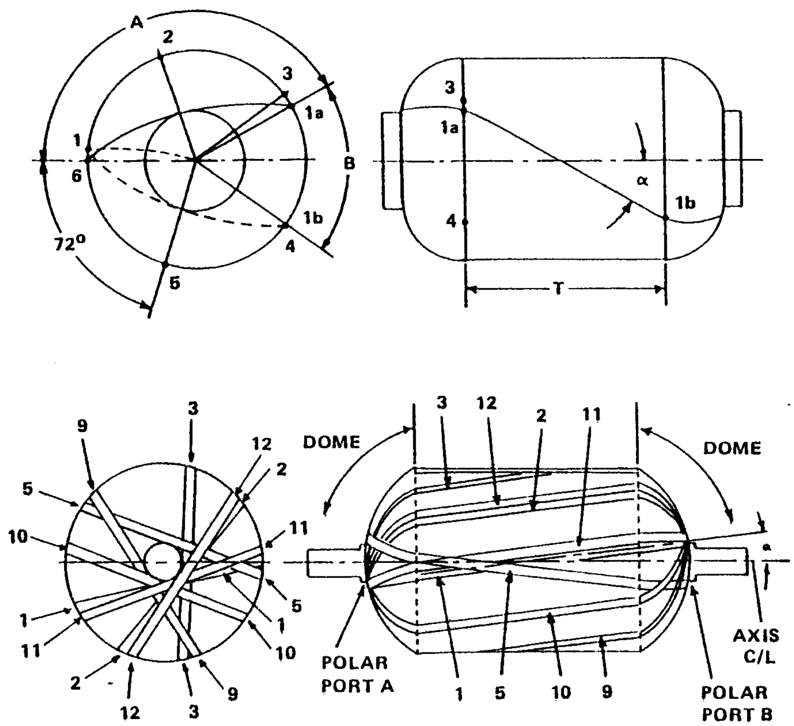


Fig. 4 Multi-circuit filament winding process. α is the helix angle. We can see the changing starting angle for each additional circuit.[2]

4. GENOA-COBSTRAN RESULTS

4.1 Input Model The following cylinder was modeled using GENOA-COBSTRAN.

Aluminum liner over-wrapped with a combination of hoop and helical windings.

Table 1 COPV specifications for simulation.

Inner Diameter	Length (Hoop section)	Length (Hoop section)	Design Burst Pressure
6.045 ”	13 ”	20 ”	62 MPa

The winding used was made up of T300 fibers in an epoxy resin. The Aluminum was a 6061-T6 alloy. The results of the analysis are discussed in the next section.

4.2 GENOA-Progressive Failure Analysis The Finite Element Mesh for COPV is shown in Figure 4-3. The code pressurizes the cylinder internally to simulate the experiment to test the sustained design pressure. As the internal pressure increases the matrix starts to degrade. This degradation in the matrix is captured as damage by the code. Upon identification of damage the code updates the stiffness and other properties of the material to take into account this degradation. For a detailed review of the GENOA progressive failure methodology please refer to references 4-7. The damage initiation under internal pressure is shown in Figure 6. It is observed that the damage initiates at the border between the hoop and the dome region. The experimental evidence confirmed this. The main modes of failure are transverse tensile for the aluminum liner and longitudinal tensile, transverse tensile, in plane shear for the tapes. For the latter this is mostly matrix damage at this early stage. During damage propagation (Fig.7) these same modes are active, but in addition other modes like modified distortion energy and compressive failure modes are also seen. The various modes of failure and their relative percentages are seen in Fig.9 for the final failure stage, wherein the fibers break and the COPV is considered to have reached its design burst pressure. The code predicted a design burst pressure of 61.5 MPa against a predicted manufacture design burst pressure of 62 MPa. As the pressure increases the damage area increases in size, eventually leading to fracture due to breakage of fibers.

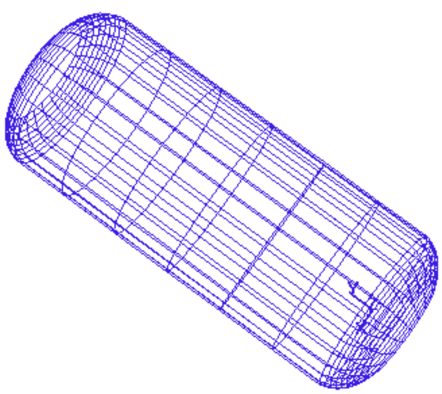


Figure 5. COPV Finite Element Mesh with Aluminum Liner 6061-T6 Under Internal Pressurization with Composite Tape Constituents of T300 Graphite Fiber immersed in Epoxy Resin with 644 Nodes, 616 QUAD4 Elements

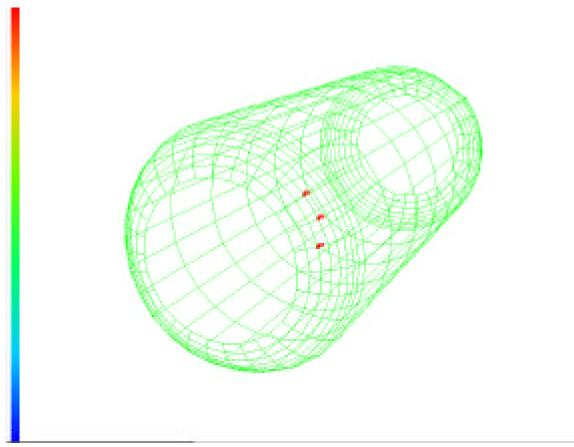


Figure 6. Damage Initiation for COPV under internal pressurization

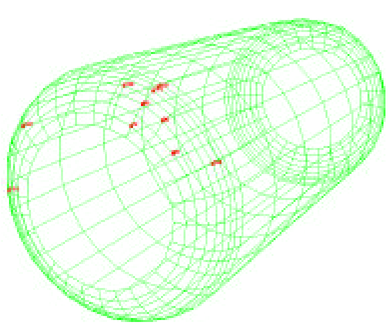


Figure 7. Damage Propagation for COPV under internal pressurization

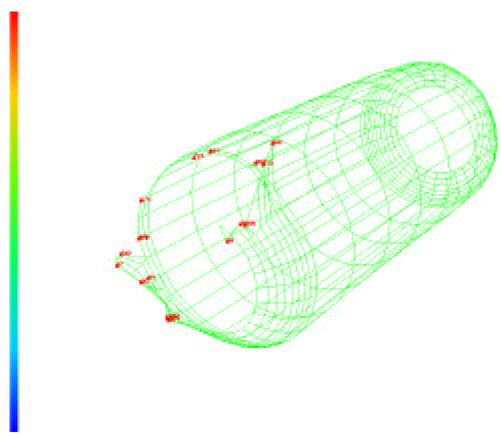


Figure 8. Final fracture for COPV under internal pressurization

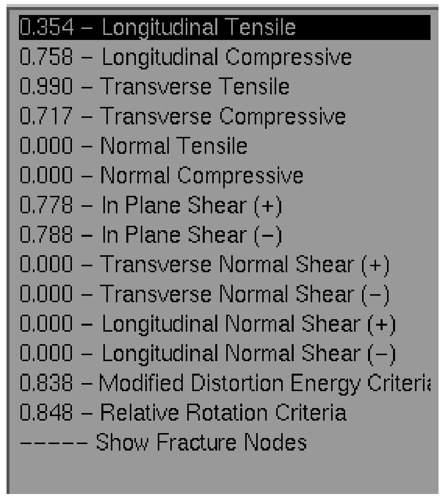


Fig.9 Various damage modes seen at the final fracture of the CPOV.

Figures 10 to 13 show the percent damage energy, damage energy release rate (DERR), and total damage energy release rate (TDERR), respectively, for COPV pressurized vessel. The rise and fall in the DERR curves shows the points on the pressurization where there are major damage events. At 13 MPa the matrix starts to damage. At 30-35 MPa the fibers start to break which then leads to final fracture. The percentage damage volume curve shows to what extent the material is [1]damaged.

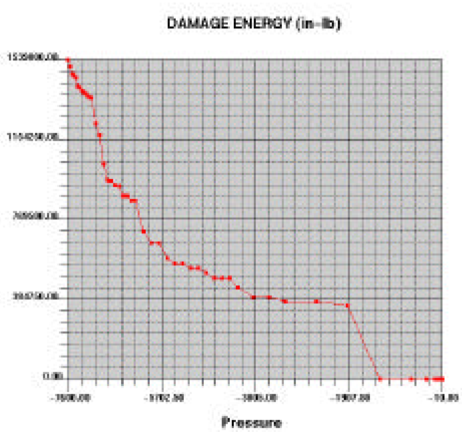


Figure 10. Percent Damage Energy for COPV under internal pressurization[1]

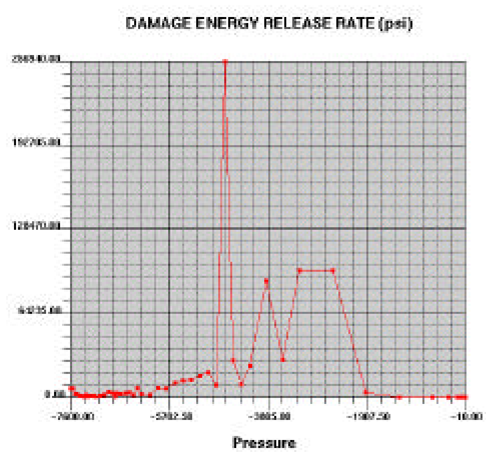


Figure 11. Damage Energy Release Rate (DERR) for COPV under internal pressurization

[1] Pressure in psi, 1psi = 0.00689 MPa, 1inch = 25.4 mm

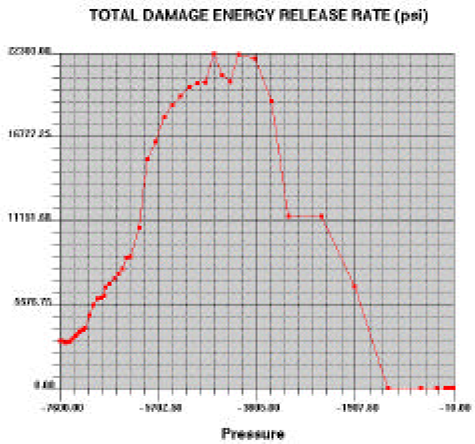


Figure 12. Total Damage Energy Release Rate (TDERR) for COPV under internal pressurization

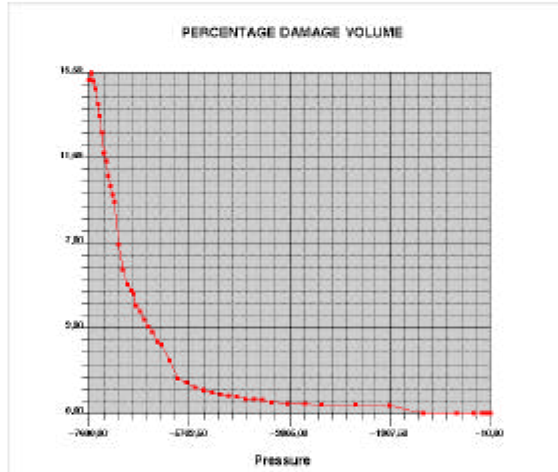


Figure 13. Percentage damage volume for COPV under internal pressurization

5. CONCLUSIONS AND USES

An overview is provided with an example of a computational procedure to evaluate filament wound pressure vessels. The procedure uses composite mechanics with finite element analysis. Unique features of the code include pre-tension calculation, damage initiation, propagation and final fracture, modes of damage. In addition to circular cross-sections with spherical end-domes the code has the flexibility to analyze diverse cross sections and domes. At present circular and elliptical cross sections are incorporated. Spherical, Elliptical and Geodesic dome caps can be simulated. As was mentioned earlier the tape tension during manufacturing can be used as an input to generate the residual pressure generated in the cylinder. The code can be effectively used to predict the sustained loads to failure of pressure vessels in critical aerospace applications as also help designers design a better pressure vessel.

The code is presently being enhanced to incorporate the visualization of the change of angles in the fibers during pressurization.

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