/N-24

372 750

By Greg Walton, Senior Writer/Mechanical Engineer

Just the right amount of reinforcement

Fiber placement tackles the X-33 liquid hydrogen fuel tank's requirements for durability, strength, consistency and light weight.

Lockheed Martin Skunk Works (Palmdale, Calif.) is taking the next step towards economical low-Earth-orbit (LEO) operations with NASA's X-33 technology demonstrator that uses composite tanks for liquid hydrogen (LH_2) fuel storage and structural support. The X-33 is a 53% scale model of the VentureStar single-stage-to-orbit (SSTO) reusable launch vehicle (RLV) projected to orbit payloads at a rate of $1,000 per pound beginning in 2004.

In order to make VentureStar completely reusable and economical, engineers are using composite materials throughout the spacecraft's structure. The first test of the design comes in 1999 on the X-33 technology demonstrator. Two of the primary structures that engineers will be evaluating are the carbon fiber/epoxy LH_2 fuel tanks. The 29-ft long by 18-ft wide tanks, which fill two-thirds of the X-33's interior, serve a dual purpose carrying fuel and providing structural support to the walls of the spacecraft.

Fiber placement makes it possible to build the fuel tanks, large, light and strong enough to satisfy X-33's requirements. Lockheed Martin chose the fabrication technology to produce the eight sections of each tank because of fiber placement's ability to handle complex surfaces, speed and repeatability.

Tank design

Lockheed Martin designed the LH_2 tank in a shape to generate as much storage volume as possible within the body of the X-33. More volume translates into more lifting capability. The tank contains more than 30,000 lbs of fuel pressurized up to 50 psi. It is a bonded assembly of four conic-section shaped lobes capped at each end by two-piece domes (see illustration). The design uses the rounded sides to achieve a higher pressure rating than that of a flat-sided tank.

In addition to holding internal pressure, the tanks endure external forces of up to 420,000 lbs during liftoff. Engineers use the tank's strength to support the outer surfaces of the X-33. The four lobes that make up the barrel section of the tank are designed as sandwich structures to improve shear strength and transfer loads from the outer skin of the spacecraft.

The tank is fabricated with [redacted] carbon fiber from Hexcel Corp. (Salt Lake City, Utah) and [redacted] epoxy resin from Cytec Fiberite (Anaheim, Calif.) in the form of prepreg tow and woven fabric. These materials demonstrate satisfactory structural requirements over the operating temperature range for the X-33 — from -423°F of cryogenic fuel to 250°F during re-entry. NASA test data verified that these materials were compatible with LH_2.

Fiber Placement Process

Lockheed Martin subcontracted Alliant Techsystems Inc. (Magna, Utah) to fabricate the tanks using fiber placement. By utilizing fiber placement, reinforcement was located precisely and only as needed, so that the tank could withstand the internal and external forces while remaining within weight constraints. **What are the constraints?**

Using CATIA (Dassault Systemes or Suresnes, France) models of the tank supplied by Lockheed Martin, Alliant generated mandrel designs for the sections. Boeing (Tulsa, Okla.) (formerly Rockwell) hand layed-up seven mandrels — four for the lobes and three for the domes — using carbon fiber/epoxy prepreg to match the coefficient of thermal expansion (CTE) of the tank sections. Alliant Techsystems also used the CATIA models to develop fiber placement paths for the fiber placement equipment. Alliant simulated several paths to determine the most efficient placement process and then proof-tested the program on the FPM-6 fiber placement machine.

Alliant uses their FPM-6 fiber placement machine to fabricate the eight sections of the X-33 LH_2 tank. It is the sixth machine designed by Alliant and built by local Utah contractors **When?** for in-house production of parts at a cost of approximately $3 million. **What else is it used to fabricate?** It is a 7-axis (seven degrees of freedom) machine capable of fabricating parts up to 47-ft long and 11.3-ft wide. FPM-6 is fed by up to 32 12K carbon fiber prepreg tows which are typically placed in a 3-inch wide band on the mandrel. While the FPM-6 can dispense tow at a rate of 1,500 inches/min, it usually runs slower as it adjusts for the contour of the part. The FPM-6 can start and stop individual tows on-the-fly, a feature that allow it to place plies as much as four times faster than machines that must stop their motion in order to cut tows.

Various ply shapes may be created by tow cutting and tow steering. Each of the individual tow ends can be started or stopped, which allows a 3-inch wide lay-up to end abruptly or be gradually narrowed to zero. Tow steering, slowing down the dispensing rate of individual tows, allows FPM-6 to lay material evenly over curved surfaces. The FPM-6 stays within a $\pm 2°$ ply orientation tolerance as it places tow for the fuel tanks. Based on the scale-up plans for the VentureStar RLV, Alliant's FPM-6 is capable of building the full-size LH_2 tanks.

In preparation for production, Alliant mounts creels of carbon fiber/epoxy prepreg tow within a refrigeration unit on the fiber placement machine which cools the tow and controls the humidity. Properties such as tackiness and flexability, which are essential to proper dispensing of the tow, are controlled by adjusting the temperature and humidity.

Layer-by-layer lobes

The FPM-6 fabricates the inner skin of the X-33 LH_2 tank lobes with 13 full coverage plies. Andy Adams, LH_2 tank design leader at Lockheed Martin, points out that, the plies for the inner skin of the lobes are placed in a modified semi-isotropic arrangement. According to Mark Messick, LH_2 tank program manager at Alliant, the FPM-6 takes approximately 4 hours to place each full coverage layer of the 176 ft^2 tank lobe surface.

The individual tows are fed through the fiber placement armature to the head where they are grouped close together to form a ribbon of material. Prior to being pressed onto the mandrel surface, the tow ribbon is warmed — increasing tackiness and improving adhesion to the mandrel — by forced air from a nip point heater. The fiber placement machine's elastomeric delivery roller conforms to the shape of the mandrel as it compacts the tow onto the surface. A relatively high durometer elastomer roller is used when placing the fuel tank's plies, because the parts have a moderate curvature.

After fiber placing the inner skin of the tank section, the lay-up is vacuum bagged and autoclave cured ~~to 350°F~~. Messick states that, Alliant conducted an extensive research and development study to determine the optimum time and pressure at which to cure a fiber placed part. Because the inner skin provides the primary strength and permeability protection for the LH_2 tank, after curing it undergoes photomicroscopy and other tests to verify the integrity and void content of the material. The void content of the parts has consistently met the less than 2% requirement.

Korex, an aramid honeycomb from DuPont (Wilmington, Del.) was chosen for the core of the lobe wall for its light weight, thermal stability, shear resistance, and limited moisture absorption properties. It can be heat formed and shaped to match a part contour. Once cut and shaped, the Korex, ranging in thickness from 1.25- to 1.5-inches depending on the shear load, is bonded to the inner skin with ~~AF191~~ adhesive film from 3M (St. Paul, Minn.). The inner skin and core is vacuum bagged and autoclave cured ~~to 350°F~~.

With the core bonded to the inner skin, Alliant begins the fiber placement of nine coverage plies to form the outer skin. Reinforcement doublers, ranging from three to seven plies thick, are placed in selected areas, such as around the joints, to strengthen the tank wall against concentrated loads and flexing. Messick notes that, positioning and sealing the vacuum bag over the completed sandwich structure must be carried out carefully to ensure that it does not fail under cure pressures. The lobe section is autoclave cured ~~to 650°F~~ and then examined again for structural integrity and void content.

Dome Construction

The tank domes are a fiber placed laminate construction of 12 coverage plies. Invar mounting rings for tank attachments, such as a manhole port, vents and sump funnels for the main propulsion system and fuel crossover, are co-bonded in the dome laminate. The mounting rings are positioned, and then build-up plies are hand layed-up over the ring flanges. The build-up plies were initially fiber placed on the dome mandrel to achieve accurate shape and then taken off and stored until needed for mounting ring installation. The assembly is autoclave cured at ~~350°F~~ to bond the mounting rings to the dome laminate.

Tank Assembly

The fiber placed tank sections are sent to Lockheed Martin's plant in Sunnyvale, Calif. for assembly and cure using their 24.7-ft diameter autoclave. Lockheed Martin fabricates three-dimensional woven carbon fiber preforms which are bonded together to form a skeleton structure using an out-of-autoclave curing process. Sections of the fuel tank are bonded, one or two at a time, to the skeleton, and then autoclave cured.

How far along are the tank sections?
When will they be completed?

Best of both technologies

Efficient use of material - Not wasted as plies are cut to shape
Overlap of plies can be prevented - By dropping off tows to precisely define edge of ply
Placement accuracy?
Fibers can be placed "tension free"