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Progressive Fracture and Damage Tolerance of Composite Pressure Vessels

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ABSTRACT

Structural performance (integrity, durability and damage tolerance) of fiber reinforced composite pressure vessels, designed for pressured shelters for planetary exploration, is investigated via computational simulation. An integrated computer code is utilized for the simulation of damage initiation, growth, and propagation under pressure. Aramid fibers are considered in a rubbery polymer matrix for the composite system. Effects of fiber orientation and fabrication defect/accidental damages are investigated with regard to the safety and durability of the shelter. Results show the viability of fiber reinforced pressure vessels as damage tolerant shelters for planetary colonization.

INTRODUCTION

Future Lunar and planetary exploration and colonization attempts require the planning, deign, and construction of shelters to accommodate expeditionary communities for extended periods of time. As a first priority, a Lunar shelter must provide a breathable atmosphere with sufficient interior pressure for pulmonary function. The most efficient shelter configurations will more than likely be a pressure vessel type which is self contained and will also provide structural support.

Candidate ply layups for the fiber composite for a half dome-type pressure vessel are investigated with regard to progressive damage and fracture of the shelter due to pressurization. The performance of aramid fibers in a rubbery polymer matrix is evaluated. For a standard thickness and geometry, hemispheres with different fiber orientations are investigated to examine the influence of ply fiber layup on the burst pressure and damage tolerance. Results indicate that structural fracture (burst) pressure is sensitive to ply fiber orientations.

In addition to defect-free hemispheres, the behavior of hemispheres with fabrication defects at the surface and at the mid thickness is examined. An additional case with local through-the-thickness damage is evaluated for damage tolerance by the use of structural progressive fracture. In general, the design of composite structures requires an evaluation of safety and durability under all loading conditions. The objective of this paper is to describe an integrated computational code that has been developed to quantify the durability of fiber reinforced composites via the simulation of damage initiation, growth,

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accumulation, progression, and propagation to structural fracture under loading. Quantification of the structural fracture resistance is also fundamental for evaluating the durability/life of composites structures. The most effective way to obtain this quantification is through integrated computer codes which couple composite mechanics with structural analysis and with fracture mechanics concepts. The COmposite Durability STRuctural Analysis (CODSTRAN) computer code (Chamis, 1978) has been developed for this purpose. Composite mechanics, (Murthy and Chamis, 1986) finite element analysis, (Nakazawa, Dias and Spiegel, 1987) and damage progression modules (Chamis, 1978) are incorporated to implement the durability analysis. The CODSTRAN code is used as a virtual computational laboratory to simulate composite damage progression mechanisms in substantial detail. The simulation of progressive fracture by CODSTRAN has been validated to be in reasonable agreement with experimental data from tensile tests (Irvine and Ginty, 1986). Recent additions to CODSTRAN have enabled investigation of the effects of composite degradation on structural response, (Minnetyan, Chamis and Murthy, 1992) composite damage induced by dynamic loading, (Minnetyan, Murthy and Chamis, 1990) composite structures global fracture toughness, (Minnetyan, Murthy and Chamis, 1990) effect of the hygrothermal environment on durability, (Minnetyan, Murthy and Chamis, 1990 (Minnetyan, Murthy and Chamis, 1992) structural damage/fracture simulation in composite thin shells subject to internal pressure, (Minnetyan, Chamis and Murthy, 1991) composite pressure vessel durability assessment, (Minnetyan, Chamis and Murthy, 1992) an overall evaluation of damage progression in composites, (Chamis , Murthy and Minnetyan, 1992) damage progression in stiffened shell panels, (Minnetyan, et al., 1992) general design concerns for progressive fracture in composite shell structures, (Minnetyan and Murthy, 1992) and damage progression in a stiffened composite panel subjected to a displacement controlled loading (Minnetyan, et al., 1993). The objective of this paper is to demonstrate an investigation of the viability of a fiber reinforced as a pressurized Lunar shelter. The terms shelter and pressure vessel are used interchangeably.

CODSTRAN METHODOLOGY AND ARCHITECTURE

CODSTRAN is an open-ended computer code integrating select modules on composite mechanics, damage progression modeling, and finite element analysis. The damage progression module (Chamis and Smith, 1978) keep a detailed account of composite degradation for the entire structure and also acts as the master executive module that directs the composite mechanics module (Murthy and Chamis, 1986) to perform micromechanics, macromechanics, laminate analysis and synthesis functions. It also calls the finite element analysis module (Nakazawa, Dias and Spiegel, 1987) with anisotropic thick shell analysis capability to model laminated composites for global structural responses. A convenient feature of the utilized finite element module is that structural properties are input and generalized stress resultants are output at the nodes rather than for the elements. The anisotropic generalized stress-strain relationships for each node are revised according to the composite damage evaluated after each finite element analysis. Subsequent to damage and composite degradation, the model is automatically updated with a new finite element mesh and properties and the structure is reanalyzed for further deformation and damage.

Figure 1 shows a schematic of the computational simulation cycle in CODSTRAN. The ICAN composite mechanics module is called before and after each finite element analysis. Prior to each finite element analysis, the ICAN module computes the composite properties from the fiber and matrix constituent characteristics and the composite layup. The laminate properties may be different at each node. The finite element analysis module accepts the composite properties that are computed by the ICAN module and performs the analysis at each load increment. After an incremental finite element analysis, the computed generalized nodal force resultants and deformations are supplied to the ICAN module that evaluates the nature and amount of local damage, if any, in the plies of the composite laminate. Individual ply failure modes monitored by CODSTRAN include the failure criteria associated with the negative and positive limits of the six ply-stress components (σ_{l11}, σ_{l22} ,σ_{l33}, σ_{l12},σ_{l23},σ_{l13}) and a combined stress or modified distortion energy (MDE) failure criterion, and interply delamination due to relative rotation (RR) of the plies (Murthy and Chamis, 1986).

The design example for this paper consists of a composite hemisphere shelter subjected to internal pressure. Loading is applied by imposing a gradually increasing uniform lateral pressure from the underside of the membrane. Large displacements are taken into account before and during damage initiation and progression.

The pressurized hemisphere has a circular foundation of 20.32 m (66.67 ft) diameter. The mid height is raised to 6.1 m (20 ft) relative to the edges. The computational model of the hemisphere vessel consists of 220 rectangular shell elements with 237 nodes, as shown in Figure 2. The quadrilateral finite element properties are determined from the laminate configuration of each node.

The composite system is made from Kevlar aramid fibers in a rubbery polymer matrix. The fiber volume ratio is 50 percent. The fiber and matrix properties used are listed in Tables 1 and 2, respectively. The hemisphere vessel is manufactured from twelve 0.127 mm (0.005 in) plies, resulting in a total thickness of 1.524 mm (0.060 in).

RESULTS AND DISCUSSIONS

Three different ply layups are considered to investigate the influence of fiber orientation on load carrying capability and durability. The three layups are $[0/90]_6$, $[0/\pm45/90]_3$, and $[0/\pm60]_4$. Each layup is independently investigated due to gradual pressurization of the shelter. Results are summarized in Table 3. Also, the damage initiation and growth stages are depicted in Figure 3. The ordinate in Figure 3 shows the percent of damage based on the volume of the membrane that is affected by the various damage mechanisms. The percent damage parameter is used as an overall indicator of damage progression.

The results in Figure 3 show the $[0/\pm60]_4$ layup to be the most effective for this shelter. Damage initiation and global fracture stages are consistently related to all three cases. Damage initiation is typically by local fiber failures near the apex of the pressurized hemisphere. After damage initiation, damage usually grows through the thickness before global fracture. Global fracture is initiated by tearing near a through-the-thickness damage with coalescence of multiple damage zones.

After selecting the design layup as $[0/\pm60]_4$, damage tolerance of the shelter is investigated by prescribing local defects near the apex of the shelter. Three cases are examined as follows: 1) Surface defect prescribed by cutting the first three surface plies ; 2) interior defect where three interior plies (plies 5-7) are cut; and 3) a through-the-thickness defect where all plies are cut. Ply cuts in all cases are 700 mm long and made perpendicular to the fiber directions. The defective shelters are simulated by subjecting them to gradually increasing pressure. A summary of the pressures for further damage growth from the existing defects is given in Table 4. Comparisons of the initial damage growth stages for these cases are shown graphically in Figure 4.

Results indicate that the $[0/\pm60]_4$ shelter has excellent damage tolerance. Even though the initial damage pressure is considerably lower for the defective shelters, the global fracture pressure is about the same for the defect-free, the surface-defective, and the internally defective shelters. The worst case is that with through-the-thickness damage which has 18 percent lower structural fracture pressure compared to the defect-free case.

CONCLUDING REMARKS

The significant results from this investigation in which CODSTRAN (Composite Durability STRuctual Analysis) is used to evaluate damage growth and propagation to fracture of a pressurized composite hemisphere vessels for planetary shelters are as follows:

1. Computational simulation, with the use of established composite mechanics and finite element modules, can be used to predict the influence of existing defects as well as loading, on the safety and durability of fiber composite pressure vessels.

2. CODSTRAN adequately tracks the damage growth and subsequently propagation to fracture for initial defects located at the surface, or in the mid-thickness of composite vessel, as well as through-the-thickness defects.

3. Initially defective vessels begin damage growth at a lower pressure compared to a defect free vessel. However, the ultimate pressure is not significantly reduced for partial-thickness defects. For the vessel with a through-the-thickness defect the ultimate pressure is reduced by 18 percent.

4. The CODSTRAN methodology and architecture is flexible and applicable to all types of constituent materials, structural geometry, and loading. Hybrid composite shells, composite containing homogenous materials such as metallic foils, as well as binary composites can be readily simulated.

5. Fracture toughness parameters such as the structural fracture load/pressure are identifiable for any structure with any defect shape.

6. Computational simulation by CODSTRAN represents a new global approach to structural integrity durability and damage tolerance assessments for design investigations.

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BIOGRAPHY

Dr. Chamis is a Senior Aerospace Scientist in the Structures and Acoustics Division of NASA Lewis Research Center. His major research has focused on the development of computational simulation methods for composite mechanics, composite structures progressive fracture, probabilistic structural analysis and probabilistic composite mechanics. His current research is in the development of computational simulation methods for coupled multidiscipline problems and for concurrent engineering.

TABLE I - KEVLAR ARAMID FIBER PROPERTIES

Number of fibers per end = 580
Fiber diameter = 0.0117 mm (0.460E-3 in)
Fiber Density = 3.94E-7 Kg/m^3 (0.053 lb/in^3)
Longitudinal normal modulus = 152 GPa (22.00E+6 psi)
Transverse normal modulus = 4.14 GPa (0.60E+6 psi)
Poisson's ratio (ν_{12}) = 0.35
Poisson's ratio (ν_{23}) = 0.35
Shear modulus (G_{12}) = 2.90 GPa (0.42E+6 psi)
Shear modulus (G_{23}) = 1.52 GPa (0.22E+6 psi)
Longitudinal thermal expansion coefficient = -0.40E-5/°C (-0.22E-5 /°F)
Transverse thermal expansion coefficient = 0.54E-4/°C (0.30E-4 /°F)
Tensile strength = 2,758 MPa (400 ksi)
Compressive strength = 517 MPa (75 ksi)

TABLE II - GV6S RUBBERY POLYMER MATRIX PROPERTIES

Matrix density = 3.42E-7 Kg/m^3 (0.0460 lb/in^3)
Normal modulus = 68.9 MPa (10 ksi)
Poisson's ratio = 0.41
Coefficient of thermal expansion = 10.3E-3/°C (0.57E-4/°F)
Tensile strength = 48.3 MPa (7.0 ksi)
Compressive strength = 145 MPa (21.0 ksi)
Shear strength = 48.3 MPa (7.0 ksi)
Allowable tensile strain = 0.014
Allowable compressive strain = 0.042
Allowable shear strain = 0.032
Allowable torsional strain = 0.038

TABLE III - EFFECT OF PLY LAYUP ON DURABILITY

	PRESSURE (KPa)		
PLY LAYUP	DAMAGE INITIATION	DAMAGE THROUGH THE THICKNESS	GLOBAL FRACTURE
$[0/90]_6$	95.95	99.22	115.42
$[0/\pm 45/90]_3$	124.01	125.99	129.35
$[0/\pm 60]_4$	132.72	134.36	140.65

TABLE IV - EFFECT OF INITIAL DEFECT ON DURABILITY

	PRESSURE (KPa)		
INITIAL DEFECT	DAMAGE INITIATION	DAMAGE THROUGH THE THICKNESS	GLOBAL FRACTURE
NONE	132.72	134.36	140.65
SURFACE	122.92	130.91	140.61
INTERIOR	122.92	129.46	131.45
THROUGH	95.95	99.22	115.38

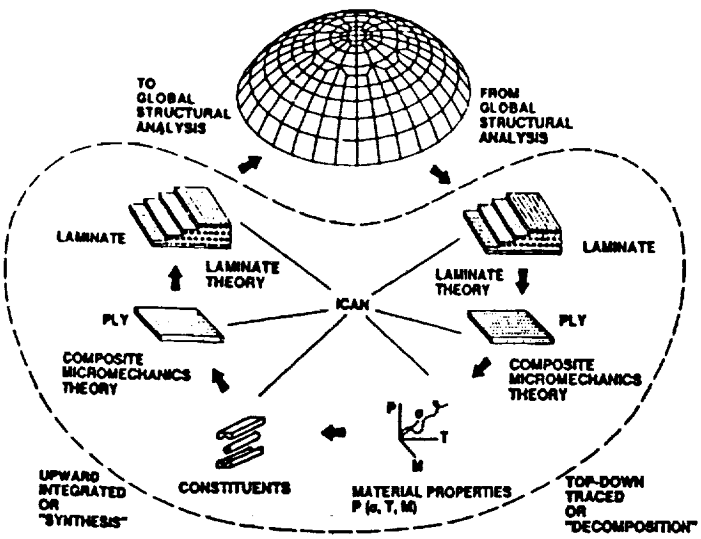

Figure 1 - CODSTRAN Simulation Cycle

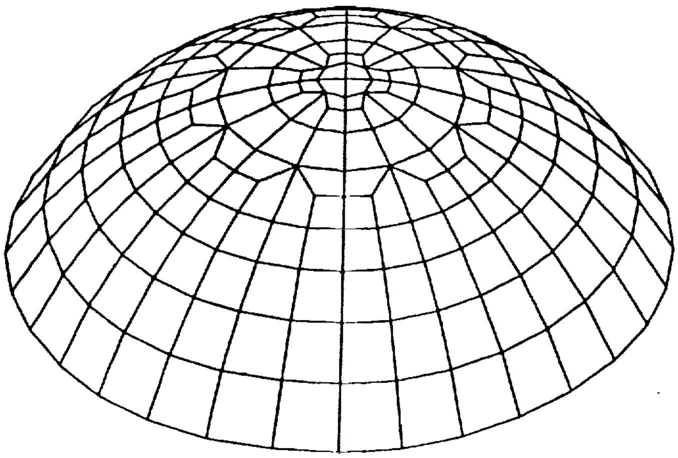

Figure 2 - Finite Element Model

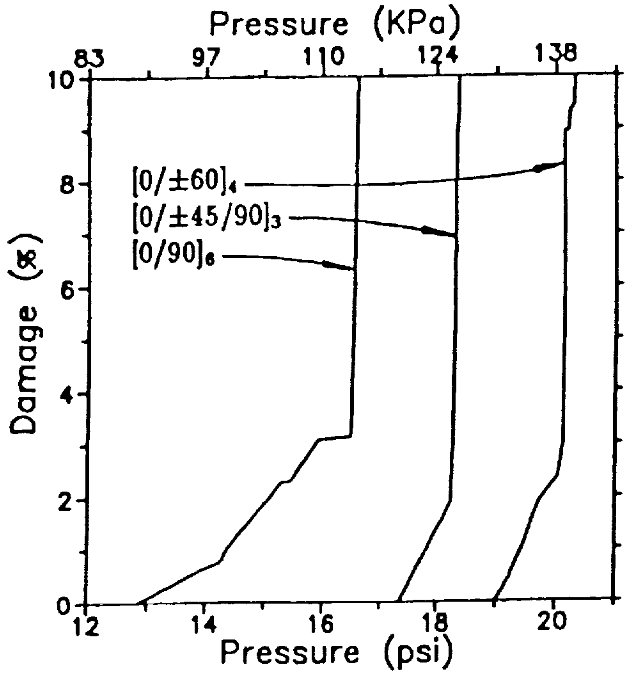

Figure 3 Ply Layup and Structural Durability

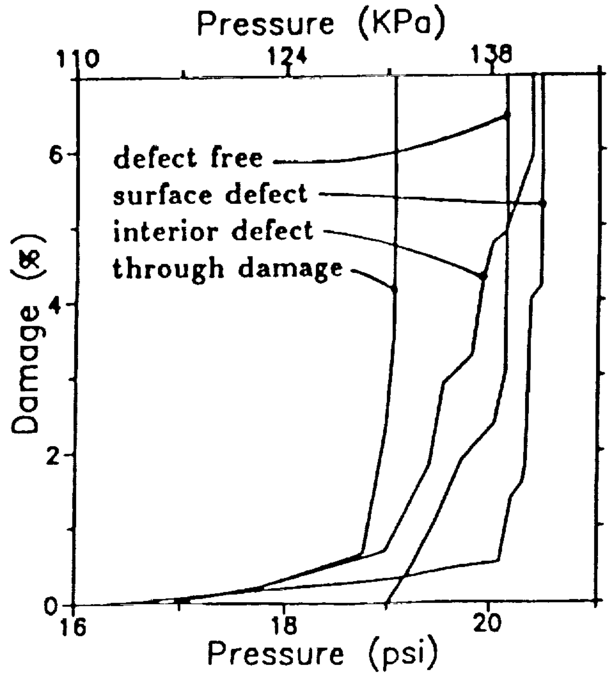

Figure 4 Defect and Damage Tolerance