

Fracture Mechanics and Finite Element Analysis: Catastrophic to Damage Tolerance (NASGRO)

Welcome to our overview of Predictive Engineering's FEA consulting services in Fracture Mechanics and Damage Tolerance. We are realists in the world of virtual simulation. That is, we are mechanically focused and come from experimental and laboratory backgrounds and we use this reality to guide us in the virtual world where it can be quite difficult to determine whether one has a cartoon or something real.

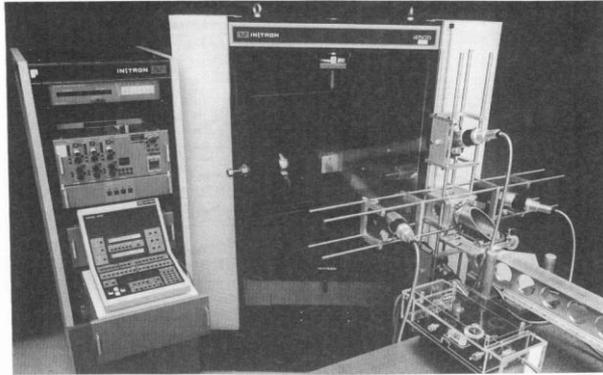
Our fracture mechanics experience has been gained in the laboratory, academically and in-the-field. We have seen first-hand how structures can catastrophically fail and how careful analysis work can lead to long-term, safe operation.

This brief note takes the reader from our origins at the Idaho National Engineering Laboratory (INEL), to our experience in mining and mineral commutation, to XFEM of aluminum ship structures, ASME Division 2, Section 3, Alternative Rules for High Pressure Vessels to finally our experience with NASGRO in the analysis of Composite Overlay Pressure Vessels (COPV).

We hope you enjoy this tour of our FEA consultants experience in Fracture and Damage Mechanics.

Fracture Mechanics and Finite Element Analysis – A Brief History at Predictive Engineering

Micromechanics of Heterogeneous Materials under Compressive Loading George Laird PhD Dissertation 1992

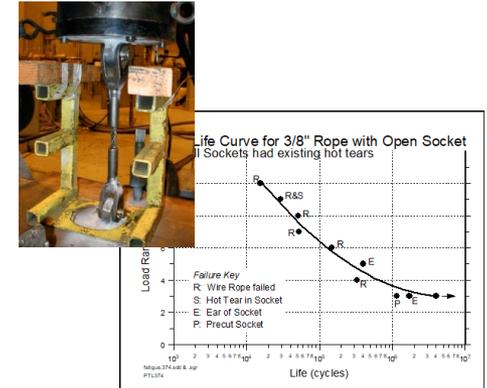


ASME Mechanical Engineering 1992

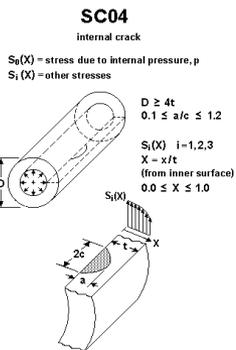
Predictive Engineering
 14100 Lake Street
 Houston, Texas 77040

Fracture Mechanics and Finite Element Analysis

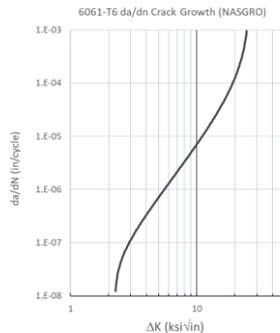
Damage Tolerance 2003



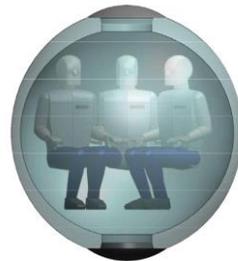
NASGRO Damage Tolerance 2022



$$\frac{da}{dN} = c \left[\frac{(1-f)}{(1-R)} \Delta K \right]^n \frac{\left(1 - \frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1 - \frac{K_{max}}{K_c}\right)^q}$$



Fracture Mechanics of Glass, Silica, & Structures 2005-2015



Fracture Mechanics of Fused Silica

Fracture toughness of fused silica (approximate):

$$K_{Ic, FS} = 0.75 \cdot 10^6 \frac{lb}{in^{3/2}}$$

Governing fracture mechanics equation for a crack in an infinite plate:

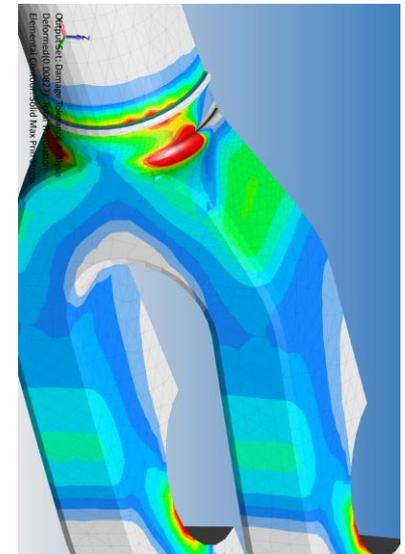
$$K_{Ic} = \sigma \sqrt{\pi a_{max}}$$

Process for determining the maximum allowable flaw size at a stress level of 10 MPa

$$a_{max} = \frac{K_{Ic}^2}{\pi \sigma^2}$$

$$a_{max} = \frac{(0.75 \cdot 10^6)^2}{\pi (10 \cdot 10^6)^2}$$

$$a_{max} = 5.74 \mu m$$



Fracture and Fatigue: XFEM Crack Propagation in Aluminum Structures

US Navy's Next Generation FFG(X) Ship



Did I Just Lose 50% of You?

Extended FEM: Level Set + Local PU (Belytschko *et al.* 2000)

Level Set

Discontinuity defined by two implicit functions: $f(X)$ and $g(X)$

Signed distance function $f(X) = \text{sign}(|X - X_c| \text{sign}(\mathbf{n} \cdot (X - X_c)))$

Discontinuity $X \in \Gamma^d$ if $f(X) = 0$ and $g(X, t) > 0$

Define implicit functions locally

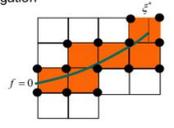
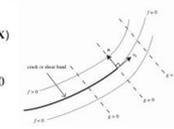
$$f(X) = \sum f_i N_i(X)$$

$g(X, t)$ replaced by index for elementwise crack propagation

Local Partition of Unity

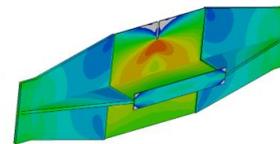
$$u^d(X) = \sum_{f \in \Gamma^d} \phi_i^{XFEM}(\xi) u_i + \sum_{f \notin \Gamma^d} \psi_j(X) u_j$$

$$\psi_j(X) = \begin{cases} \phi_j^{XFEM}(\xi) [H(f(X)) - H(f(X_c))] & \text{fully cut element} \\ \phi_j^{XFEM}(\xi) [H(f(X)) - H(f(X_c))] & \text{contain crack tip} \end{cases}$$

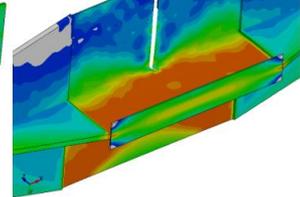


What XFEM Does

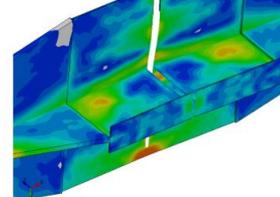
XFEM Experimental Test Panel with Stiffener Rev-200417



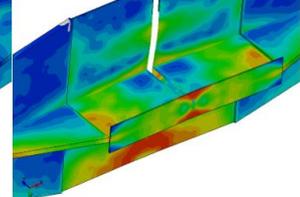
XFEM Experimental Test Panel with Stiffener Rev-200417



XFEM Experimental Test Panel with Stiffener Rev-200417



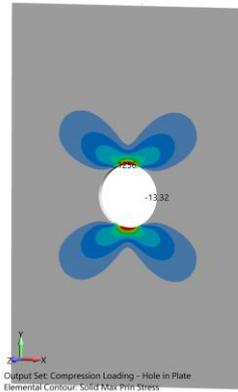
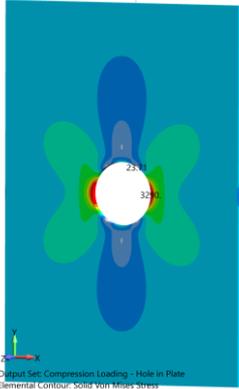
XFEM Experimental Test Panel with Stiffener Rev-200417



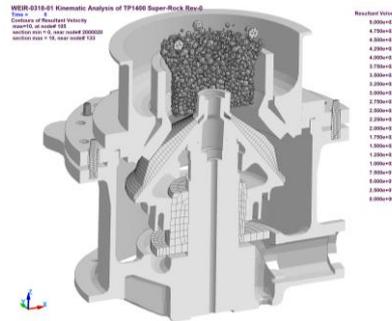
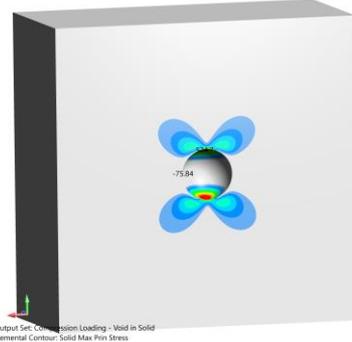
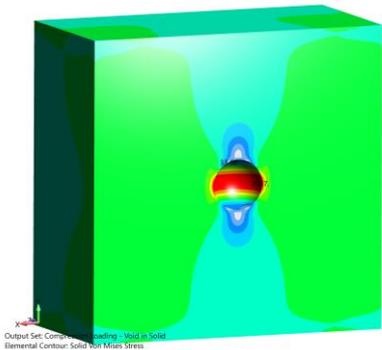
Fracture and fatigue mechanics is a core wheelhouse activity at Predictive Engineering. Our FEA consultants have years of laboratory and real-world experience in solving industry specific fracture and fatigue problems. We have done projects from naval vessels to submarines to satellites where understanding how laboratory data is applied to as-built structures was the key to the projects' success. We do not get lost in the math, whether Griffith-Irwin or XFEM, but keep it relevant that for a crack to grow, one needs a tensile stress field (Mode I) and never forget the role of environmentally induced stress corrosion cracking.

Low-Cycle Fatigue: The Basics of Damage Mechanics

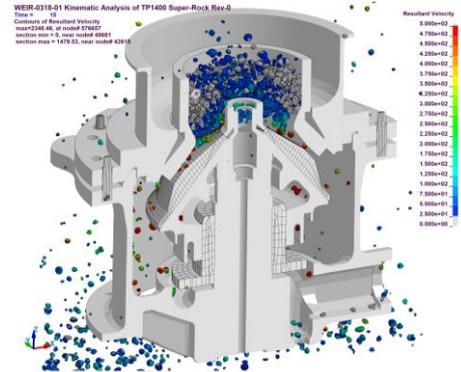
Hole in Plate: Tension +3/-1 or Compression +1/-3



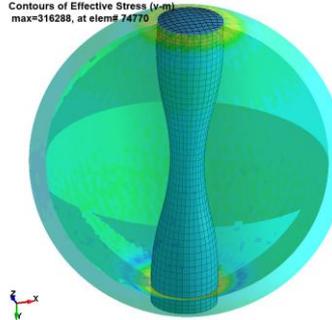
Void in Solid: Tension +2/-0.5 or Compression +0.5/-2



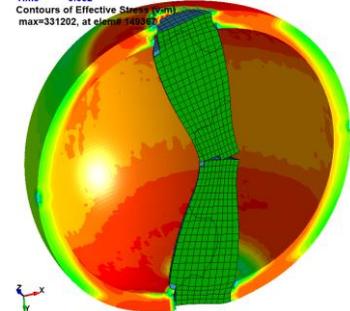
Fracture Mechanics of Rocks High-Speed Cone Crusher



DOER Deep Search Submarine - Glass Sphere Buckling An.
 Time = 0.017399
 Contours of Effective Stress (v-m)
 max=316288, at elem= 74770



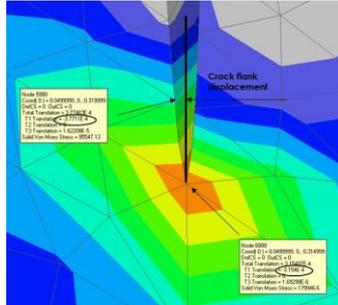
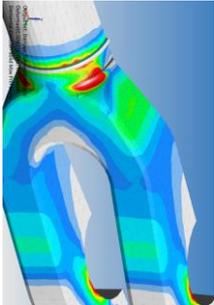
DOER Deep Search Submarine - Glass Sphere Buckling An.
 Time = 0.032
 Contours of Effective Stress (v-m)
 max=331202, at elem= 149367



Why do materials fail and how can we predict how fast they can fail? Fracture is the pulling apart of the material and that only occurs under tension. Many engineers have this false impression that materials don't fail under compression load, but they do since all materials contain defects! At the poles of these voids and defects, tensile stresses develop under compressive load. This is how rocks are crushed, materials wear and structures blow apart.

ASME BPVC VIII.3: Alternative Rules for Construction of High-Pressure Vessels

Classic FEA Fracture Mechanics

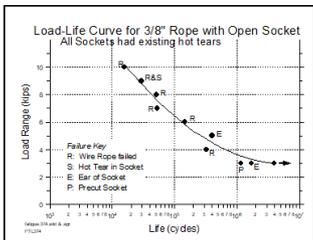


$$K_I = \frac{E \cdot \Delta u}{4 \cdot (1 - \nu^2)} \cdot \sqrt{\frac{2\pi}{r}}$$

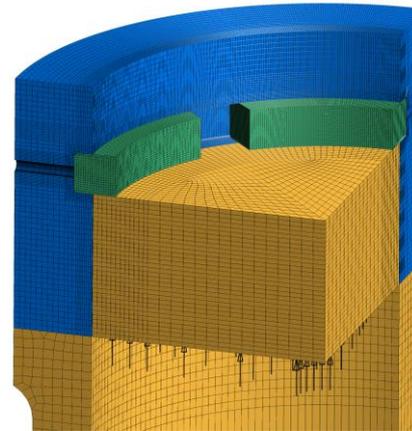
$$K_I = \frac{29 \cdot 10^6 \cdot \Delta(3.77 - 3.15) \cdot 10^{-4}}{4 \cdot (1 - 0.3^2)} \cdot \sqrt{\frac{2\pi}{(0.320 - 0.315)}}$$

$$K_I = \frac{29 \cdot 10^6 \cdot \Delta 0.62 \cdot 10^{-4}}{3.64} \cdot \sqrt{\frac{2\pi}{0.005}}$$

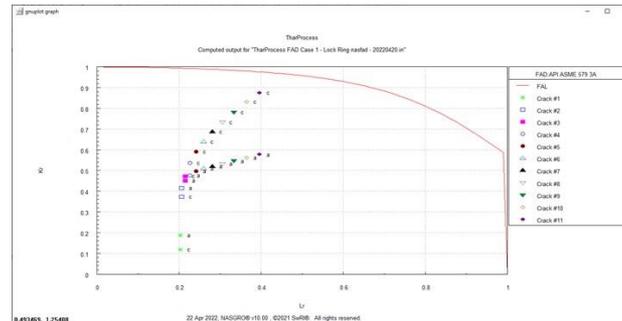
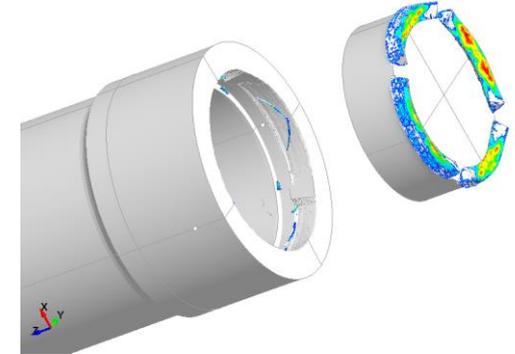
$$K_I = 17500 \text{ psi} \cdot \sqrt{\text{in}}$$



NASGRO: ASME Section VIII, Division 3



ASME Section VIII Division 3 Alternative Rules for High-Pressure Vessels
 Time = 0.01
 Contours of Maximum Principal Stress
 max=208371, at elem# 171668

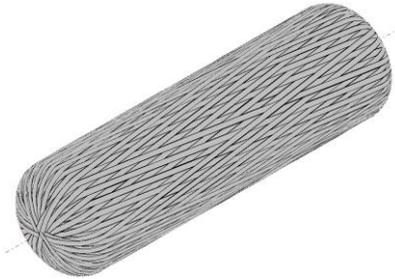


ASME FFS-1 FAD
 (Failure Assessment Diagram)

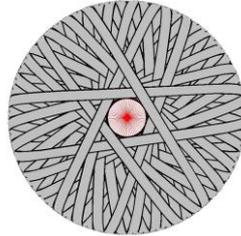
ASME Section VIII, Division 3 Alternative Rules for High-Pressure Vessels calls out Methods API 579-1 and ASME FFS-1 (Fit-For-Service) as procedures for calculating the low-cycle fatigue lives of metallic structures. Historically, Predictive Engineering has done such work via spreadsheets and MathCAD, nowadays, we have NASGRO, which more or less automates, the procedure. Our goal as FEA BPVC consultants is to ensure that our vessels don't blow their tops!

COPV: Damage Mechanics

Winding Pattern

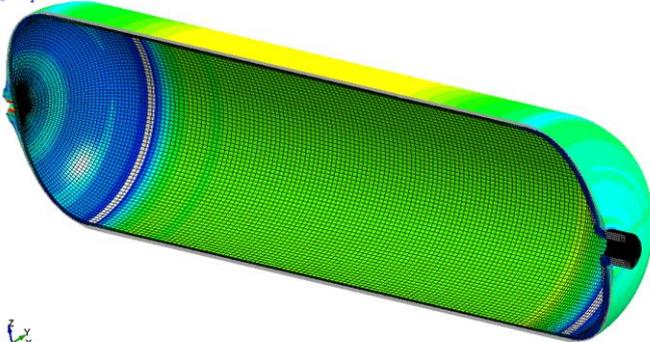


Nozzle End



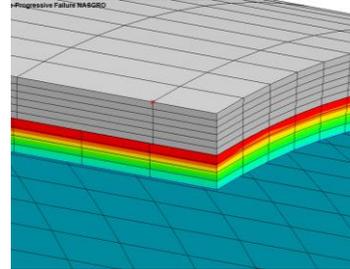
Autofrettage

COPV Type III Autofrettage-Progressive Failure NASGRO
 Time = 2

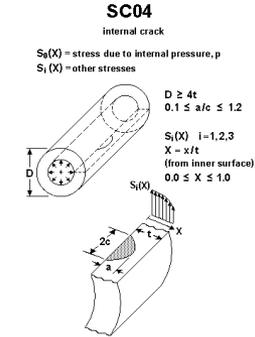


NASGRO Damage Mechanics

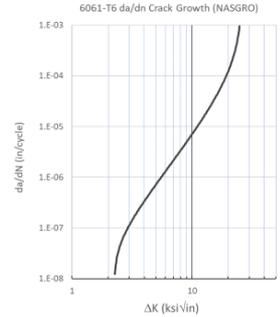
Section Stress



Crack Case SC04

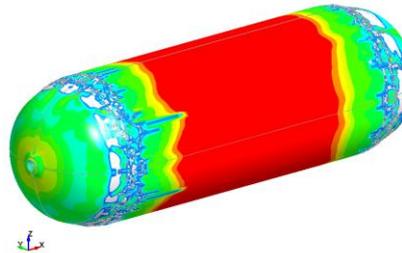


da/dN

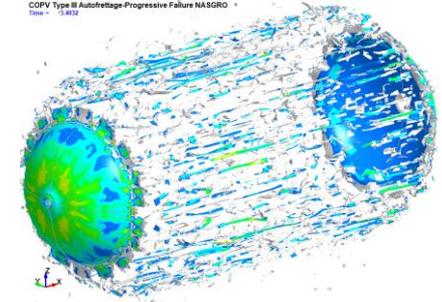


Burst Prediction

COPV Type III Autofrettage-Progressive Failure NASGRO
 Time = 1.011E11

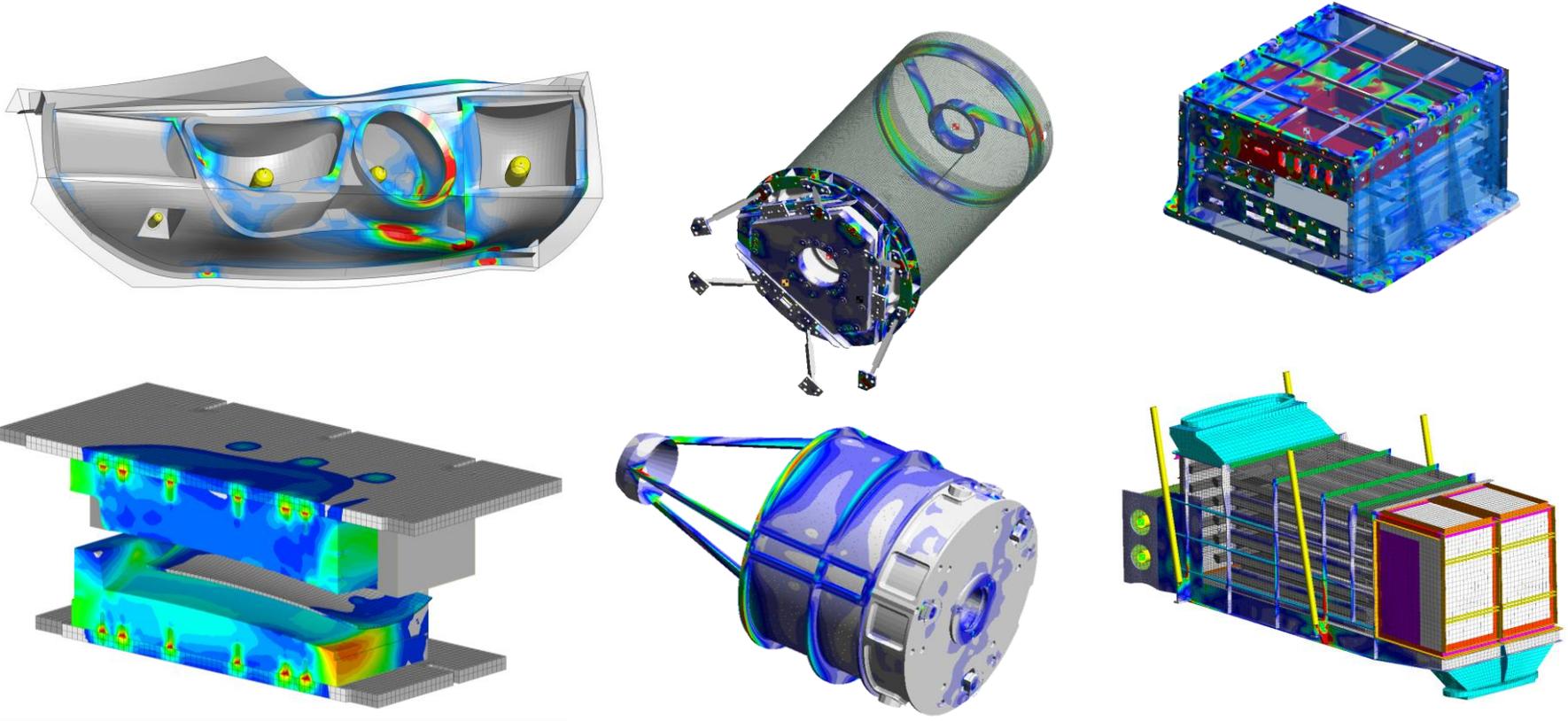


COPV Type III Autofrettage-Progressive Failure NASGRO
 Time = 1.011E11



Composite Overlay Pressure Vessels (COPV) Type 3 use an aluminum or steel liner. One of the advantages of using a metallic liner is the option to apply an autofrettage treatment to create a compressive stress in the liner. Autofrettage greatly enhances the damage tolerance of the liner during operation. In the analysis of COPV Type 3 and Type 4 cylinders for aerospace applications, the analysis is completely nonlinear from autofrettage to burst prediction. At operational levels, FEA stress numbers are used in the NASGRO damage tolerance calculations.

FEA Predictive Engineering – The Advantage of Getting it Right the First Time



We welcome your inquiries on how we can help your business get it right the first time.