INTERNATIONAL ASSOCIATION
FOR THE ADVANCEMENT OF
SPACE SAFETY

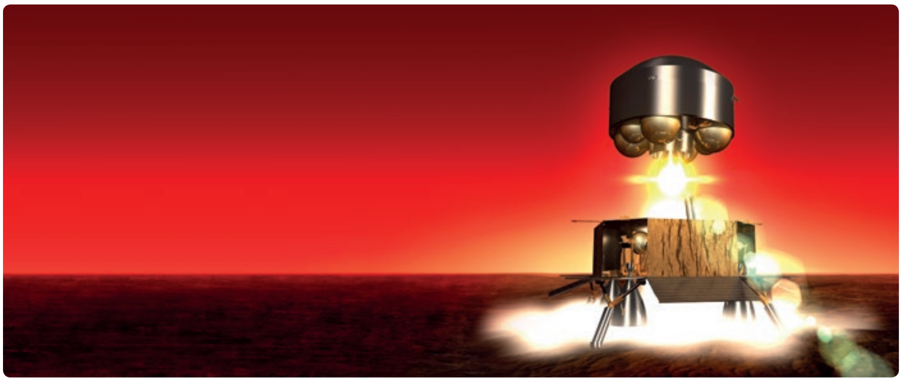
IAASS Professional Training Course

DESIGN AND OPERATIONS OF COMPOSITE OVERWRAPPED PRESSURE VESSELS (COPV)

20-24 November 2017
London (Stevenage) - England, UK

DESIGN AND OPERATIONS OF COMPOSITE OVERWRAPPED PRESSURE VESSELS

Code 005



The Challenge

High performance Composite Overwrapped Pressure Vessels (COPVs) have been utilized in the aerospace and automotive industries for many years, providing an inherently safe, lightweight and cost effective storage source for pressurized fluids. COPVs are commonly used for gas and propellant storage in spacecraft and launch vehicles. The consequence of a COPV rupture can be the release of caustic fluids, loss of necessary fluids and the release of stored energy equivalent to several pounds of trinitrotoluene (TNT) depending on the quantity, pressure and fluid contained in the COPV.

In the aerospace sector, the development of a commercial space industry has reinforced the need for light and low cost yet safe and reliable pressure vessels. In the automotive sector, new demands for alternative fuel vehicles driven by changes in the energy sector have given rise to opportunities for durable and low cost, and also safe and reliable pressure vessels, particularly for hydrogen and compressed natural gas.

Safety and high reliability are achieved by adhering to rigorous processes throughout the life cycle of a pressure vessel, including the design, manufacture, testing, handling, and operation phases.

Scope of the course

This course will provide an introduction to the basic principles governing the design and operation of Composite Overwrapped Pressure Vessels (COPV). The comprehensive overview of current technological understanding will provide both engineering mechanics fundamentals and practical applications drawn from experience to educate program managers, design engineers, ground and flight operators, safety analysts, quality inspectors and users/customers.

Course Description

Fundamental to the use of COPVs in space applications is the relevant failure modes and the design techniques introduced to ensure safe operation. Flight safety can only be properly understood through appropriate engineering design and quality throughout the vessel lifecycle from design, qualification, manufacturing, acceptance testing, handling and finally operational use. Each step of the product lifecycle has relevant safety considerations, which will ultimately affect the likelihood for catastrophic failure resulting in loss of life during operations.

This course has been developed based on requirements developed for space applications for COPVs. The relative requirements are documented in NASA- developed standards applicable to US and international partners for use on the International Space Station, as well as for future programs such as the NASA Commercial Requirements. These various standards reference the appropriate AIAA requirements and these will be directly addressed in this course. The course is directly relevant to individuals concerned with COPVs in automotive applications. The failure modes are common across these industries. However, there is a difference in usage and need for robustness of typical pressure vessels and a difference in materials commonly selected for these products. Consequently there are different standards and approaches to certification. The class will explore these differences.

Participants in this workshop will gain appreciation of a wide range of epoxy-matrix composites that are used in overwraps based on fibers such as: S-glass, aramids (e.g., Kevlar®49) and carbon (e.g., T1000), and also various current liner materials including metals such as aluminum, stainless steel, titanium and Inconel, and polymers such as high density polyethylene. Attention will be paid to the potential effects of processing variables (e.g., heat treatment, welding, annealing) on ultimate liner performance as influenced also by the fiber used in the overwrap.

Various steps in the COPV design and manufacturing processes will be discussed, particularly aspects strongly influenced by end-use requirements and vessel geometry (cylindrical vs. spherical). To manufacture the overwrap, both wet filament winding and pre-preg winding methods will be discussed, including their respective pros and cons and their relative importance in various designs. Another topic discussed will be the potential for liner distortion and buckling during winding, the consequences and candidate countermeasures to protect this phenomenon from occurring. Advantages and risks in bonding the overwrap to the liner will be discussed with respect to the overall design and potential failure mechanisms. Autofrettage and proof-testing will be discussed in terms of plastic yielding of the liner that induces a significant compressive stress component beneficial to improving fatigue life. In this context, the Bauschinger effect on the final liner stress state and the potential for liner buckling will also be discussed.

The relevant analysis and test methods used to demonstrate compliance to appropriate certification standards are presented. These include factors of safety set to mitigate against stress rupture failure modes of the overwrap and Leak-Before-Burst liner/overwrap concepts and demonstration, and finally FEA/NDE approaches to establish Safe Life with respect to risk of liner fatigue failure from crack initiation and growth.

Current non-destructive evaluation (NDE) techniques will be discussed as are used to detect flaws and damage in the liner and overwrap. NDE methods for detecting flaws and small cracks in liners include: visual, dye penetrant, X-ray, ultrasonic, eddy current, and borescope inspection. NDE methods for the overwrap include: Acoustic emission, Flash/Infrared thermography, laser shearography, digital image correlation of overwrap strains, and Raman spectroscopy to measure residual fiber stress.

Students will gain familiarity with the computational design tools that are used to analyze COPV. The majority of the examples in the course are created using the commercially available Abaqus FEA product suite and associated Wound Composite Module (from Dassault Systemes). Computational results with this tool will be discussed to underscore the importance of proper design, manufacture, and operations to prevent the occurrence of various failure modes. Through these structured learning examples, users will gain an appreciation for the complexities of modeling these vessels.

The AIAA is currently updating the national standards which are used to certify metallic and composite overwrapped pressure vessels. The course will also review the updates to these standards which will be released by the time of the teaching of the course.

Target Audience

- Engineers and Managers who are interested in the latest techniques for COPV design, development, manufacture and test
- System engineers who develop requirements for systems which incorporate the use of pressure vessels
- Safety, reliability and quality engineers who want to understand the approach to safety and mission assurance of systems which incorporate the use of pressure vessels
- Ground Operators and test engineers who performed non-destructive evaluation of pressure vessels. The course would be beneficial to both seasoned experts in the field and new engineers to the technology.

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What You Will Learn

- Failure modes in COPVs and requirements for safe operation in space environments
- Designing for Maximum Operational Pressure and Relevant Factors of Safety
- Approaches to Liner Fatigue Modeling under Pressure Cycling
- Liner Buckling: Models, Trigger and Methods of Prevention
- Composite Stress-Rupture Phenomenon and Reliability Modeling
- Nondestructive Evaluation (NDE)
- Considerations for Ground Operations and Damage Control Mitigation Techniques.

Course Length and Duration

5 days

Instructors

Instructors: The course instructors are internationally recognized experts in the field of COPV Design and Operations:


S. Leigh Phoenix

S. Leigh Phoenix (PhD Cornell) is professor of Mechanical and Aerospace Engineering at Cornell University, where he has been on the faculty since 1974, and teaches courses in composite materials, solid mechanics and applied mathematics. Much of his research involves micromechanically–based statistical modeling and experiments on long-term reliability of fibrous composites (e.g., aramids, carbon, S-glass, PBO) under high stress in difficult environments. Examples include composite-overwrapped pressure vessels, pressurized hydraulic lines and wind turbine blades. He also models ballistic impact into fibrous materials in support of developing improved materials and architectures for soft body armor and flexible composite panels.
In 1983 Phoenix received the Fiber Society Award for Distinguished Achievement in Basic or Applied Fiber Science, and in 1992 he won the ASTM Harold DeWitt Smith Award in fiber mechanics. In 2005 he was awarded the NASA-NESC Engineering Excellence Award for his pressure vessel work in support of the Shuttle's Return to Flight.


Michael T. Kezirian

Michael T. Kezirian is an Associate Technical Fellow with the Boeing Company. He has brought extensive experience in composite materials, propulsion systems and system safety to address safety concerns for the Space Shuttle, International Space Station and Commercial Crew CST-100 Starliner Programs. As an Adjunct Associate Professor of Astronautical Engineering at the University of Southern California, he has taught undergraduate and graduate classes in Polymer Science, Spacecraft Dynamics and Safety of Space Systems and Space Missions. He is the founding Editor-in-Chief of the *Journal of Space Safety Engineering*. Dr. Kezirian is an Associate Fellow of the AIAA and Fellow Member of IAASS. In 2009 he was awarded the NASA Astronaut Personal Achievement Award (Silver Snoopy).

COURSE AGENDA

Day 1
Afternoon

1. General Introduction
- a. Definitions and Examples
- b. Spherical and Cylindrical COPV architecture and wind patterns
  - Overwrap wind patterns and implications
- c. Overwrap materials (and fiber properties): carbon, Kevlar®, S2-Glass
- d. Liner materials (and properties): aluminum, titanium, Inconel, stainless steel
- e. Manufacturing processes: wet winding, and prepreg, elevated temperature curing
- f. Manufacturing: autofrettage

2. Failure Modes
- a. Liner fatigue (parent material and welds)
- b. Composite Stress Rupture
- c. Collateral damage/impact damage
- d. Liner failure during autofrettage or first pressurization
- e. Liner buckling

3. Standards
- a. NASA Requirements
  - Commercial Crew Requirements (ESMD-CCTSCR-12.10) and flow down to CCT-REQ-1130 and others
  - ISS Visiting Vehicle Requirements (SSP 50808 and 30558/30559)
  - Unmanned Programs
- b. AIAA Standard (S-080, S-081a and future versions)
- c. MIL-STD-1522
- d. Other requirements and standards (ISO, EU, UN)

Day 2
Morning

4A. COPV Design & Analysis using FEA Software – Part A Spherical Vessels

4B. COPV Design & Analysis using FEA Software – Part B Cylindrical Vessels
- a. Basic Concepts and Definitions
  - Elastic vs. Plastic Response of composite
- b. Introduction to orthotropic elasticity of a lamina
  - Unidirectional composite forms (tow, band, lamina)
  - Definition of various moduli and Poisson's ratios
  - Layered composite stiffness properties
  - Through thickness compression (important to thick overwraps)
- c. Thermal effects in overwrap mechanical response
  - Thermal expansion coefficients (fibers, liners and COPV)
  - Effects of temperature excursions on overwrap and liner response

Day 2
Afternoon

5. Overwrap Design Considerations
- Considerations for Thick-Walled vs. Thin Walled COPV

6. Winding Pattern Effects
- a. Implications on overwrap shear stress profiles within layers and between layers
- b. Isotensoid and other dome designs in cylindrical pressure vessels
- c. Theoretical models for liner and overwrap response
- d. Shear stress behavior and influence on the liner
- e. Potential for delamination and debonding
- f. Effects of winding pattern on impact damage sensitivity

7. Autofrettage and Proof Testing
- a. Effect on stress state
- b. Role of Bauschinger effect
- c. Connection to buckling risk and fatigue risk

Day 3
Morning

8. Liner Fatigue Modeling
- a. Advanced fracture mechanics approaches, modeling fatigue crack growth
  (connection to Safe Life and Leak Before Burst concepts)
- b. Description of NASA-developed NASGRO, fracture mechanics and fatigue crack growth analysis software
- c. NDE methods for detecting small cracks and flaws (probabilities of detection)
- d. Strain-life models (Morrow, Fatemi-Socie)
- e. Cyclic stress-strain laws (Ramberg-Osgood)
- f. MLE-based statistical analysis approaches, reliability modeling, test data generation, including size effects, uncertainty

9. Liner Buckling
- a. Mechanical models (including effects of autofrettage)
- b. Bonded vs. unbonded liners
- c. Triggers and methods of prevention
- d. Rippling effects from wrap pattern imprint

Day 3
Afternoon

10. Composite Stress Rupture Phenomena and Reliability Modeling
- a. Background and Definitions
- b. Mechanisms and Micro-Mechanics
- c. Fiber, Tow and Vessel (including sub-scale) Testing
- d. Factors affecting stress rupture and testing
- e. Weibul based probability models

f. Effects of Proof Testing
g. Model Parameter Estimation to Enable Reliability Calculation (and incorporating uncertainty)
h. Relevance to Standards

Day 4
Morning

11. NonDestructive Evaluation – Liner
a. Visual (dents, scuff marks)
b. Dye penetrant methods
c. X-ray and ultrasonic
d. Eddy current
e. Borescope based profilometry

12. NonDestructive Evaluation – Liner Special Topic Laser Profilometry

Day 4
Afternoon

13. NonDestructive Evaluation – Overwrap
Raman Spectroscopy

14. Mechanical Impact Damage Control
a. Purpose
b. Element of a Damage Control Plan
c. Failure Consequences
d. Quantifying Consequences
e. Threat Assessment
f. Reporting
g. Protective Covers

Day 5
Morning

15. Risk to the Public
a. Range Safety Approaches
b. Risk Factors
c. Failure Consequences
d. Quantifying Consequences

16. Micro Meteoroid and Orbital Debris (MMOD)
a. The (Un) Natural Environment
- Measurement
- Sources
- Characterization

b. Modeling
c. Government Regulations (US and International)
d. Space Vehicle Protection
- Thermal expansion coefficients (fibers, liners and COPV)
- Effects of temperature excursions on overwrap and liner response

e. Recent Hyper Velocity Impact Experiments on Metallic Pressure Vessels
f. Implications for Pressure Vessel/COPV operations in Space

17. Special Topics

18. Summary

Computational Workshop:

Students will be provided the student version of Abaqus FEA (Dassault Systèmes (3DS)) and workbooks on the Wound Composite Modeler (WCM). Results of Abaqus simulations are used throughout the course.

Computational Workbook A

In this workshop, the user step through the process of generating an axisymmetric model of a COPV and post processing the results using the Wound Composite Modeler (WCM). The model will consist of both helical and hoop layers.

Computational Workbook B

In this workshop, the user steps through the process of generating a three-dimensional model of a COPV and post processing the results using the WCM.

Computational Workbook C

The focus of this workshop is the use of the WCM as a COPV design tool. The WCM will be used to gauge the effect of parameters such as wind angle, number of layers, and liner materials on the stresses during operations (changes in COPV pressure).

Computational Workbook D

This workshop explores the concept of autofrettage. An autofrettage analysis will be performed to demonstrate how tensile stresses in the liner may be reduced in order to extend the fatigue life of a COPV.

IAASS PROFESSIONAL TRAINING COURSE

REGISTRATION FORM

Course: **Design and Operations of Composite Overwrapped Pressure Vessels (COPV)** Code 005
Date: 20-24 November 2017
Location: London (Stevenage) - England, UK

Please fill in all details on this registration form. One registration form per person.

DETAILS:

First name: ______________________________

Last name: ______________________________

Organization name: ______________________

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Organization billing address:

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Phone number: _________________________

Email: __________________________________

Signature/date: _________________________

HOW TO REGISTER

Please fill in and sign this registration form, and email to: iaass.academy@gmail.com not later than **8 SEPTEMBER 2017**. If you require more information please call: +31643552918 or +31712020023

TERMS & CONDITIONS

The course enrollment fee is Euro **1950** for non-IAASS Member; Euro **1850** for IAASS Members. Course material included.

PAYMENT

The IAASS will send an invoice to the organization of the enrolling participant. The payment shall be performed not later than two weeks before the start of the course.

CONFIRMATION

Confirmation of registration will be sent by email.

CANCELLATIONS/TRANSFERS

If the minimum number of participants (12) will not be reached, the IAASS reserves the right to cancel the course.

REFUNDS

- Refunds will be made if the course is cancelled.
- Refunds can be issued if more than ten working days' notice is provided prior to the course.
- Transfers between staff from the same organization are permitted.
- Registered participant which does not attend will incur the full fee.