TEST METHODS FOR HOOP TENSILE STRENGTH OF CERAMIC COMPOSITE TUBES FOR LIGHT WATER NUCLEAR REACTOR APPLICATIONS

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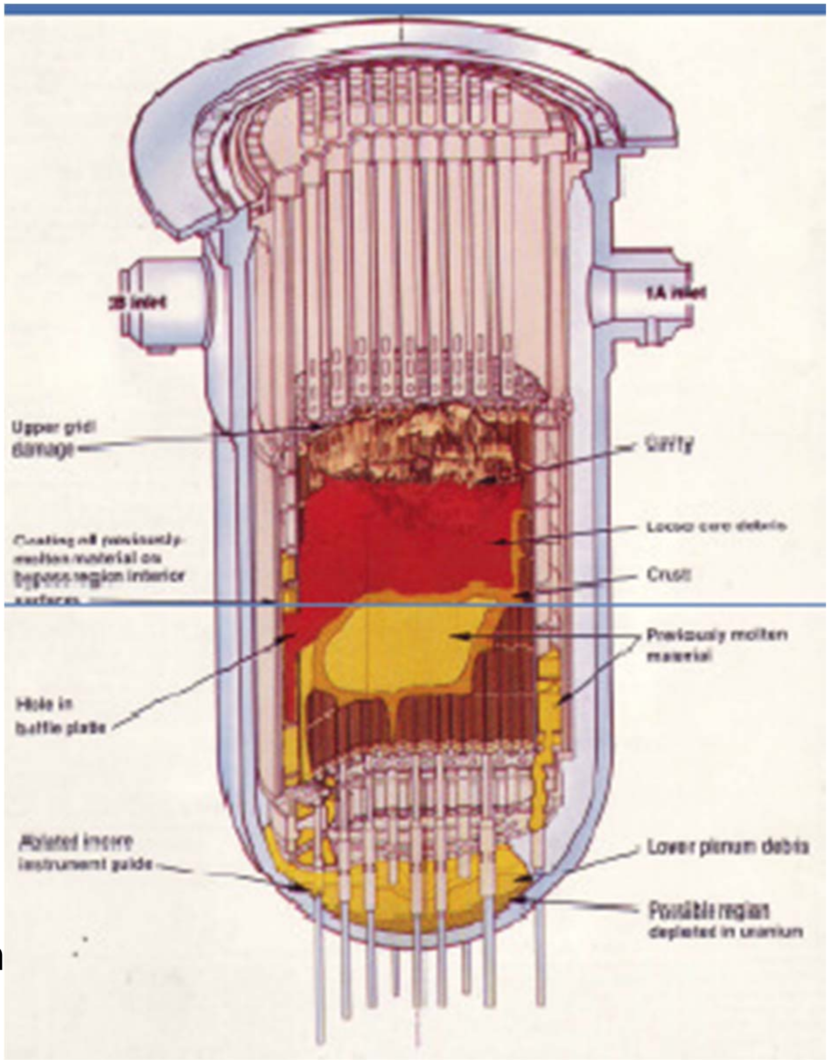
Outline

- **Introduction**
  - **--** Light Water Reactors (LWR)
  - -- CMC Tube Application and Function
  - -- The Need for Tube-Specific Tests
- **CMC Tube Hoop Tensile Strength Test Methods**
- **Proposed Standand Test Methods**
  - -- Experimental Test Factors for Composites
  - -- Test Specimen and Gage Section Geometry
  - -- Preparation and Setup
  - -- Test Procedures and Parameters
  - -- Calculations and Reporting
  - -- Precision
- **Current Status and Future Work**

Introduction

- **US DOE Light Water Reactor Sustainability (LWRS) program**
  - **Demonstrate successful advanced fuels technology suitable for commercial development to support nuclear relicensing.**
  - **Increase safety by delaying core damage and reduce the extent of damage in severe station black out or LOCA events.**
  - **Improve economics of current nuclear power plant operation by increasing fuel cycle lengths, burn-up or higher power density.**
  - **Help maintain safe and efficient operation of nuclear power plants beyond the current 60 year licensing period.**



Introduction

- **Zirconium cladding can exhibit exothermic reaction with water at elevated temperatures**
- **SiC/SiC CMCs have demonstrated high strength at high temperatures and low chemical activity (including no exothermic reaction with water) at elevated temperatures.**
- **Use of SiC/SiC CMCs and elimination of zirconium allows**

1) increased temperatures at which fuel can operate,

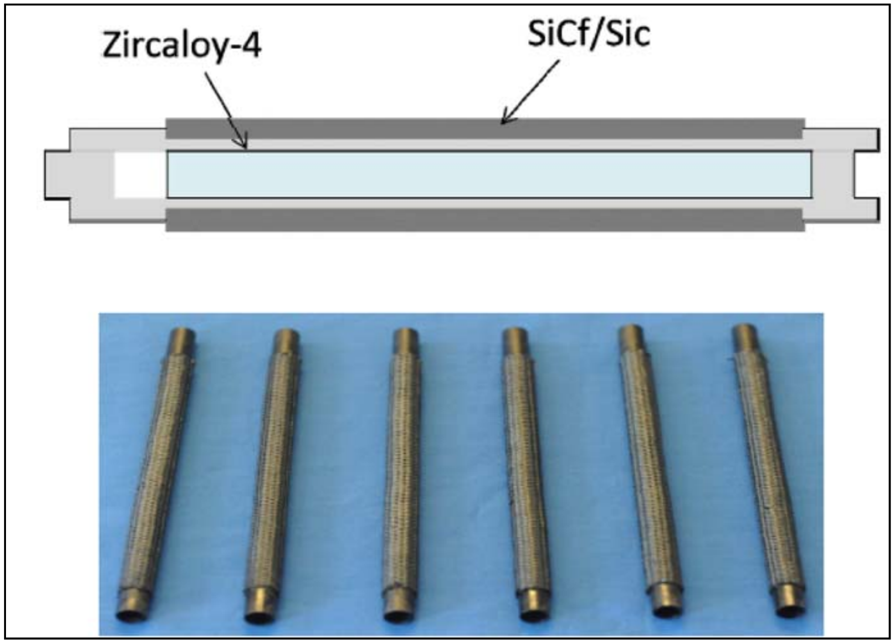
2) retention of geometry and fuel protection during an accident,

3) Elimination of free hydrogen by removal of zirconium/water exothermic reaction and reducing the severity of severe accidents

Introduction

SiC-SiC CMC Reactor Fuel Rods –

- Initial plan is to use zirconium inner liner and CMC outer liner.
- Advantages include:
  - Known chemical environment at UO_2/Zr interface
  - Zr liner allows the matrix to remain fully sealed even if the CMC cracks through.
  - Inner Zr layer allows for a reliable welded end cap
- Disadvantages include;
  - Fission product or heavy metal reaction could create undesirable reactions with a SiC inner layer
- Later designs is to use SiC inner layer and CMC outer liner.



Introduction

Fortunately the LWRS applications of SiC/SiC CMC builds on experience allowing nuclear applications to advance an existing mature specialized technology:

- SiC/SiC CMC materials and structure technology was funded by the aerospace and defense industries/agencies.

- Current evaluations and applications of SiC/SiC CMCs in fusion reactors (first wall) and TRISO fuel forms that have established properties under extended neutron irradiation and at high temperatures as well as very hot steam environment.

- Growing, credible data bases for SiC/SiC CMCs now exist because of the evolution of consensus test methods and design codes.

- Maturation of volume-scale manufacturing capability for all types of CMCs including SiC/SiC CMC adds to availability and understanding of these material.

Introduction

HOWEVER, the tubular geometry for the LWRS fuel rod application presents challenges for both “makers” and “lookers” of SiC/SiC CMCs

For “makers”

- How to make seamless tubes with multiple direction architectures

-How to ensure integrity in the radial direction

-How to create create uniform wall thickness and uniform/nonporous matrices

For “lookers”

-How to build on decades of experience with consensus standards and data bases for “flat” material forms

-How to interpret information of tests of test specimen in component form

-How to adapt RT, ambient environment expertise to HT, use environment conditions.

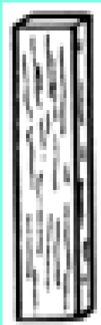
Tube Specific Tests

- Composite tubes can have a 1-D filament wound, 2-D laminate, or 3-D (weave or braid) construction depending on what tensile, shear, and hoop stresses are considered.
  - The fiber architecture -- tailored for highly anisotropic or uniform isotropic mechanical and thermal properties.
- Mechanical testing of composite tube geometries is distinctly different from testing flat plates because of the differences in --
  - fiber architecture (weaves, braids, filament wound),
  - stress conditions (tension, hoop, torsion, and flexure stresses),
  - gage section definition, gripping, bending stresses, and scaling issues
- Direct strength tests of composite tubes are needed to provide reliable information on mechanical behavior and strength for those tube geometries.

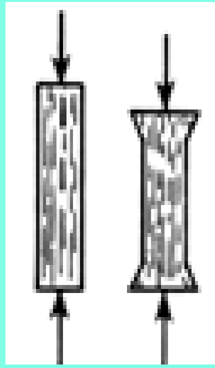
Al_2O_3 Fabric in SiC, Carter PhD Thesis, 2000

Hoop Tensile Strength Test is Critical for LWRS Applications

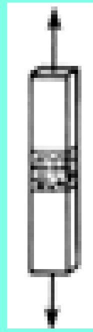
ASTM C28.07 CMC Test Standards



C 1275 CFCC Tensile strength
C 1359 Tensile strength (Hi Temp)
C 1337 Creep, Creep Rupture
C 1360 Cyclic fatigue

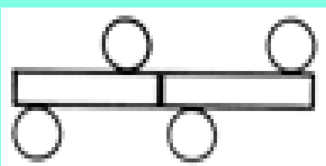


C 1358 CFCC Compression

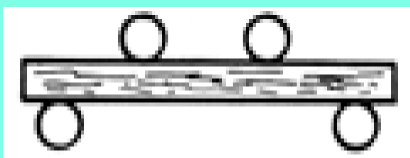


C 1468 CFCC Tensile Trans thickness

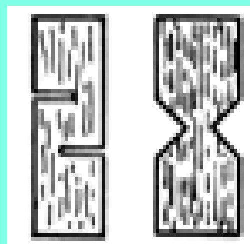
C 1557 Filament Tensile strength and Elastic modulus



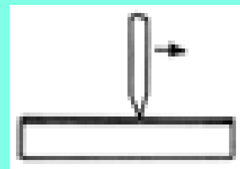
C 1469 Joint strength



C 1341 CFCC Flexure strength
C 1674 Honeycomb Flex strength



C 1292 CFCC Shear strength
C 1425 Shear strength (HiTemp)



C 1624 Coatings – Scratch Adhesion

CEN TC184 Test Standards
ISO TC206 Test Standards

Some Related Test Standards and References

CMC and PMC Tube Hoop Tensile Test Articles

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- F. A. R. Al-Salehi, S. T. S. Al-Hassani, H. Haftchenari and M. J. Hinton, **"Temperature and Rate Effects on GRP Tubes Under Tensile Hoop Loading"** Applied Composite Materials, Vol. 8, No.1 (2001) pp. 1-24
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- Pinar Karpuz, **"Mechanical Characterization Of Filament Wound Composite Tubes By Internal Pressure Testing"** Thesis, Middle East Technical University, Ankara, Turkey, May 2005
- J.A. Salem and J.Z. Gyekenyesi, **"Burst Pressure Testing of Ceramic Rings,"** NASA/TM-2007-214695, April 2007.
- J. Cain, S. Case, and J. Lesko, J., **"Testing of Hygrothermally Aged E-Glass/Epoxy Cylindrical Laminates Using a Novel Fixture for Simulating Internal Pressure."** *J. Compos. Constr.*, Vol. 13 No. 4 (2009) pp. 325–331.

Some Related Test Standards and References

CMC and PMC Tube Hoop Tensile Test Articles

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Classification of Test Methods for Hoop Tensile Strength of CMCs

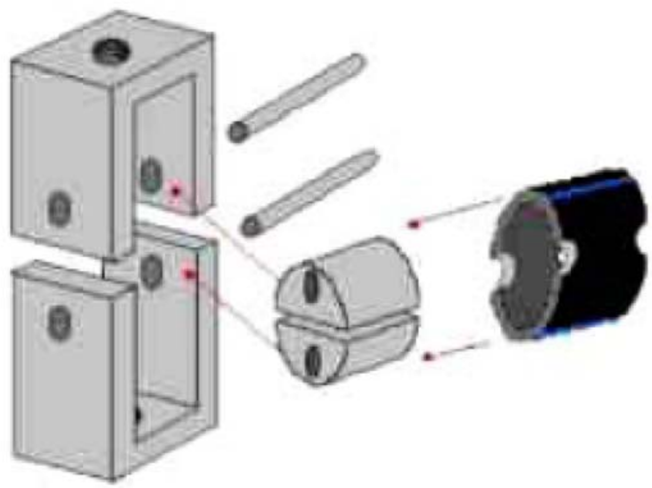
A review of experimental and analytical methods applied to assessing behavior of tubes subjected to hoop tensile stress resulted in the following categories.

1) Mechanical loading methods applied to short sections of tubes

2) Viscoelastic loading methods applied to short and/or long sections of tubes

3) Pressure loading methods applied to short and/or long sections of tubes

Mechanical loading methods applied to short sections of tubes

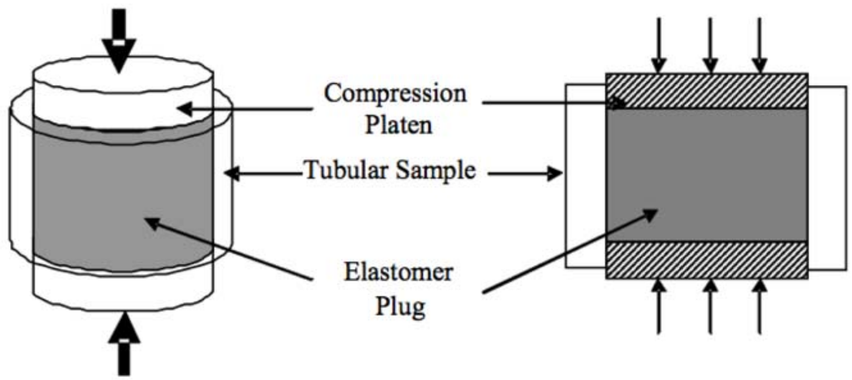


Standard- for example: ASTM D2290 - 08 Standard Test Method for Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe by Split Disk Method,

Reference- for example: M. Rozental-Evesque, B. Rabaud, M. Sanchez, S. Louis and C-E. Bruzek, “The NOL Ring Test an Improved Tool for Characterising the Mechanical Degradation of Non-Failed Polyethylene Pipe House Connections” Plastic Pipes XIV, Budapest, Hungary, 2008

Pros	Cons
- Simple fixtures	- Samples only part of tube
- Uses small sections of tube	- Edge effects
- Uses existing test machines	- Does not represent internal pressure loading
- Simple equations	- Limited to proof testing

Viscoelastic loading methods applied to short and/or long sections of tubes

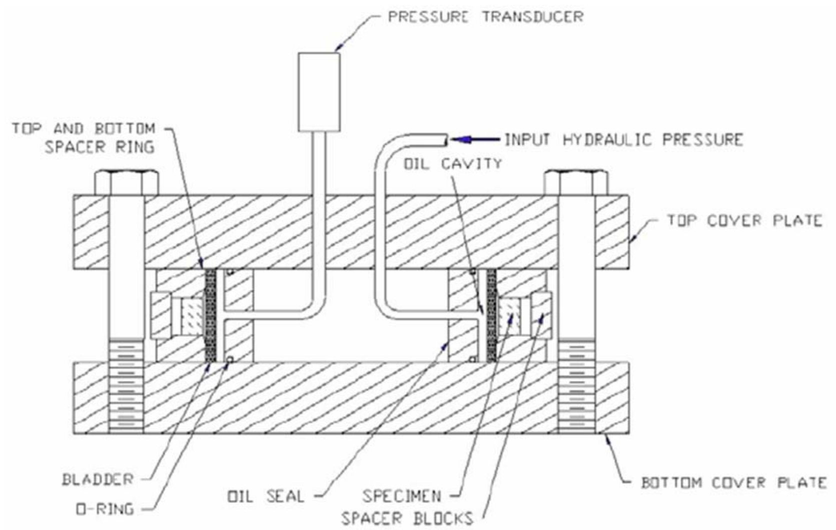


Standard- None

Reference- for example: K. Mosley, "The Stressing for Test Purposes in Tubular Form Using Elastomeric Inserts-Experimental and Theoretical Development, " Proc. Instn Mech Engrs, pp. 123-139, Vol 196, 1982

Pros	Cons
- Simple fixtures	- May be complex stress states
- Uses short or long sections of tube	- Friction effects for rough surfaces
- Uses existing test machines	- May be force/pressure limited
- Has been extended to high temp	- May be limited to material selection

Pressure loading methods applied to short and/or long sections of tubes



Standard- for example: ASTM D 1599-99 Standard Test Method for Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings

Ref- for example: T.R. Barnett, G.C. Ojard, and R.R. Cairo, "Relationships of Test Materiall and Standards Development to Emerging Retrofit CFCC Markets, in Mechanical, Thermal and Environmental Testing and Performance of Ceramic Composites and Components, ASTM STP 1392, M.G. Jenkins, E. Lara-Curzio, S. T. Gonczy, eds. American Society for Testing and Materials, West Conshohocken, Pennsylvania (2000)

Pros	Cons
- Real internal pressure loading	- May require internal bladders
- Uses short or long sections of tube	- Stress state may be biaxial
- Simple equations	- May require special equipment
- Related directly to applications	- May be high-temp problematic

Proposed ASTM C28 Hoop Tensile Strength Test Standard

Two new standards are proposed:

1) **"Hoop Tensile Strength of Continuous Fiber-Reinforced Advanced Ceramic Composite Tubular Test Specimens at Ambient Temperature Using Hydrostatic Pressurization"**

Wide applicability, design data generation, model verification

2) **"Hoop Tensile Strength of Continuous Fiber-Reinforced Advanced Ceramic Composite Tubular Test Specimens at Ambient Temperature Using Elastomeric Inserts"**

Limited applicability, material down selection / screening

Proposed ASTM C28 Hoop Tensile Strength Test Standards

What are the standards about?

A ceramic composite tube/cylinder or tube/cylinder section with a **defined gage section and a known wall thickness** is selected to be the test specimen.

The test specimen is inserted into the appropriate test fixture assembly is subject to one of the following monotonic loading depending on the standard:

1) Direct internal hydrostatic pressure produced from hydraulic fluid

or

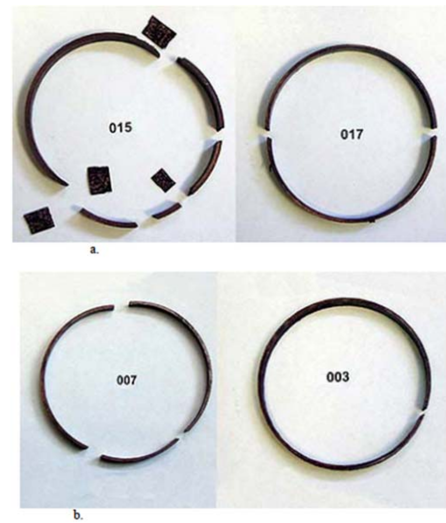
2) Indirect pressure produced by axial loading of an elastomeric insert

Either pressure or axial load is recorded along with **hoop displacement/strain** in the gage section. Results include hoop tensile stress/strain, ultimate hoop tensile strength, fracture hoop tensile strength and proportional limit hoop tensile stress along with corresponding strain, elastic constants

Proposed ASTM C28 Tube Hoop Tensile Test Standards

It is applicable to a wide range of CMC tubes with 1-D filament, 2-D laminate, and 3-D weave and braid architectures.

- The test method addresses –
  - test equipment
  - interferences
  - gripping and coupling methods
  - testing modes and procedures
  - tubular test specimen geometries
  - test specimen preparation and conditioning
  - data collection
  - calculation
  - reporting requirements
  - precision/bias.



Critical Experimental Factors

CMCs generally exhibit "graceful" failure from a cumulative damage process, unlike monolithic advanced ceramics that fracture catastrophically from a single dominant flaw.

The tensile testing of CMC (both flats and tubes) has a range of different material and experimental factors that interact and must be controlled and managed:

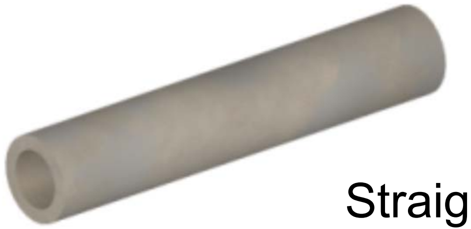
- Material Variability, including Anisotropy, Porosity, and Surface Condition
- Test Specimen Size, Fiber Architecture, and Gage Section Geometry Effects
- Out-Of-Gage Failures and Extraneous Stresses
- Slow Crack Growth, Strain Rate Effects, and Test Environment
- Accurate Strain/Elongation Measurement

C-SiC Composite Tube
NASA-Glenn

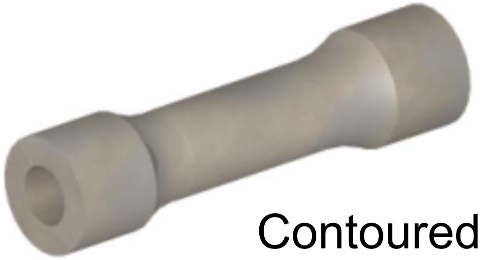
Test Specimen Geometry

CMC tubes are fabricated in a wide range of geometries and sizes, across a spectrum of fiber-matrix-architecture combinations.

- **It is not practical to define a single test specimen geometry that is universally applicable.**



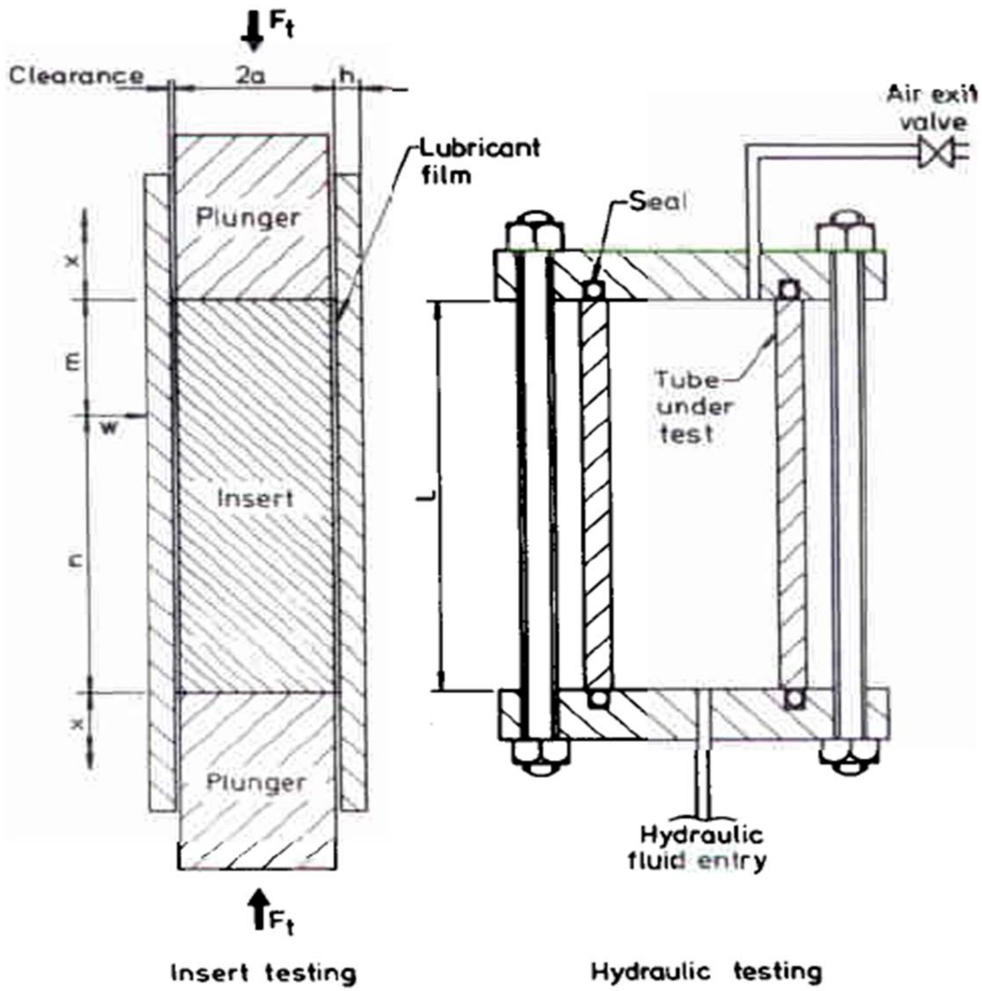
Straight Sided
Tube Specimen



Contoured Gage Section
Tube Specimen

- A range of specimen sizes –
  - outer diameters (d_o) of 10 to 150 mm
  - wall thicknesses (t) of 1 to 25 mm,
  - where d_o/t = 5 to 30.
  - tube section may vary depending type of test (25 mm to 1000 mm)
- In many cases, the wall thickness is defined by the fiber-reinforcement architecture, particularly for woven and braided configurations.

Test Procedures



- **Primary strain measurement by strain gages and/or string extensometers in the "gage section"**
- **Data collection at 50 Hz or greater**
- **Failure time in 5-50 s**
  - Minimize slow crack growth
- **Minimum valid test specimen count = 5**

Internal Hydraulic Pressurization

- **Controlled pressurized fluid**

Elastomeric Insert Pressurization

- **Controlled axial loading**

Calculations and Reporting

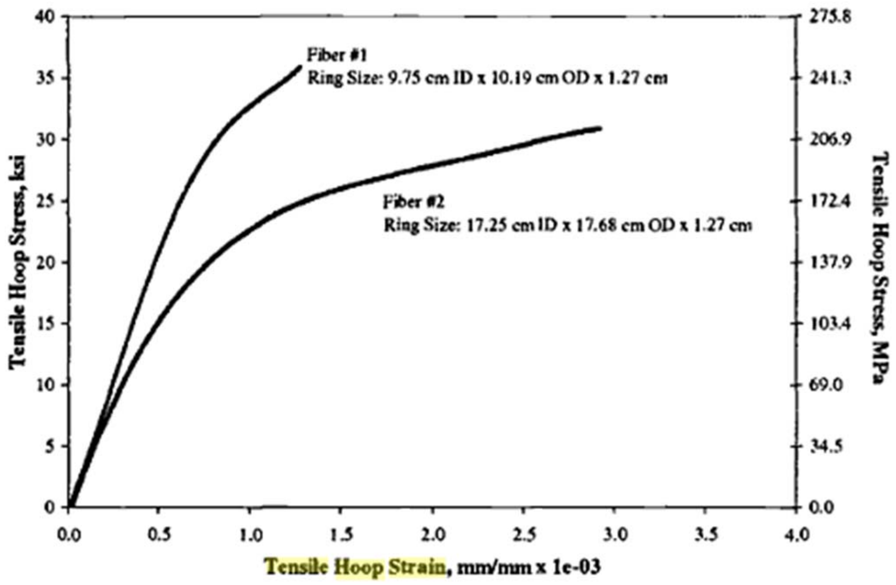


Figure 4 – *Typical EPM SiC/SiC CMC circumferential stress-strain response at room temperature*

- **Hoop tensile stress-strain curve**
- **ultimate hoop tensile strength and corresponding strain,**
- **fracture hoop tensile strength and corresponding strain,**
- **proportional limit hoop tensile stress,**
- **elastic modulus in circumferential direction**

REPORT Requirements

- test identification,
- material description
- test specimen description and preparation,
- equipment description
- test parameters,
- test results (statistical summary and individual test data.)

$$\sigma_\theta = P\left[\frac{2r_i^2}{r_o^2 - r_i^2}\right] \quad \text{and } \varepsilon_\theta = \text{ measured directly}$$

[at outer radius for internal pressure]

where: P = pressure

[internal hydraulic pressurization]

or

P= f (F_{axial}, A_{insert}, Elastic constants, stiffnesses)

[elastomeric insert loading]

Precision

CMCs have probabilistic strength distributions, based on the inherent variability in the composite:

fibers, matrix, porosity, fiber interface coatings,
fiber architecture, alignment, and anisotropy,
inherent surface and volume flaws.

Variability occurs spatially within single test specimens and between test specimens.

Data variation also develops from experimental variability –

test specimen dimensions and volume/size effects,
extraneous bending stresses,
slow crack growth, temperature and humidity effects

ASTM Committee C28 is planning an interlaboratory testing program per ASTM Practice E691 to determine the precision (repeatability and reproducibility) for a range of ceramic composites, considering different compositions, fiber architectures, and specimen geometries.

Volunteers for the C28 Nuclear CMC Working Group

C28.07 Working Group
Strength of Tubes

Yutai Katoh	ORNL (Oak Ridge National Laboratory)
Taiju Shibata	JAEA (Japan Atomic Energy Agency)
Brad Stocking	Touchstone Research Laboratory
Terry Barnett	Southern Research
John K. Shigley	ATK Aerospace Systems
Roberta Hines	HITCO
Marc Melin	SGL Carbon GmbH, HITCO
Fred Stover	Matrix Enterprises
Jon Salem	NASA Glenn Research Center
Mike Verrili	GE Aviation
Rob Carter	ARL
Stefan Dancila	U.Texas Arlington
Kai David, Brad Kibbel	Boeing R& D
April Cuaresma	PW Rocketdyne
Takashi Nozawa	JAEA (Japan Atomic Energy Agency)
John Garnier	INL (Idaho National Laboratory)
Gerard Pelletier	PW Rocketdyne
Adam Chamberlain	Rolls Royce

Progress and Plans

1. Draft Standards distributed for comment in May/June 2013
2. Initial C28.07 Subcommittee Ballot – June 2013
3. Revise Draft Standards as needed – Summer 2013
4. C28 Main Committee + C28.07 Subcommittee Ballots - Fall 2013
5. Publish – Fall/Winter 2013-14
6. Organize round-robin interlaboratory testing project, given available material, funding, and participating laboratories – Spring 2014

This work was done with U.S. Department of Energy funding under the technical direction of Dr. Yutai Katoh at Oak Ridge National Laboratory, Oak Ridge, TN

Conclusion

1. There is a real need for a comprehensive and detailed consensus test standard for hoop tensile testing of CMC tubes.
2. The proposed ASTM standard test methods for hoop tensile testing of CMC tubes (1-D, 2-D, and 3-D architectures) is in the drafting stage and should be balloted by the end of 2013

Your advice and support for new CMC standards is welcome.

If you have expertise and/or interest, please join the C28.07 working group – jenkinsmg@bothellest.com

Any Kwestions, Komments,

Kriticisms, Koncerns, Kudus…??