GAS-COOLED REACTOR
ADVANCED REACTOR TECHNOLOGIES PROGRAM

07/17/2024

Analysis of the ASME Code Rules for Subsection III-5-HHB on Composites

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DOE ART GCR Review Meeting

Hybrid Meeting at INL

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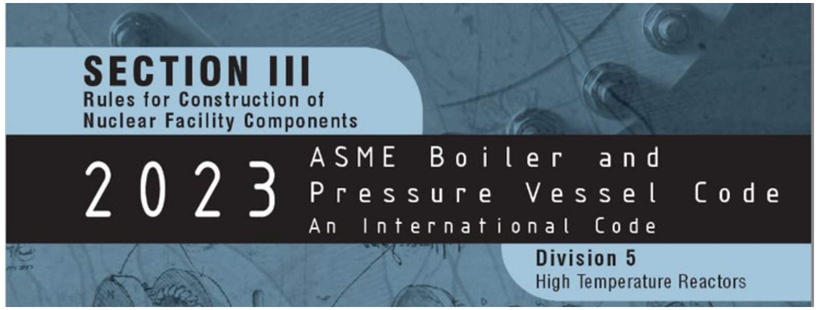
ASME Sec. III-5 Nonmetallic Design Rules Status

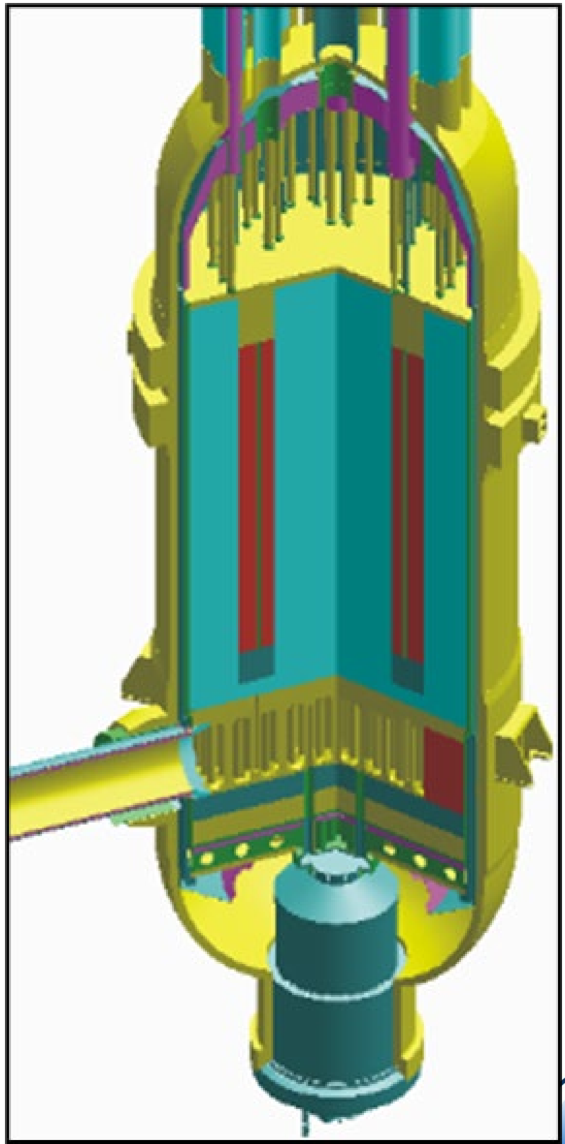
Nonmetallic Core Component Code Relevancy

- ASME Sec. III Nuclear Codes Div. 5 HTR
- Design and Materials code for the use of graphite and CMC components in HTR
- The code is process based to allow for future applications and the unique nature of the material.
- The rules are probabilistic as failure is derived from the variability in the material strength.
- It includes the evaluation of environmental effects such as irradiation, oxidation / chemical attack and stress-time-temperature (in the case of CMCs).

Technical Approach and Progress



- **Subsection HAB**
- **Subsection HHA (Graphite)**
- **Subsection HHB (Composites)**
  - **Analysis review of HHB complete**



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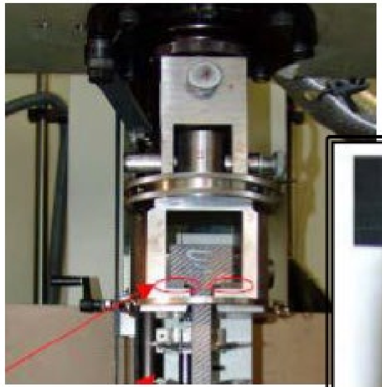
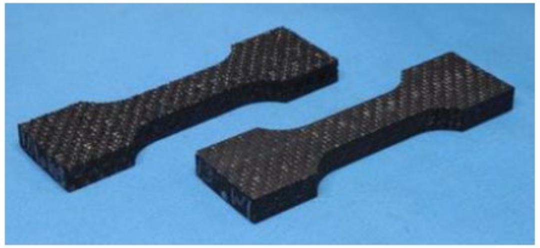
Type CMC Applications

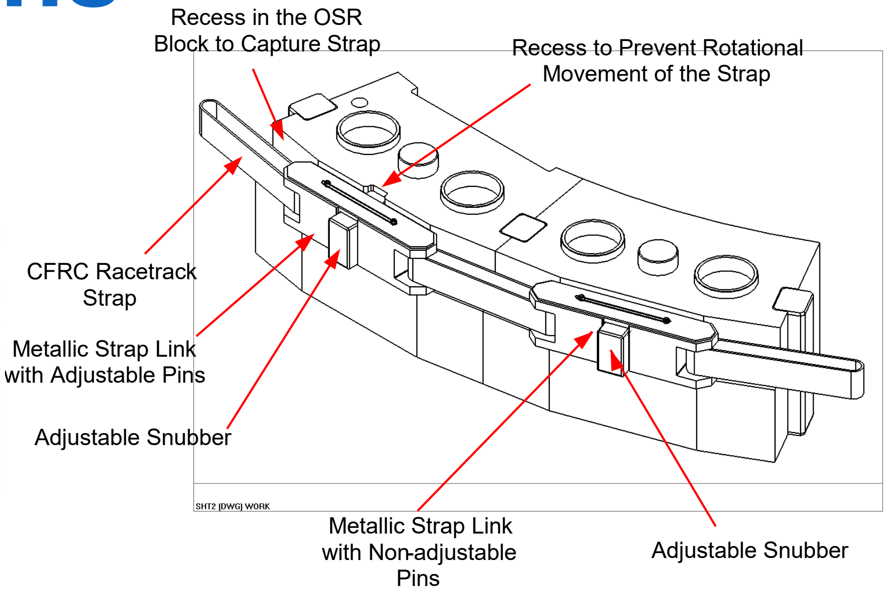
Tie Rods



PBMR Pty.

Material Test Coupons





Restraint Straps

Examples from the PBMR design

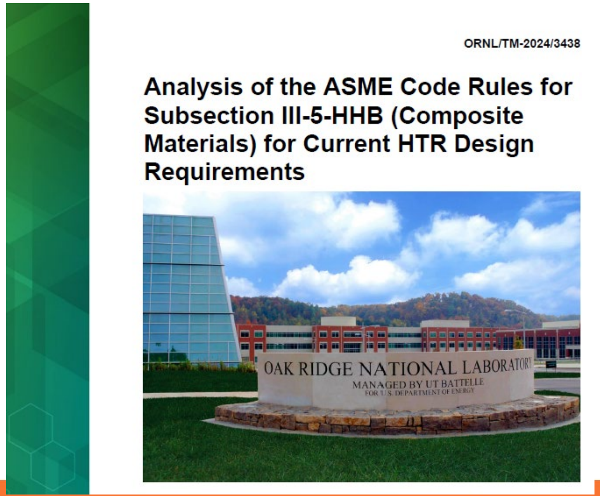
Status of code rules for CMCs (HHB):

Previous Status

- Code rules established within the ASME design framework
- Allows the use of fiber reinforced CMCs for structural core components in HTRs.
- Provides a method to qualify new CMCs, acceptable for use of nuclear application (NQA-1)

Recent Achievements

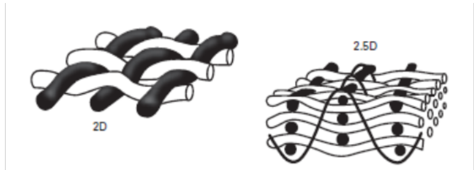
- Completed critical analysis review
- Initiated optimization and refinement efforts (e.g. design by test, maximum failure mode, material qual.)



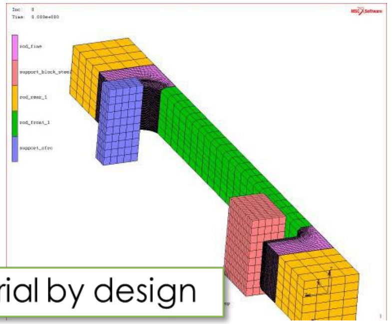
Future Work

- Technical basis and benchmarking
- Continue with optimization and refinement
- NRC endorsement review

WG-Nonmetallic Design and Material: Task Group on Composites



Examples of Fiber Architecture



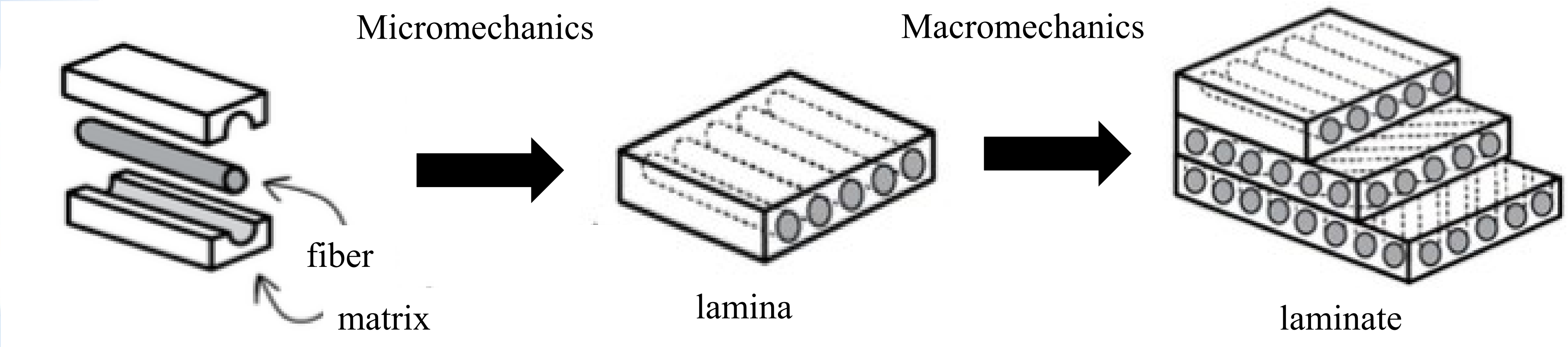
Optimization Areas

- Qualification Methodology:
  - Is it possible to optimize and/or accelerate the qualification process by reducing the material qualification effort?
  - How can technologies & analytical methods be used to reduce testing efforts?
  - What is mandatory or non-mandatory in the code considering HHB-2000 and appendices?
- Composite design rule assessment
  - Does the “simplified assessment” design approach clearly explain how to address anisotropic differences in mechanical properties?
  - Is there sufficient detail for the design by test methodology?
  - When should which method be applied?

Next: demonstrate or benchmark the code methodology using combined modelling and testing techniques

CMC Qualification Design and Analysis

The mechanical material analytical models for composites are well established



Utilizing compiled data with analysis provide process for design
Model validation through limited material and component testing

- **Material data compiled for unique manufacturing process**
- **Component data compiled for properties specific to the product form**

*CMH-17 Composite Materials Handbook, Vol 5, June 2017

Structural Assessment Procedure

HHB-3213 Basis for Determining Stresses

The design rules in this Article do not make use of a theory for combining stresses. The design approach requires comparing the maximum stresses resulting from the loading of the component to the stress at failure of the material. It is key that the stress at failure be determined for the mode of failure that is exercised by the applied stress. For example, if the stresses primarily result in shear stresses in the matrix, then the stress at failure for matrix shear stress shall be used for acceptance of the design.

HHB-3214.2 Maximum Loading Mode Stress. The maximum loading mode stress in a Composite Core Component is the highest loading mode stress computed from the total stress in the Composite Core Component in accordance with the provisions of HHB-3215.

This stress shall be calculated for the case in which all of the loads in a load case are simultaneously applied. The maximum loading mode stress for a Service Level is the most severe maximum loading mode stress for all of the loadings or combinations of loadings comprising the Service Level.

HHB-3220 STRESS LIMITS FOR COMPOSITE CORE COMPONENTS

As a simplified assessment, the maximum loading mode stress (see HHB-3214.2) calculated for the Composite Core Component (per HHB-3215) shall be compared directly to an allowable stress value. The allowable stress value depends on the target POF derived from the SRC (HHB-3110) of the Composite Core Component and the Service Level of the load. The Design Loadings are as de-

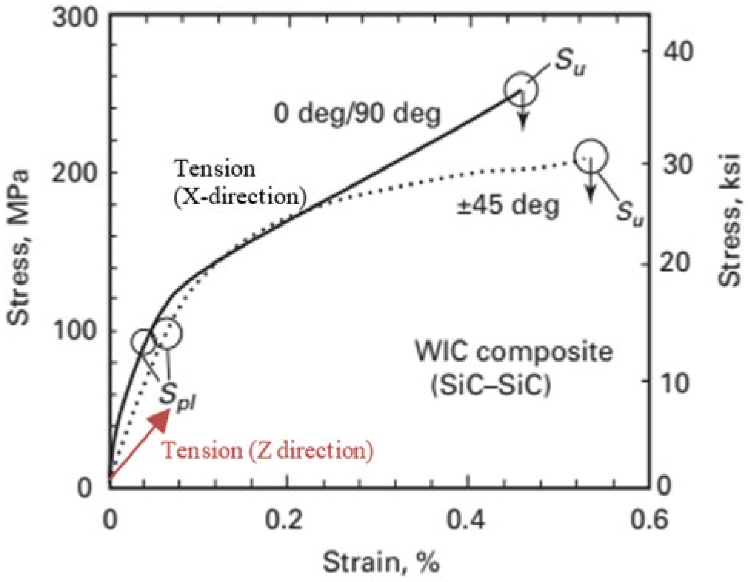
Questions:

1) How is Maximum Loading Mode (MLM) stress determined and is it singular global value? Or is there an MLM stress for each direction and loading mode?
2) How are Mode-Specific Failure Strengths (S_f) determined and assessed across all the different load mode-directions-architecture in the CMCs?
3) How are Mode Specific Design Allowables (S_{gm}) calculated from Experimental Failure Strengths (S_f)?

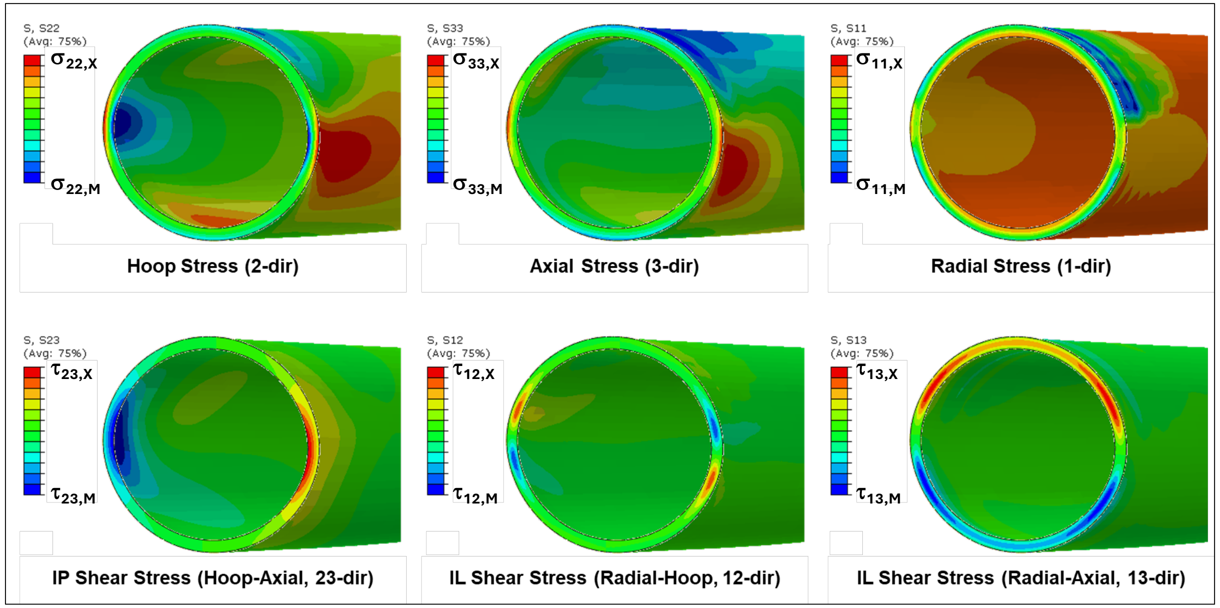
Structural Assessment Procedure

Example:

For tube under transverse shear stress – what is the peak or MLM stress and in which direction?



Tube under Transverse Shear



S22 (Hoop)		S33 (Axial)		S11 (Radial)		S23 (IPS)	S12 (ILS)	S13 (ILS)
Min	Max	Min	Max	Min	Max	Max	Max	Max
$\sigma_{22,M}$	$\sigma_{22,X}$	$\sigma_{33,M}$	$\sigma_{33,X}$	$\sigma_{11,M}$	$\sigma_{11,X}$	$\max\lvert\tau_{23,X}, \tau_{23,M}\rvert$	$\max\lvert\tau_{12,X}, \tau_{12,M}\rvert$	$\max\lvert\tau_{13,X}, \tau_{13,M}\rvert$
$S_{22,C}$	$S_{22,T}$	$S_{33,C}$	$S_{33,T}$	$S_{11,C}$	$S_{11,T}$	S_{23}	S_{12}	S_{13}
$_{22,M} / S_{22,C}$	$\sigma_{22,X} / S_{22,T}$	$\sigma_{33,M} / S_{33,C}$	$\sigma_{33,X} / S_{33,T}$	$\sigma_{11,M} / S_{11,C}$	$\sigma_{11,X} / S_{11,T}$	$\tau_{23,X} / S_{23}$	$\tau_{12,X} / S_{12}$	$\tau_{13,X} / S_{13}$

Structural Assessment Procedure

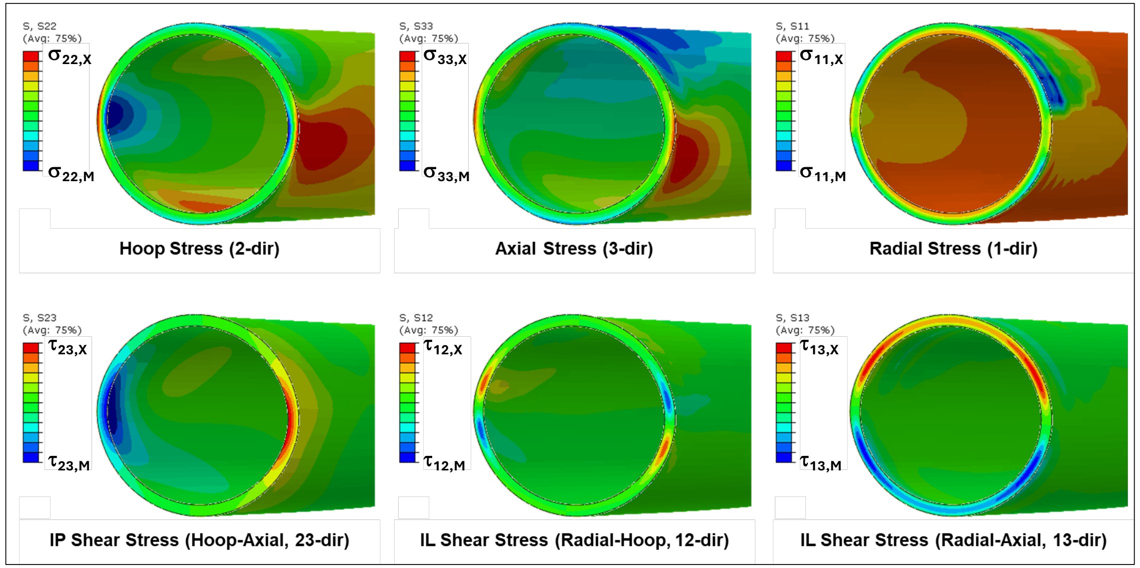
MLM stress can't be applied as a singular global value.

Each orthogonal direction and each load case needs to be analyzed to established if design loads are met.

Code areas affected:

HHB-3213, HHB-3214.1 thru 4

Tube under Transverse Shear



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$S_{22,C}$	$S_{22,T}$	$S_{33,C}$	$S_{33,T}$	$S_{11,C}$	$S_{11,T}$	S_{23}	S_{12}	S_{13}
$\sigma_{22,M} / S_{22,C}$	$\sigma_{22,X} / S_{22,T}$	$\sigma_{33,M} / S_{33,C}$	$\sigma_{33,X} / S_{33,T}$	$\sigma_{11,M} / S_{11,C}$	$\sigma_{11,X} / S_{11,T}$	$\tau_{23,X} / S_{23}$	$\tau_{12,X} / S_{12}$	$\tau_{13,X} / S_{13}$

R23-2452 under review by the SG-HTR committee

Design-by-Analysis and Design-by-Test

HHB-3100 GENERAL DESIGN

Rules for the design of Composite Core Components (Core Components manufactured from C–C composites and SiC–SiC composites) and their integration into Core Assemblies are described in this Article.

Design of Composite Core Components is addressed in HHB-3200. Provisions are made for the following two approaches to design:

(a) design of Composite Core Components to meet the reliability targets based on stress limits derived from the material reliability curve (HHB-3220). This is referred to as a simplified assessment.

(b) design of Composite Core Components to meet the reliability targets based on experimental proof testing of Composite Core Component performance with margins derived from the material reliability curve (HHB-3240).This is referred to as design by test.

HHB-3220 STRESS LIMITS FOR COMPOSITE CORE COMPONENTS

This assessment is conservative, and not meeting the prescribed limit does not mean that the Composite Core Component is not acceptable. Design by test (HHB-3240) may be completed to accept the Composite Core Component.

HHB-3240 EXPERIMENTAL LIMITS — DESIGN BY TEST

It is permissible to declare a design in compliance with the requirements of this Article based on component testing or design by test. Design by test either demonstrates that the POF of the Composite Core Component subjected to an enveloping load meets the requirements of this Article or establishes a Load Rating for the component consistent with the limits provided in this Article. The POF limits are summarized in Table HHB-3221-1.

Note that not all parts and loadings are suitable to design by test, as complex loadings and environmental effects may not be adequately reproducible in a test. In such a case, the method in HHB-3220 shall apply for the design of such a part (in the applicable loading mode).

A combined Analysis/Testing approach is not explicitly outlined in the code.

Design-by-Analysis and Design-by-Test

A combined Analysis/Testing approach is desired to reduce the amount of material testing through supplemental subcomponent and component level testing.

HHB-3100 GENERAL DESIGN

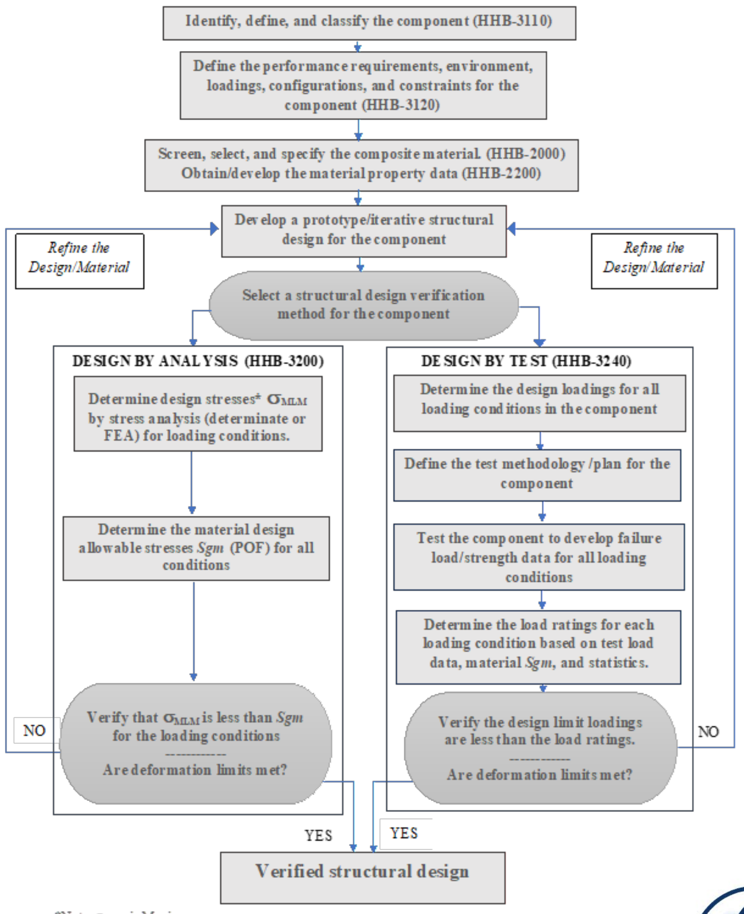
Rules for the design of Composite Core Components (Core Components manufactured from C–C composites

Application of the two design approaches to Composite Core Components is illustrated in Figure 3100-1. Note that once a structural design verification method is chosen, it is applied to the all loading conditions and material directions to determine if the strength or loading conditions as well as deformation limit conditions are met. If these conditions are not met, iterative steps are applied to the structural design verification method to refine the design process or material until the conditions are met.

Combined Analysis/Testing approach is not explicitly outlined in the code.

R23-2453 under review by the SG-HTR committee

Figure HHB-3100-1 Flow Chart for Component Structural Design



*Note: σ_{MLM} is Maximum Loading Mode Stress

Generating Material Properties

HHB-III-4100 AS-MANUFACTURED CERAMIC COMPOSITE MATERIAL

As-manufactured material property data shall be obtained from tests of composite components or witness coupons from each production lot of material meeting all of the requirements of the Designer (Mandatory Appendix HHB-I).

Revise the code to require the as-manufactured property data to be collected from at least three production lots and to make the designer responsible for the determination or justification of the representative data.

R23-1572 approved by Sec III

Other code actions identified but not yet addressed

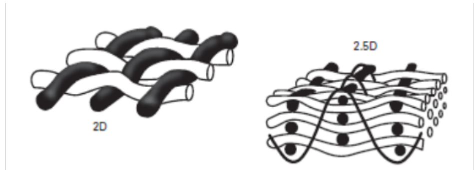
Actions still to be addressed	Records
Need to address material properties to be measured in all three orthogonal material directions. (HHB-2000)	R24-1439
Need to address revision on “highest use” definition in HHB-3112.	R24-1442
Need to address the concern regarding the use of limited material specifications. (HHB-I-1120)	R24-1445
Need to address the revision on the means of how to obtain moduli response in HHB-II-2000 and the mandate on the use of dynamic modulus in HHB-3230.	R24-1460

(Aiming to have these addressed in 2027 edition)

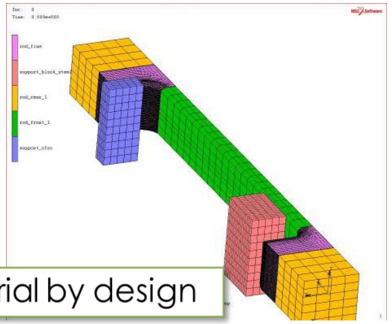
NRC Endorsement of ASME Section III, Division 5 -Status

- NRC supports the development of industry consensus codes and standards, which is valuable to both industry and the regulator.
- Codes and standards provide guidance as to what constitutes good practice, and it enables technology for life cycle or supply chain applications
- NRC endorsed (with exceptions and limitations) ASME Section III, Division 5 (2017 Edition) and accompanying Code Cases
- On April 5, 2023, the NRC announced that they intend to perform periodic reviews of Sec.III-5 and Section XI Division 2
- Rules on ceramic matrix composites (CMCs) first published in the 2019 Edition and excluded from NRCs first review.
- Next code review expected on the 2023 Edition of the code. (Gaps on CMC code are expected…)

WG-Nonmetallic Design and Material: Task Group on Composites



Examples of Fiber Architecture



Optimization Areas

- Qualification Methodology:
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Next: demonstrate or benchmark the code methodology using combined modelling and testing techniques

Benchmark Case Study

In progress

- The task team is preparing a white paper that discusses a suggested analysis approach for an exemplar 2D CMC structural component for use within a nuclear reactor core.
- The first section will generate an estimated set of properties for the identified CMC material, including elastic properties in the as-fabricated material condition and irradiation dimensional change up to 3 dpa.
- The effective orthotropic properties of the constituents will be initially defined using literature data on irradiated materials

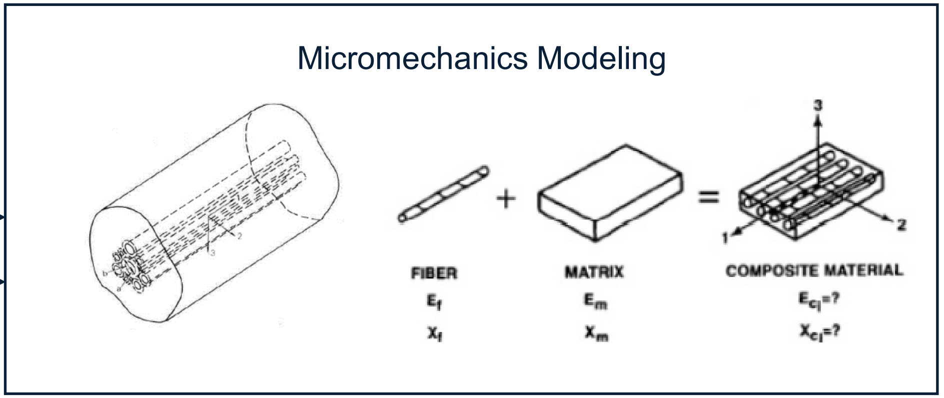
Estimated Representative Composite Properties

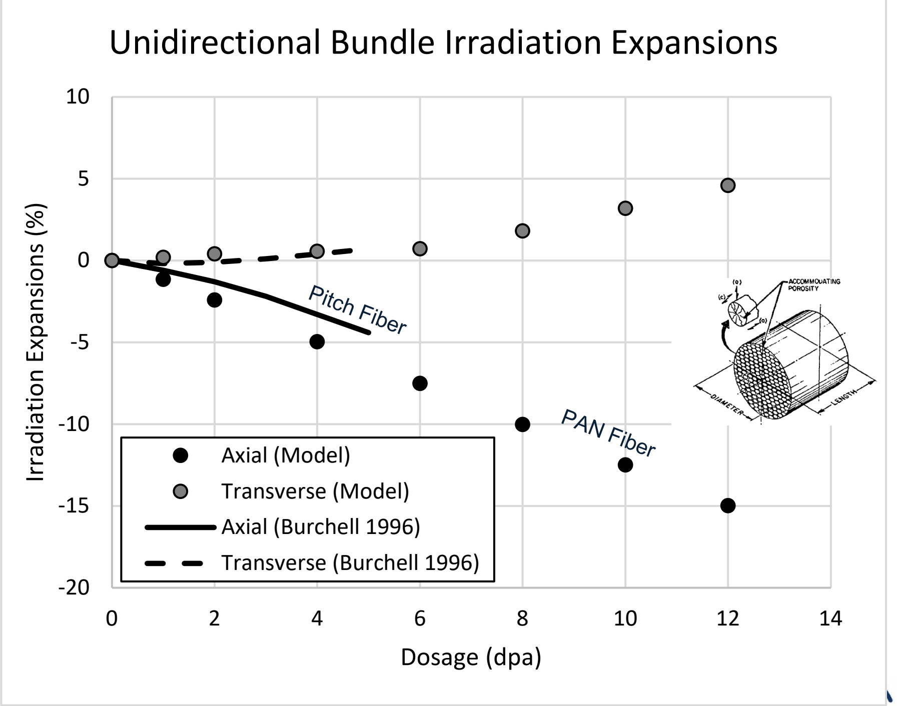
Carbon fibers (modeled using carbon fiber data and graphite crystal data) shrink axially and expand diametrically.

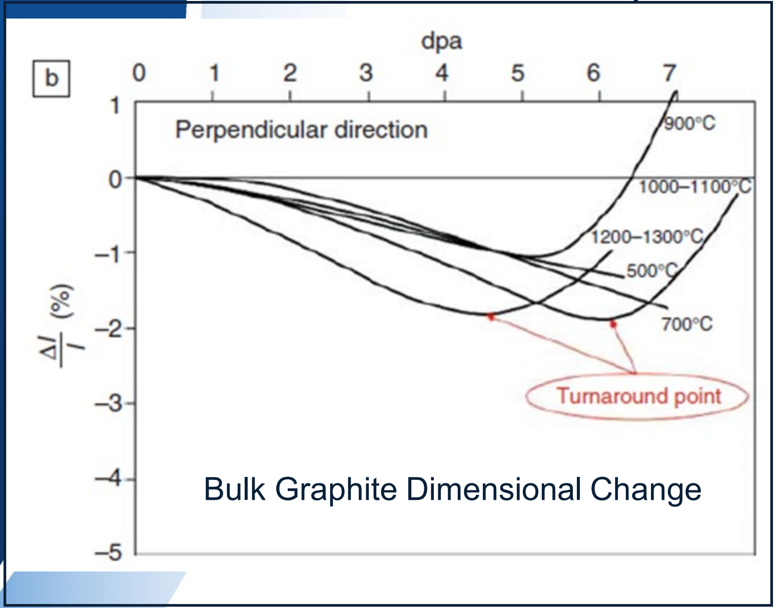
Carbon matrix (modeled using bulk graphite data) shrinks, but less than carbon fiber in the axial direction.

Use published constituent data to calculate composite properties and compare with published composite properties → close agreement indicates a valid micromechanics model.

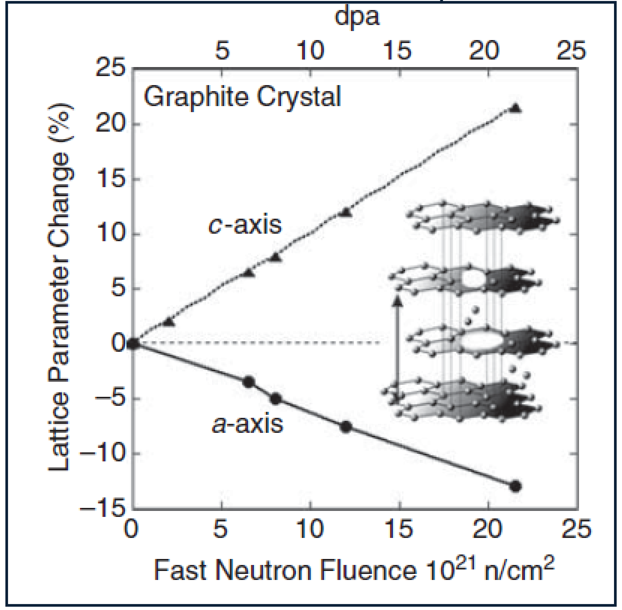
Exercise micromechanics model to calculate composite properties for the architectures of interest across the relevant range of dpa.







Bulk Graphite Dimensional Change



C/C composite example

Estimated Representative Composite Properties

From Structural Reliability Class (SRC), POF requirements range from $5 \cdot 10^{-2}$ to $1 \cdot 10^{-4}$ (Table HHB-3221-1).

Weibull characteristic strengths (S_C^*) are reduced to allowable stress values through two knockdowns:

- variability in the measured strengths, through the 95% Weibull parameters → $S_{C95\%}$
- application of the relevant POF → $S_g(POF)$

$$m_{95\%} = \frac{m^*}{t(n; 0.95)} \quad (6)$$

$$S_{c95\%} = S_C^* \times \exp[-t'(n; 0.95)/m^*] \quad (7)$$

$$S_g(\text{POF}) = S_{c95\%}(-\ln(1 - \text{POF}))^{\frac{1}{m_{95\%}}} \quad (21)$$

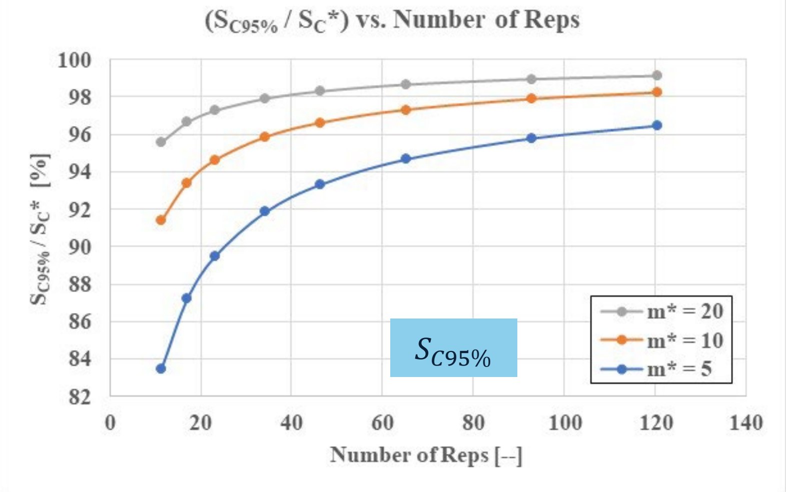
Two-parameter approach

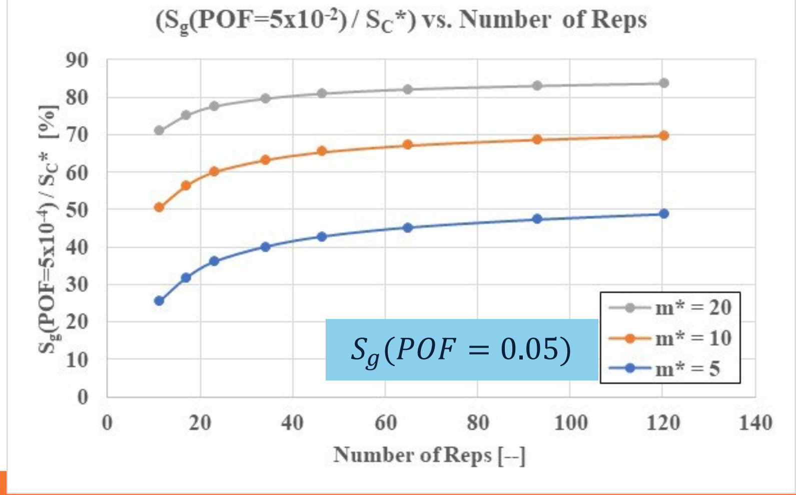
These knockdowns, result in allowable values that are significantly reduced relative to S_C^*.

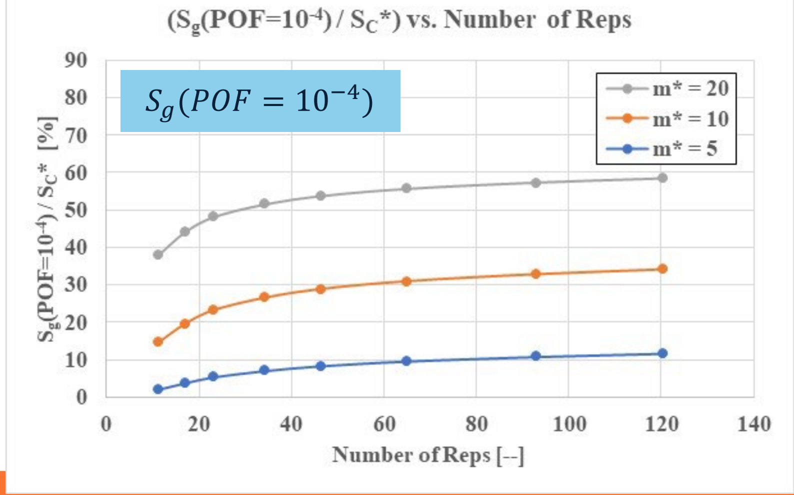
C/C composites in the **interlaminar direction** are likely to have a **lower Weibull modulus than graphite**, and therefore larger knockdown factors (i.e., lower values of S_g/S_C^*).

These knockdowns could cause qualification challenges for components made from C/C composites, particularly for 2D materials in interlaminar tension and interlaminar shear modes (typically the modes with lowest strength and highest variability).

Exemplar POF-adjusted allowable stresses will be calculated using the ASME code approach and a selected number of test reps, together with representative Weibull parameters for C/C.







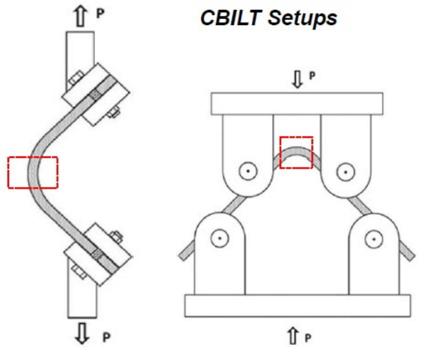
Stress Analysis of an Exemplar C/C Component

Using the composite elastic properties to be generated in the previous task (including CTEs and irradiation dimensional change), the analysis procedure will be demonstrated on an example angle bracket component (i.e., CBILT specimen).

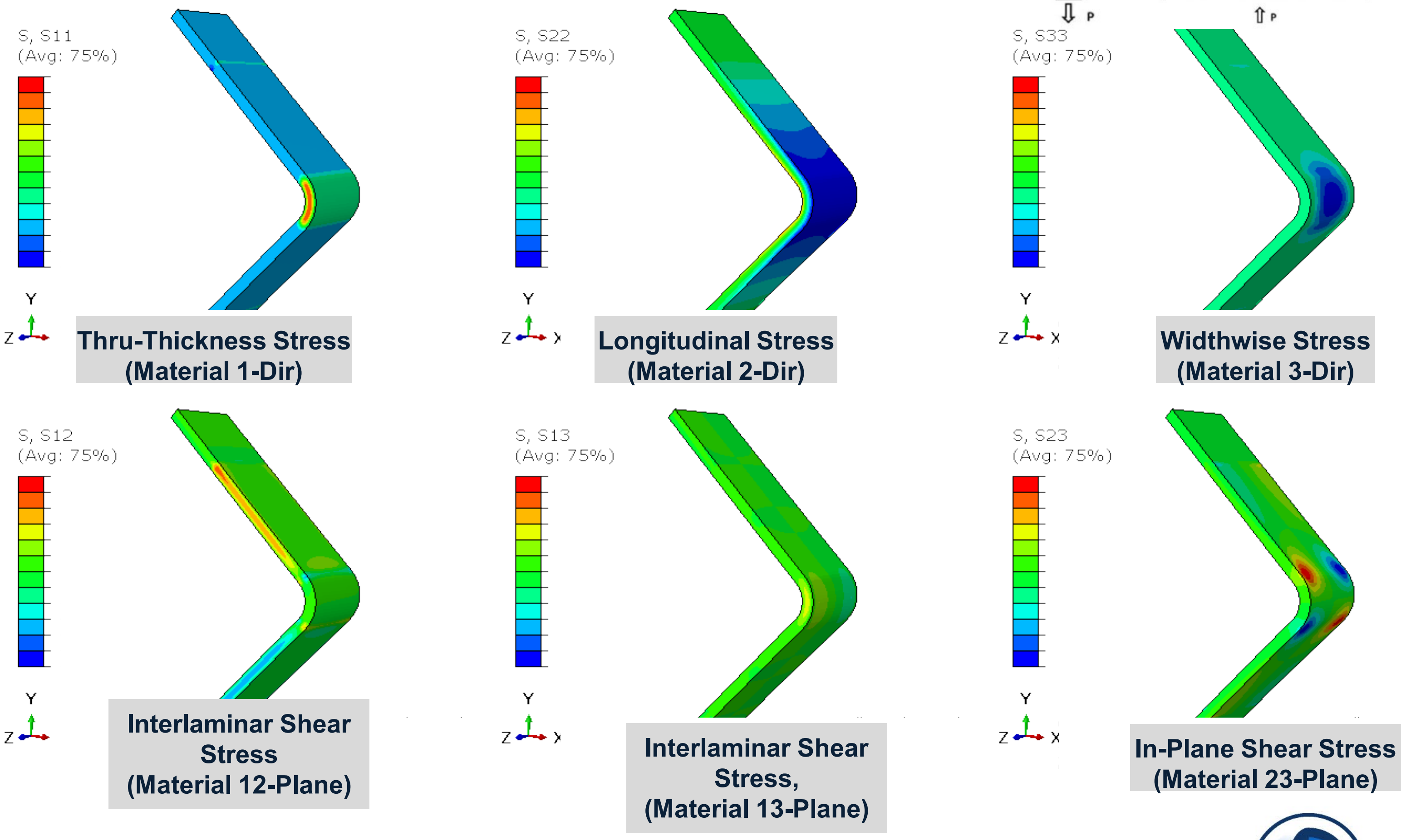
FE model is constructed with relevant loads, BCs, temperatures, etc., and with proper assignments of material orientations.

Peak stresses in all material directions (normal and shear, σ and τ) are extracted and compared with the corresponding strength (S) or allowable to assess structural performance and reliability.

1. S incorporates POF effects.



Angle Bracket



Conclusion and Acknowledgements

This work is reported in ORNL/TM-2024/3438.

The benchmark study case is identified and in progress.

Inputs were provided by Materials Research & Design, Westinghouse Electric Company, Gateway Technologies, and Bothell Engineering Technology Solutions.

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Thank you

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