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OAK RIDGE National Laboratory

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Material Science and Technology Division

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ACRONYMS AND ABBREVIATIONS

ASME	American Society of Mechanical Engineers
ASTM	ASTM International (formerly American Society for Testing and Materials)
ATR	Advanced Test Reactor
BPVC	Boiler and Pressure Vessel Code
CBILT	curved beam interlaminar tension
C/C	carbon–carbon
CFR	Code of Federal Regulations
CMC	ceramic matrix composite
CMH-17-5	Ceramic Materials Handbook 2017 Volume 5
CTE	coefficient of thermal expansion
CVI	chemical vapor infiltration
DOE	US Department of Energy
DOE-NE	US Department of Energy, Office of Nuclear Energy
ECF	environmental correction factor
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FEA	finite element analysis
HAB	ASME Boiler and Pressure Vessel Code Subsection HA Subpart B
HHA	ASME Boiler and Pressure Vessel Code Subsection HH Subpart A
HHB	ASME Boiler and Pressure Vessel Code Subsection HH Subpart B
HTR	High-temperature reactor
MDS	material data sheet
MLM	maximum loading mode
NDM	nonmetallic design and materials
NRC	US Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
POF	probability of failure
SC	subcommittee
Sec. III-5	Section III Division 5
SG-HTR	Subgroup on High Temperature Reactors
SiC/SiC	silicon carbide–silicon carbide
SRC	structural reliability class
STT	stress–time–temperature
WG-NDM	Working Group on Nonmetallic Design and Materials
XCT	x-ray computed tomography

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EXECUTIVE SUMMARY

This document includes the critical analysis review of the American Society of Mechanical Engineers (ASME) Section III Division 5 Subsection HH Subpart B (HHB), including Mandatory Appendices, that was published in 2023. In the context of this document, reference to "the code" is specific to this subsection unless otherwise specified.

A specific composites task group within the ASME Nonmetallic Design and Materials Working Group, with the support of external experts, was established to perform a gap analysis review.

The significant findings are summarized here. The committee response with suggested action items are detailed in the body of the report.

Structural Assessment Procedure

The current text of HHB-3200 could be interpreted in a way that leads a designer to assess only selected stress components when performing stress analyses of a composite core component, as opposed to assessing all nine orthogonal stress components. The content that discusses structural assessments of composite core components should be revised by clearly stating that all nine orthogonal stress components are to be compared with corresponding relevant probability of failure (POF)-adjusted allowable stress values in each mode, which are generated by the data in material data sheet (MDS)-3 or MDS-4. These comments and actions are discussed in more detail in this report, primarily in the comments on HHB-3214 and HHB-3215.

Generating Material Properties

The code does not appear to identify in detail a process by which irradiated material data are to be gathered, at least not to the level of detail that is provided for gathering data for as-fabricated material. The last paragraph of HHB-II-3400 mentions the irradiation correction factor, and HHB-II-4000 provides general guidance on how to define irradiated properties (e.g., conditions must span the temperature range and irradiation levels expected in service, "sufficient" intervals of each variable must be used), but other important aspects do not appear to be addressed. For example, it is unclear whether the statistical approach used for as-fabricated material should also be applied to irradiated material.

Moreover, the code does not appear to directly address how to account for potential variability in the irradiation conditions or the irradiated material data. Both of these classes of potential variability would seem to present a challenge for designers, because material properties (especially in the interlaminar direction) can exhibit significant variation, and because it can be difficult to precisely control the irradiation dosage and temperature experienced by material coupons in irradiation testing. These two classes of variability may lead to (1) a limited quantity of material data being available at any given combination of exposure temperature and irradiation level and (2) wide scatter in the properties. These conditions could be insufficient to generate POF-adjusted allowables following the procedure for as-fabricated material or could result in POF-adjusted allowables that are so low that the material has no practical structural utility. Conversely, if the as-fabricated material approach is to be used, then obtaining sufficient data for irradiated material to populate a form similar to MDS-3 or MDS-4 would likely be a significant challenge in terms of the time and funding required.

Furthermore, the code does not appear to outline any required tests for verification of material properties, either in the as-fabricated or in the irradiated state. Such tests would be worth discussing in the code (perhaps as a nonmandatory appendix to HHB) because they serve to assess whether the effective homogeneous material properties obtained from material coupon testing can accurately reproduce the response of a structure when used in closed-form or finite-element-based structural analyses. Such tests could be relatively simple (e.g., beam bending with strain instrumentation), and suggested notional configurations could be included in the appendix to further assist the designer.

Material Specification

Mandatory Appendix HHB-I outlines the requirements for material specifications for carbon–carbon (C/C) and silicon carbide–silicon carbide (SiC/SiC) materials and references ASTM International (ASTM) C1783 and C1793. A detailed specification is required for the general reason outlined in the second paragraph of HHB-2111: “There are currently no industry-wide material specification standards for C/C and SiC/SiC composites, because of the wide range of composition, fiber architecture, manufacture, and properties of those composites.”

Understandably, the ASTM documents in particular require a significant depth of information to be provided. However, the depth of required information could present a challenge for adoption of these materials because material fabricators are likely to consider some aspects of the required information to be proprietary or sensitive. One potential way to reduce the full scope of detail outlined in ASTM C1783 and C1793, while ensuring that material is consistently made within specification, could be implementation of ongoing persistent testing at the material fabricator. However, this approach would likely require some degree of information from the fabricator, such as the constituent materials, steps of the fabrication process, and more, some of which may be considered proprietary.

1. INTRODUCTION

1.1 BACKGROUND

The use and benefits of ceramic matrix composites (CMCs) for the core components of high-temperature reactors (HTRs) were introduced in the early 2000s when these material systems were also investigated for fusion systems owing to their light weight, strength in extreme conditions, and relatively moderate to great neutron irradiation resistance. With the first of its kind publication on the rules of graphite component design (American Society for Mechanical Engineers [ASME] Boiler and Pressure Vessel Code [BVPC] Section III Division 5 [Sec. III-5] Subsection HH Subpart A [1], hereafter referred to as HHA) in 2013, a modest effort was initiated to define rules for composite materials with the prospects of future benefits as the material matures for this application.

From the beginning, integration with the aerospace industry—more familiar with the use of these materials for structural applications—was recognized as necessary. However, because of the proprietary (and secret) nature associated with manufacturing and application of CMCs (especially carbon–carbon [C/C] applications), the integration efforts were not optimal. The code relies heavily on industry to align itself in the nuclear environment to further improve on what it considers best practices.

With the first publication of the CMC code in ASME BPVC Sec. III-5 for high-temperature reactors (HTRs) [1], the technical basis to support and demonstrate the design rules remained lacking. This code was still developing, composite materials had not been considered for any prior HTR license application. The US Nuclear Regulatory Commission (NRC) also stated that ASME BPVC Sec. III-5 Subsection HH Subpart B (HHB), on the topic of CMCs, was not included in the 2017 edition of ASME BPVC Sec. III-5 and as such was outside of their initial review and therefore not endorsed. The rules in their current state had no real safety consequence for the ASME community at the time of publication, but since then, several design concepts have been presented that place a higher level of scrutiny on these rules.

Since the gap analysis effort started, several design concepts now suggest the use of CMC materials to be used as a reactor core material, putting more urgency on the revision of parts that have been identified as critical for industry application and implementation.

Moreover, on April 5, 2023, the NRC announced that they intend to perform periodic reviews of Sec.-5 and Section XI Division 2 after their endorsement of the 2017 edition of the code. The NRC initiated efforts to review the 2023 edition of the code, including new code editions, to assess whether the issued Regulatory Guide (RG) 1.87 [2] on the Acceptability of the ASME code Sec. III-5 for HTRs needs to be revised. Consequently, HHB, which was first introduced in the 2019 edition, will be subject to its first review by the NRC [3].

This document includes the critical review of HHB, including mandatory appendices, that was published in 2023. In the context of this document, reference to “the code” is specific to this subsection unless otherwise specified.

1.2 REVIEW OBJECTIVES

With the knowledge that the code, defined in HHB, needs additional basis to support and demonstrate the rules, together with questions and interest from the community, a specific task group within the ASME Working Group on Nonmetallic Design and Materials (WG-NDM) was established. The composites task group focused on addressing mission-relevant activities as they relate to ASME BPVC Sec. III-5 Subsection HA Subpart B (HAB) and HHB on CMCs.

First, the task group identified the most critical gap areas where the design code, as described in HHB, may need further consideration or revision. Then, they established the needed basis to support and demonstrate the design and qualification process.

This review addressed the first part; assessing the code readiness, by performing an external code review by designers with specific expertise in CMCs for aerospace applications. Output from the analysis review supports design and/or material/component qualification efforts with vendor benchmarking and/or code case development to demonstrate the rules and processes (where lacking).

Task group meetings were held to the discuss sections of the code, specifically areas for which questions were presented. In general, the meetings were well attended and represented by vendors, industry specialists, material experts, and ASME working group members. Participants included Westinghouse Electric Company; BWX Technologies Inc.; Ultra Safe Nuclear Corporation; Materials Research & Design, Inc. (MR&D); Wichita State University; Kratos Defense (previously Southern Nuclear); Idaho National Laboratory; Oak Ridge National Laboratory (ORNL); California State University, Fresno; independent specialists; and the NRC (attended as observer only).

The external reviews presented in this report comprise comments provided by MR&D with inputs from others in industry. The committee response is that of the task group members who serve on the WG-NDM. Several actions were initiated, including code revisions to address the critical gaps that were identified.

2. ABOUT SECTION III DIVISION 5 FOR HIGH-TEMPERATURE REACTORS

Codes and standards are valuable to both industry and the regulator because they provide criteria, requirements, and/or methods that represent industry best practices. They reduce technical risk for industry because they can be applied to satisfy regulatory requirements as well as reduce regulatory uncertainty for industry, and they guide review processes and enhance review efficiency for the regulator.

The US Department of Energy (DOE) supports industry codes and standards development through focused research that provides the technical bases for new or modified codes and standards and the participation of subject matter experts on codes and standards committees.

The ASME (Section III: Nuclear) Committee's function is to

> *establish rules of safety relating to pressure integrity, which govern the Construction of boilers, pressure vessels, transport tanks, and nuclear components, and the in-service inspection of nuclear components and transport tanks. For nuclear items other than pressure-retaining components, the Committee also establishes rules of safety related to structural integrity.*

The term "construction" refers to the all-inclusive effort comprising materials, design, fabrication, examination, inspection, testing, certification, and pressure relief [1].

The design and construction rules for composite components and assemblies were published for the first time in the 2019 edition of HHB. The general requirements are in HAB. This significant accomplishment, which was first proposed in 2008, was achieved after an undertaking of several years (at moderate effort).

The general requirements described in HAB also incorporate rules for composite components because they constitute requirements for the design, construction, examination, and testing of core components and core assemblies used within the reactor pressure vessels of nuclear power plants. The articles under HHB cover materials selection and qualification, composite core component design, machining and installation, examination, testing, and preparation of reports. These articles are supported by information provided in the mandatory appendices and nonmandatory appendices. The mandatory appendices contain requirements that must be followed in construction for components and assemblies described in HHB. The nonmandatory appendices provide additional information or guidance on CMCs.

The existing mandatory appendices describe details that must be applied for composites. Within this category, two groups of materials are being considered: C/C and SiC/SiC. Currently, no industry-wide materials standards exist for composites because of their range of composition, fiber architecture, manufacture, and properties. Therefore, composite materials are tailored for their intended application. Current descriptions in the nonmandatory appendices largely focus on the properties and behavior of SiC/SiC materials.

3. CLASS SN COMPONENTS: THE NONMETALLIC RULES FOR HTRs

A code class is a set of rules that provides a reasonable assurance of structural integrity and quality commensurate with the relative importance assigned to the individual components of the advanced reactor plant. The components described in ASME BPVC Sec. III-5 Subsection HH on nonmetallic HTR core components are classified as class SN components. HHA refers to graphite components, and HHB refers to composite components. HHA and HHB are similar in approach and structure, but, owing to composition and architectural material differences, the application of the design modeling technique varies. Furthermore, the anisotropic nature of the CMCs extends itself to a larger testing program than what is required for graphite.

For reference, the ASME BPVC Sec III-5 [1] defines a CMC as follows:

> *"A material consisting of two or more materials (insoluble in one another) in which the major continuous component (matrix component) is a ceramic, while the secondary component(s) (reinforcing component) may be ceramic, glass-ceramic, metal, or organic in nature. These components are combined on a macroscale to form a useful engineering material possessing certain properties or behaviors not possessed by the individual constituents."*

Part of the challenge for class SN components is the process required to qualify materials before or even during design. The raw material mix and the nature of the manufacturing processes to produce graphite and CMC materials contributes to the wide distribution of material property behavior. By contrast, metallic components for which metals or steels need to be qualified are reviewed and published in Section II, the materials code, before it can be applied in Sec. III-5, the construction and design code for HTRs.

Although the Section III process for Class SN components gives freedom to the designer on materials selection, composition, and use, it adds complexity that is often less desired because the code requires the evaluation of environmental effects (mentioned in HAB) for the life of the component. This evaluation includes the effects of irradiation, oxidation, and/or chemical attack as well as stress–time–temperature (STT) effects in the case of CMCs.

4. SIMILARITIES AND DIFFERENCES AMONG ASME, FAA, AND CMH-17

ASME is a professional standards organization that developed codes, specifications, and standards for metal, concrete, graphite, and composites components. The ASME BPVC has been developed over several years by contributions from volunteers. So, it is safe to say, that the code is developed by industry for industry.

The NRC's mission and objective are to establish regulation and requirements to ensure public health and safety in the operation of commercial nuclear facilities. From this position, they support the development of industry consensus codes and standards, which provide guidance as to what constitutes good practice, and it enables technology for life cycle applications.

When applying for a license, the process requires applicants to specify the design methodology, material specifications, quality assurance, and inspection and installation requirements for NRC approval, as stipulated under Title 10 Code of Federal Regulation (10 CFR) 50 regulations. Applicants or designers can use in-house developed standards or industry consensus standards. [4,5]

Similarly, but different to the NRC, the U.S. Federal Aviation Administration (FAA) issues and enforces regulations and minimum standards covering the safe manufacture, operation, and maintenance of civil aircraft. The FAA prescribes the in the Federal Aviation Regulations (FARs) which comprise of Title 14 of the Code of Federal Regulations (14 CFR). The Ceramics Materials Handbook first issued in 2017 (CMH-17), was developed with the objective to define and codify key design, production and regulatory issues for the FAA and aerospace community. [6]

Stated by the Composite Materials Handbook (CMH) organization, its purpose is to create, publish and maintain proven, reliable engineering information and standards, subjected to thorough technical review, to support the development and use of composite materials and structures. The handbook supports the development and use of CMCs through publishing and maintaining proven, reliable engineering information and standards that have been reviewed. CMH-17 provides information and guidance necessary to design and fabricate structural components from composite materials. Its primary purposes are "a) the standardization of engineering data development methodologies related to testing, data reduction, and data reporting of property data for current and emerging composite materials, b) guidance on material and process specifications and procedures for utilization of the material data presented in the handbook, and c) methodologies for the design, analysis, certification, manufacture, and field support of composite structures". In support of these objectives, Volume 5 of CMH-17 (CMH-17-5) on Composite Materials, includes composite materials properties that meet specific data requirements. The Handbook therefore constitutes an overview of the field of composites technology and engineering. [7]

Different from CMH-17, but similar to the FAR, ASME BPVC Sec. III-5 is not a handbook. Instead, it is a set of rules or regulations that must be adhered to. ASME does not tell a person how to calculate stress loads, but it provides rules and restrictions on what is acceptable or allowed for the design of construction. A distinct difference is the methodology on how to derive allowable stresses or knock-down factors and the A-basis or B-basis experimental basis that is applied for material testing. In general, ASME Sec III-5 works on the principle deriving Probability of Failure (POF) values from Weibull statistics using 95% lower bound confidence interval.

5. CODE REVIEW COMMENTS BY SECTION

5.1 HHB-2111 DEVELOPMENT OF MATERIAL SPECIFICATIONS

External review comment:

Section (a) cites that the designer shall develop a detailed material specification as outlined in Mandatory Appendix HHB-I and in related ASTM standards, which are C1783 (for C/C) and C1793 (for SiC/SiC) [8,9]. The intent of this requirement is certainly recognized, as the designer must have a complete understanding of the behavior of any material being used for a core component. However, meeting this requirement appears to pose several practical challenges owing to the degree of detail cited both in HHB-I and (to a greater extent) in ASTM C1783 and C1793. As an example of one such practical challenge, a number of the requested details in ASTM C1783 (e.g., constituent material selections or formulations, microstructure features, processing aspects) are likely to be considered proprietary by material fabricators. Additional challenges related to the material specification are discussed in a subsequent section.

Committee response:

Generally, code policy (Sec. II Mandatory Appendix IV [10]) is to approve only those materials for which a recognized national or international specification exists. The nature of CMC materials (C/C and SiC/SiC) prevents derivation of a standard for each material grade; such a standard is more typical for metallics. Instead, the two ASTM test standards are provided as guidelines for specifying the material selected for component design, particularly how to specify the material to ensure production quality and traceability to control material performance.

Action:

Practical challenges may exist, but these concerns should be addressed through the ASTM C28.07 Committee.

5.2 HHB-2133 THE CONSTRUCTION SPECIFICATION

External review comment:

This section cites that the construction specification for the composite core component shall include a detailed material specification "that defines the full requirements for material manufacture and acceptance." Of the 10 material aspect areas that are subsequently listed, at least 5 (composition, chemistry, manufacturing process control, quality control, examination, and testing) could potentially require a fabricator to disclose sensitive information.

Committee response:

This paragraph is supported by the text describing the process under HAB on the general requirements for graphite and composite materials. From a safety point of view, a detailed description of the material specification must be included as part of the construction specification. This requirement is especially important because the details of the material's composition are not sufficiently documented elsewhere to a traceable extent. However, this requirement presents a challenge to materials that are generally protected through export control (often the case with C/C). Contractual and legal mechanisms exist to manage and control sensitive information between various parties.

Action:

No action required.

5.3 HHB-2200 CERAMIC COMPOSITE MATERIAL PROPERTIES FOR DESIGN

External review comment:

Section (a) references composition and chemistry as requirements that must be defined for the CMC. This information may be sensitive to a fabricator, depending on the level of detail that is required. Section (a) also cites that a material data sheet "shall be generated for each Composite Core Component or each Ceramic Composite Material production lot used in the Core Assembly." Defining a *production lot* in more detail, either in this section or elsewhere in the code, would be helpful. This definition appears to influence the amount of material testing that is required based on HHB-III-4100, which cites that material property data shall be gathered from tests of material from each production lot.

Committee response:

As-manufactured material properties documented in MDS forms must be generated per composite core component or ceramic composite material production lot used to construct the core assembly. Properties for design are determined by material testing documented in MDS forms as described in section HHB-2000. Proper statistics cannot be collected by the designer unless more than one lot is tested to demonstrate the reliable production process.

HHB-III-4100 should be revised require testing at least three production lots and to allow the designer to consider representative data to generate properties for design as opposed to generating properties for design for each composite core component or ceramic composite material production lot used to construct the core assembly.

Action:

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. See discussion on record changes for record 23-1572 in Section 6 of this report.

5.4 HHB-2220 IRRADIATED CERAMIC COMPOSITE MATERIAL PROPERTIES

External review comment:

Section (a) cites six material properties that must be measured on material that has been irradiated. However, the lack of material directions cited for any of these properties seems ambiguous and potentially subject to misinterpretation. Considering that Section (b) specifically says that "the designer may require assessments of other irradiated properties, such as compression, interlaminar shear, and interlaminar tensile strength," Section (a) appears to refer to in-plane tensile properties. However, interlaminar shear and interlaminar tension are typically the lowest strengths for 2D C/C continuous fiber-reinforced materials, and properties generally depend upon and could be appreciably different in the material directions (e.g., irradiation shrinkage in fiber-dominated directions and irradiation swelling in matrix-dominated directions). Therefore, for continuous fiber-reinforced materials, the list in Section (a) should be modified to include all three orthogonal material directions, or, at a minimum, the in-plane and across-ply directions. This change would effectively relocate the optional strength quantities in Section (c) to Section (a) and make them required properties. HHB-2220 as written is likely sufficient for C/C materials that are effectively isotropic (e.g., those that are reinforced with fibers that are randomly oriented and relatively short, such as aircraft brake materials). Furthermore, this section does not cite a method or type of modulus measurement, whereas HHB-2230 cites dynamic modulus. For clarity, one or more acceptable methods for measuring modulus should be cited. Typically, when analyzing of C/C or SiC/SiC aerospace structures, modulus data are obtained from quasi-static mechanical tests (not from dynamic tests).

Committee response:

HHB-2200 states that the properties of the ceramic composite materials used for the design shall be determined by the designer and documented in the MDS. Mandatory appendix HHB-II defines the requirements for completing the MDS and states that the properties must be obtained in each primary direction of the material. However, the proposed suggestion does remove initial ambiguity for the paragraphs in HHB-2000 and should be considered to be included in the text as proposed.

In regard to the review comment on dynamic modulus, refer to the response for HHB-2230.

Action:

Include code revision to address material properties to be measured in all three orthogonal material directions. Record 24-1439 has been created to address this change.

5.5 HHB-2230 CERAMIC COMPOSITE MATERIAL PROPERTIES AND CHEMICAL ATTACK/OXIDATION

External review comment:

Section (a) cites a minimum of three material properties but does not cite material directions, and Section (c) cites the same three optional additional strength modes as HHB-2220. As with HHB-2220, the list of properties in Section (a) should be modified to cite all three material directions, effectively relocating the three optional strength modes into Section (c) as required properties.

In addition, Item (2) in Section (a) cites that the elastic modulus is to be measured using dynamic methods, but no method is specified in HHB-2220. Furthermore, Notes 28 and 30 in Table HHB-II-2000-1 indicate that Young's modulus via mechanical testing is mandatory, whereas Young's modulus via sonic resonance (i.e., a dynamic method) is designer specified. The reference to dynamic modulus in this section should likely be removed.

Committee response:

The concerns regarding three material directions are discussed in Section 5.4 (comment on HHB-2220) and should be applied to all relevant paragraphs of HHB-2200. However, in response to the remark related to Item (2), an error seems to have been made in reference to the dynamic method. This method stems from the ASTM specifications, namely C1783 (for C/C) and C1793 (for SiC/SiC) [8,9], which call out ASTM C769 [11] to perform sonic velocity as a technique to determine Poisson's ratio. An earlier study [12] on a SiC/Ti composite noted that a dynamic correction is necessary when velocity along the fiber is used to determine interphase moduli and that attenuation in the fiber direction increases rapidly at higher frequencies. It may be worth investigating lower frequencies tests. In essence, values that accurately reflect true modulus are difficult to obtain via dynamic methods. Section 5.24 on review comments for HHB-II-2000 the MDS forms. The reference to dynamic modulus in HHB-2230 should be removed. It is realized the measuring the modulus through static tests will be more difficult for degraded materials.

Action:

Revise the code to address material properties to be measured in all three orthogonal material directions. Record 24-1439 has been created to address this change.

Assess and revise the use of dynamic modulus and alert the ASTM community of the finding related to sonic velocity. Record 24-1460 was created to revise the rules on the dynamic modulus mandate.

5.6 HHB-2240 STRESS–TIME–TEMPERATURE EFFECTS ON CERAMIC COMPOSITE MATERIAL PROPERTIES—CREEP, STRESS RUPTURE, SLOW CRACK GROWTH, AND FATIGUE

External review comment:

Section (a) cites a minimum of four material properties that must be characterized if STT effects are expected. As with HHB-2220 and HHB-2230, the list in Section (a) should be modified to include required material directions, effectively relocating the properties in Section (b) to Section (a) as required quantities.

Committee response:

The concerns regarding three material directions are discussed in Section 5.4 (on HHB-2220) and should be applied to all relevant paragraphs of HHB-2200.

Action:

Revise the code to address material properties to be measured in all three orthogonal material directions. Record R24-1439 has been created to address this change.

5.7 HHB-2520 REPAIR

External review comment:

Section (b) discusses the use of repaired items. Generally, verifying that a mechanically damaged and subsequently repaired CMC item meets the requirements of the as-fabricated CMC material specification could be difficult, considering typical aspects of the materials (relatively brittle, with relatively high densities of flaws or initial cracks, at least for C/C). However, the language of Section (b) is certainly general and simply offers a route for a designer to utilize a damaged part and effectively applies the as-fabricated requirements to the damaged and repaired part.

Committee response:

The paragraph on repair is generic in that it provides the designer with a pathway to use a damage part, but it can be brought to the committee to review whether a mechanically damaged section should be repaired.

Action:

No change required, but further discussion will be entertained for potential change.

5.8 HHB-3100 GENERAL DESIGN

External review comment:

The final paragraph states "The Designer shall evaluate the effects of cracking of individual Composite Core Components in the course of the design of the Core Assembly and ensure that the assembly is damage tolerant." The intent of this requirement is clear, but it also seems to be somewhat vague and potentially difficult to determine whether a particular design satisfies the requirement.

Committee response:

A previous review performed on the graphite design rules found that technical requirements for quantifying and assessing damage tolerance were absent and should be investigated for the ways in which degradation affects structural reliability [13]. For composites, damage tolerance refers to failure that has occurred below the design-allowable stress (or the determined POF value). For graphite and monolithic ceramics, this failure can be the result of slow crack growth (a failure, due to stress-induced cracking not caused by environmental degradation).

Graphite and monolithic ceramics exhibit very high strength but low toughness or low tolerance to stress-induced growth. In general, CMCs with reinforced fiber bundles, as defined by the code, are designed through microstructural development to allow microcracks in the matrix to pass around the fibers (instead of through), and then the stiff fibers are used to bridge the microcrack to minimize the crack opening. In addition, by orienting fibers in the principal tensile stress direction, durability can be further enhanced.

Given that the code is not prescriptive on the CMC composition, architecture, nor specific application, rules for each potential case cannot be provided. In this regard, the onus is on the designer and the material scientist to define the potential damage mechanisms to ensure the components in the assembly are damage tolerant.

Action:

No action at this time. When the use and application of CMC components mature in HTR designs, more explicit rules can be developed.

5.9 HHB-3111 CLASSIFICATION OF COMPOSITE CORE COMPONENTS

External review comment:

Sections (a) through (c) mention three structural reliability classes (SRCs), SRC-1 through SRC-3, with definitions between the graded level of reliability. However, after this paragraph, no allowances or restrictions are provided for SRC-2 graded components as is the case for SRC-1 (safety related) and SRC-3 (not safety related). Section (b) does state that the particular class, SRC-2, is not available for composite core components, but mentioning it in the code indicates that the designer should have different stress allowables if the component is not important to reactor core safety and is subjected to environmental degradation during service.

Committee response:

Historically, several types of components were mentioned as potential applications for composite core components in an HTR. These components included control rod guides/sleeves, lateral restraint straps, and tie rods [14] and referred to components that fell within either SRC-1 or SRC-3. That is, either it is outside of the reactive core so that it has minimal exposure to radiation, or it is inside the core with safety significance to the core. Although Section (b) of Par HHB-3110 states that SRC-2 is unavailable for composite core components, removing this section may eliminate some ambiguity in the future.

Action:

Prepare this action for the working group discussion to consider removal of Section (b).

5.10 HHB-3112 ENVELOPING COMPOSITE CORE COMPONENTS

External review comment:

The second paragraph in HHB-3112 states that "Design analysis shall be completed for the Composite Core Components of each group subject to the highest use (defined as the ratio of applied loads, both internal and external, to the load to failure)." The phrase in parentheses (i.e., the definition of "highest use") should be revised to the following: defined as the load case that induces the highest stress-to-allowable ratio in any stress mode, to be calculated by dividing each of the nine stress components resulting from the applied loads by the corresponding allowable stress in each mode, where the allowable value used has been adjusted for the relevant POF.

Committee response:

The task group agreed with the suggestion because it provides a more accurate definition of the highest use terminology.

Action:

Record 24-1442 was created to address revision on "highest use" definition in HHB-3112.

5.11 HHB-3123 DESIGN LOADINGS

External review comment:

The second paragraph in HHB-3123 states that "The Design Loadings are the worst combination of nominal specified Service Level A sustained operating loads." This approach seems to suggest that the designer should determine the most severe load case based on the magnitudes of the applied loads. However, given that the strengths of composite materials are generally different in each stress mode, such an approach could misidentify the worst loading case for some combinations of loads and material strengths.

Committee response:

This observation is a good one. Wording of the paragraph should be revised to remove the reference to the worst combination of Service Level A sustained operating loads.

Action:

Reconsider and revise this paragraph. Record 23-2452 has been assigned to address this action.

5.12 HHB-3130 NOMENCLATURE

External review comment:

Experts in the field noted that composite components are more often analyzed using finite element analysis (FEA) methods (as the preferred method of analysis), and the combined bending stress and combined membrane stress (as mentioned in this section of the code) are not used to perform the assessment. Nomenclature that would be more directly applicable to FEA methods should be added to improve the clarity of the code for designers who plan to use FEA tools.

Committee response:

This feedback is good. A previous revision on the 2021 edition removed the ratio of compressive strength to tensile strength from its analysis method. The nomenclature was revised accordingly. Furthermore, the notation reference to the failure-mode-specific design stress, S_{gm}, and the mean failure-mode-specific design stress, S_{um}, calculations as derived in the MDSs (HHB-II-2000) were also recorded for revision (Record 22-2267) to align with the notations discussed in HHA-3000 and HHA-II. However, to revise the nomenclature by omitting combined bending stress and combined membrane stress, the sections and paragraphs discussing those rules must be reconsidered. Should the committee decide to remove those sections, all can be removed in one action.

Action:

Review paragraphs HHB-3214.5 on membrane stress, HHB-3214.6 on bending stress, and HHB-3214.7 on combined stress ($C_m + C_b$) for the specific purpose of composite component analysis. If the working group committee decides it is redundant, then text can be removed and record for motion can be prepared.

5.13 HHB-3141 CHEMICAL ATTACK AND OXIDATION

Internal review comment:

This paragraph, specifically the statement in Section (c) where the amount of weight loss that exceeds 30% shall be regarded as completely removed from the core structure for both chemical attack (including oxidation) and strength calculations, was flagged as potentially detrimental to maintaining structural integrity in the case of graphite components [13]. Consequently, it was rejected for endorsement by the NRC. Instead, they stated that designers should determine the amount of weight loss above which the region should be regarded as completely removed from the structure and then justify that the limit is adequate for the design-specific oxidation analysis [2].

Although this concern applied to graphite, the same types of reactions will likely affect C/C, and to a lesser extend SiC/SiC. This paragraph and conditions were adapted from the code language for graphite in HHA-3141, so similar criticism can be expected.

Committee response:

The community should perform oxidative testing to investigate the effect of oxidation on various C/C and SiC/SiC specimens and evaluate the strength reduction, as was done for graphite, to provide more meaningful rules. By contrast, unlike HHA-3141, HHB-3141 has a Section (d), which allows the designer to develop an alternative methodology. This revision will support the statement that the NRC suggested that the designer should determine the amount of weight loss acceptable and justify why it is adequate.

Action:

Several unknowns remain, especially with respect to material qualifications. Additional experiment tests to determine oxidative and other chemical degradation effects should be performed.

5.14 HHB-3142 IRRADIATION EFFECTS

External review comment:

The basis is for the limits provided for the classification of nonirradiated materials is unclear. The C/C limits seem to agree with the conditions provided for graphite in Paragraph HHA-3142.1 (c). However, it is not clear why the SiC/SiC limits are different and higher. It is set after the swelling saturated because of neutron irradiation (~1 dpa). The irradiation swelling behavior of graphite [15] is compared with the irradiation swelling behavior of SiC monolith ceramic [16] in Figure 1.

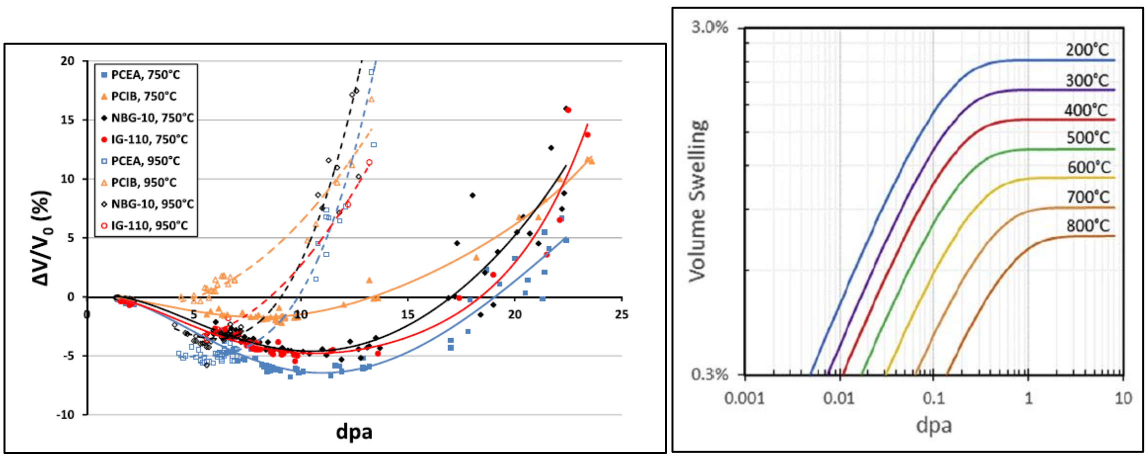


Figure 1. Irradiation swelling behavior. (left) Graphite and (right) SiC ceramic.

Figure 1 shows that, in the case of graphite, the code acknowledges the effect of even a small dose on the the component, but, for SiC, the code seems to ignore the transient regions, which cause bending and component deformation owing to thermal gradients. The purpose of the nonirradiated classification limits should be to avoid complexities that can result in component deformation because of irradiation. The limits for SiC/SiC seems to be contradictory to the intent or the meaning of non-irradiated materials.

Committee response:

Carbon-based materials such as graphite and C/C share many similar irradiation effects largely because of carbon's hexagonal microstructure. For the purpose of the code, irradiation growth should be accounted from a damage dose of 0.25 dpa (neutron irradiation). Figure 1displaying SiC ceramics (right) shows that, even for low temperatures, the volumetric swelling starts to saturate around 1%; at higher temperatures, it is less than 0.5%. For a fix dose and temperature, these changes could be considered within design tolerances. Temperature gradients with or without dose gradients can lead to different swelling rates across the component and can still affect component deformation. This can lead to premature failure and should be considered during the design phase Although the volumetric swelling rate for SiC ceramics is almost an order of magnitude smaller than for graphite, the dose limit to classify a SiC/SiC composite component as unirradiated for neutron dose exposure should be reconsidered.

As with oxidation exposure, C/C composites are not expected to sustain high-dose irradiations (to the same degree as SiC/SiC composites) because of its rather poor radiation performance. However, C/C composites may still be preferred in some niche applications. Few experimental tests are performed to understand what the true implications because of neutron irradiation will be. Basic studies should be performed to investigate the radiation response of C/C compared with SiC/SiC.

Action:

Consider performing basic irradiation tests on both C/C and SiC/SiC composites to compare various responses for initial material qualification efforts. This information can be valuable to the community because limited literature, especially considering C/C, exists.

Entertain further discussion to determine whether the damage dose limit must be reduced for SiC/SiC material systems.

5.15 HHB-3142 ABRASION AND EROSION

Internal review comment:

Section (b) of Paragraph HHB-3142 states that erosion should be evaluated in areas where the mean gas flow exceeds a flow velocity of 100 m/s. This paragraph lists the same requirements stated in Paragraph HHA-3143, which is required for graphite. The premise of this limit was previously rejected because it is applicable only to high-temperature gas-cooled reactors and does not consider the effects of erosion in a molten salt reactor.

Committee response:

This finding was from the previous NRC review [2] on paragraph HHA-3134, and an extensive study was performed to determine appropriate fluid velocities [17]. The study revealed that the designer should determine the mean fluid flow velocity limit above which an evaluation of erosion is necessary and justify that the limit is adequate for the design. This code change on graphite was also suggested for the 2023 edition (record 23-2484). Because a basis for the limit is lacking as far as composite components are concerned, it may be appropriate to follow suit using the revised proposal from the graphite community and put the onus on the designer to determine such a limit.

Action:

Review this potential code change with the broader working group to obtain consensus on the proposed revision.

5.16 HHB-3145 COMPRESSIVE LOADING

External review comment:

This section discusses designing for buckling failure. It requires the designer to determine the critical stress (σ_d) that causes such failure, and then requires that the structure experiences a stress less than $0.25\sigma_d$ (Level A or Level B), $0.50\sigma_d$ (Level C), or $0.60\sigma_d$ (Level D). For some, a critical stress for buckling may be unclear terminology for components that are subjected to loads that are not strictly compressive. More specifically, buckling is frequently assessed in terms of the multiplier that must be applied to the loads on the system to induce buckling. Therefore, citing a critical applied loading factor that induces buckling may be clearer and more general, and this factor should be at least 4 for Level A and Level B, at least 2 for Level C, and at least 1.67 for Level D.

Methods of calculating the critical stress (or load factor as suggested immediately above) are not cited in this section of the code, but different analysis methods will generally provide different results and therefore different levels of conservatism. Specifically, linear eigenvalue buckling analysis (a common approach in both closed form and FEA form) tends to overpredict the critical buckling load for real structures, whereas approaches that can include nonlinear effects (such as the Riks method) and post-buckling behavior are generally more accurate. Notional differences in results among the different methods are illustrated in Figure 2.

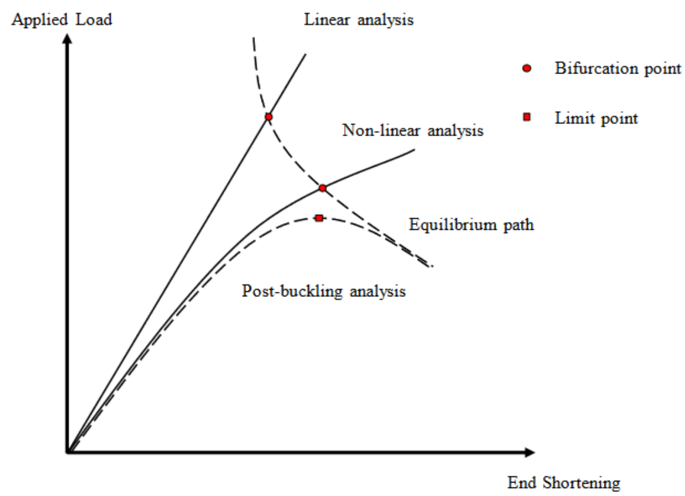


Figure 2. Notional plot of load versus compression distance for a slender tube under buckling load. Extracted from NASA report on buckling of cylinders [18].

If the intent of the code is to allow multiple buckling analysis methods, then different safety factors should be considered for each method. This reasoning also prompts a question of whether different safety factors should be considered for testing vs. analysis of buckling performance. One potential option would be to allow a lower safety factor for testing (because of higher confidence) and require a higher safety factor for analysis, as indicated in a NASA report on structural design of spaceflight hardware [19].

Committee response:

The strategy proposed is to some extent very similar to what has been suggested for concrete containment structures in Section III Division 2. In these rules, several allowable compression stresses for factoral loads are provided. Section III Division 2 further states that these stress allowables shall be reduced, if necessary, to maintain structural stability.

The paragraph in HHB-3145 states that the designer is responsible to establish a design critical stress in compressive loading, σ_d, for the component, either by analysis or by test. It does not dictate the method to be used and leave it to the designer to define.

Action:

Although this observation is interesting, no specific action is identified for this item. It can be considered in the future if a request is made to do so.

5.17 HHB-3213 BASIS FOR DETERMINING STRESSES

External review comment:

This entire section is reproduced below for reference:

> *"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."*

The paragraph clearly states that a combined stress approach is not used. However, the wording could benefit from additional detail regarding how to assess failure (or whether the stress levels in the component are below the POF-adjusted stress allowables). Specifically, the current wording of this section could lead to a designer to assess only the stress component that appears to be the most severe, perhaps based on an intuitive assessment of the applied loading, geometry, material strengths, or some combination thereof. However, because strengths of a C/C composite are generally anisotropic (i.e., vary with stress mode), a more robust approach is to compare peak values of all directional stresses (i.e., orthogonal stress components) with corresponding directional strengths. This approach requires assessing a total of nine stresses: the peak values of the three normal-direction tensile stresses, the peak values of the three normal-direction compressive stresses, and the peak values of the three shear stresses. Each of these stresses is then compared with a corresponding strength or allowable in the appropriate mode (which is consistent with the data required to complete MDS-3 or MDS-4). The approach outlined here may very well be the intent of the current content of this section, but the content can be misinterpreted.

For clarity, an example of the calculations that are performed in this method are summarized in general form in Table 1. In the table, σ_{ij} and τ_{ij} denote the peak stresses in all material directions (normal and shear, respectively) as extracted from FEA results (shown in Figure 3), and the corresponding strength or allowable stress values are denoted by S_{ij}, which incorporate POF effects as needed. Design acceptability is determined by assessing the shaded quantities in the table, which are ratios of the peak stress experienced to the allowable stress, which is consistent with the simplified assessment approach discussed in HHB-3100(a).

Table 1. Summary of peak stresses, allowable stresses, and stress ratios, in all nine stress components, from a notional FEA of a composite component as illustrated in Figure 3

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

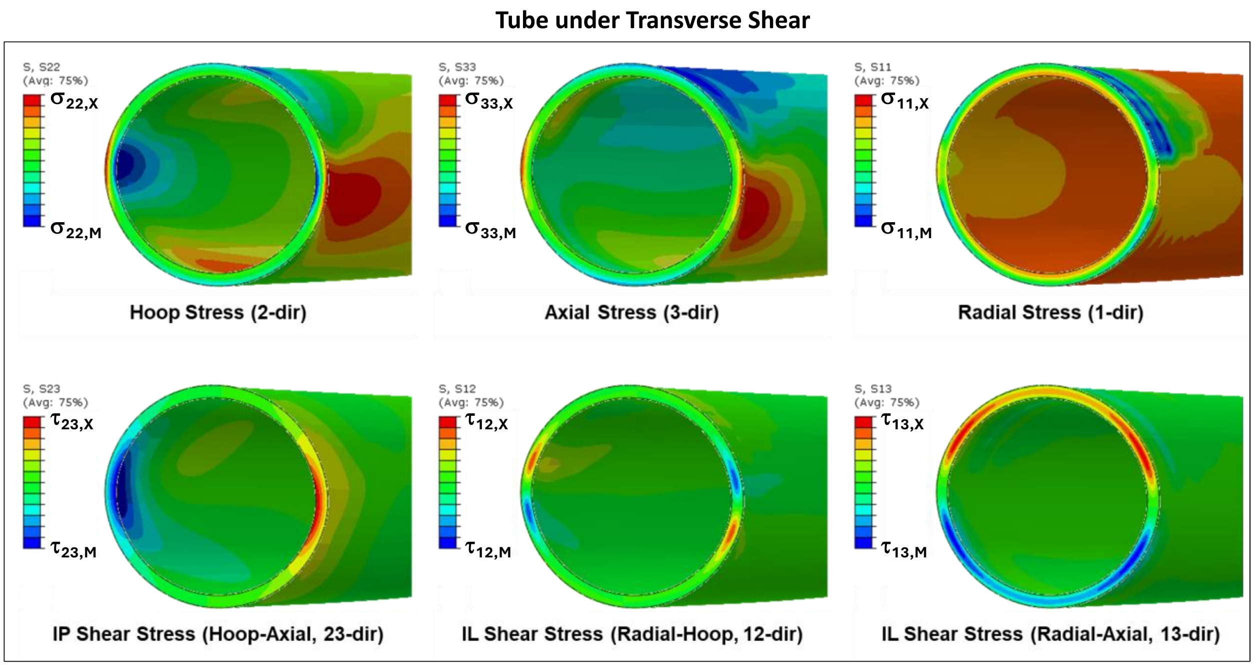


Figure 3. Example FEA of a tube. The resulting stress contours for each of the six stress components of a tube under a transverse shear stress load. The peak values of the stress components provide the $\boldsymbol{\sigma}$ and $\boldsymbol{\tau}$ quantities in Table 1.

The above discussion and the associated example illustrate that the current text describing the basis of determining stresses is dubious or vague at best. It is also not clear whether the loading mode stress is a singular global value or whether a loading mode stress occurs in each orthogonal direction. This simplified approach can be completely misinterpreted by ignoring the anisotropic differences in the mechanical properties that exist in CMCs and is probably the most significant concern with the current code as written.

To further illustrate this point from a materials perspective, Figure 4 [6] shows a SiC/SiC 2D composite with a 2D woven fabric layup architecture, where the fabric plies are laid up in the *xy*-plane.

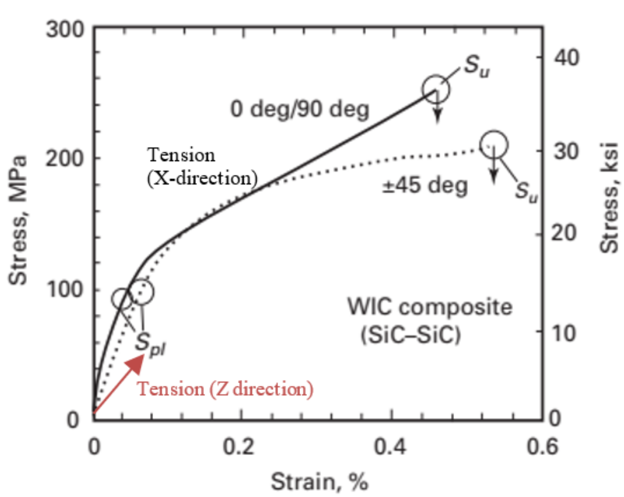


Figure 4. Example of a 2D woven fabric SiC/SiC composite case.

For simple tension in the *x*-direction, the fiber and the matrix carry the load, and the composite typically has a pseudo-ductile stress–strain curve with a failure/proportional limit/matrix cracking (S_{pl}) strength of ~18 ksi.

By contrast, when the tension is in the translaminar *z*-direction, the fibers carry no significant load, and the matrix will crack and fail brittlely at (S_{pl}) ~8ksi. Therefore, the "tensile design allowable stress" will be much higher in the *x*-direction than in the *z*-direction. Consequently, the "maximum tensile stress" must be determined in each direction to ensure that the directional design allowable stresses are not exceeded. In a similar manner, the shear design allowable stress will also vary with direction depending on architecture, and the "maximum shear stress" in each given direction cannot exceed the shear design allowable stress in each direction.

So, how are the mode-specific failure strengths determined and assessed across all the different load modes, directions, and architectures in the CMCs? How are the maximum loading mode (MLM) stresses (discussed in the following paragraphs) and failure strengths compared and used to determine the design allowable stresses (S_{gm})in each direction or mode?

This theme transpires throughout the rest of HHB-3000, including HHB-3214.2, HHB-3215 and HHB-3220, which are discussed in more detail in the following subsections.

Committee response:

The commentary here and in the following subsections are the most critical findings from this review. The maximum failure mode method lacks sufficient detail to address failure assessment for all the component stresses when considering anisotropic materials, and further details are required. This lack should be addressed as the most urgent code change to remove any ambiguity regarding the method.

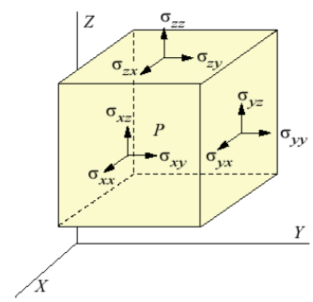
As demonstrated by the previous examples, the anisotropy in composite mechanical properties (elastic modulus, Poisson's ratio) will factor into the FEA stress analysis, rather than assuming isotropic mechanical properties. This result is part of the complexity when working and designing with composite materials.

The actual anisotropic differences are strongly dependent on the reinforcement architecture (1D, 2D, 3D, and fiber loading) effects. In addition, it will be more pronounced in C/C composites, where the matrix is much weaker and more compliant than the SiC matrix in SiC/SiC composites.

For the most complete (and most complicated) composite design methodology, the composite design must consider the MLM stress for all modes (tensile, compression, and shear) in each anisotropic direction and then compare those maximum stresses to the design-allowable stress values for tensile, compression, and shear in each anisotropic direction.

Table 2 details the intent to include the primary directions for all conditions that must be evaluated as part of the design methodology. The detail in the table is not currently explicitly mentioned in the code.

Table 2. Suggested details to determine the maximum loading mode and design allowable stress

Maximum loading mode stress	σ_{max} *tensile* (xx,yy,zz), σ_{max} *compression* (xx,yy,zz), σ_{max} *shear* (x-y, x-z, y-z, y-z, z-x, z-y)	
Design-allowable stress (reliability factor)	S_{gm} *tensile* (xx,yy,zz), S_{gm} *compression* (xx,yy,zz), S_{gm} *shear* (x-y, x-z, y-z, y-z, z-x, z-y)	

The challenge is that full stress analysis for maximum stresses in all modes and directions and full material testing for material design allowable stresses is very expensive and time-consuming.

Action:

Explain the issue of anisotropy in ceramic composite mechanical properties in more detail and describe more fully how that anisotropy is considered in the "simple assessment" design approach.

Specifically, paragraph HHB-3213 clearly states that the theory of combining stresses approach is not used, but additional detail regarding failure assessment (in all nine component stresses) is lacking and should be expanded. Moreover, Paragraph HHB-3214 may need a more robust approach to assess all combinations of applied loading, and not the load case in which all loads are simultaneously applied. Similar to paragraph HHB-3213, HHB-3220 should indicate that all nine component stresses should be compared with the corresponding strengths. More discussion is needed. Record 23-2452 was created to support these changes.

5.18 HHB-3214 TERMS RELATING TO STRESS ANALYSIS

5.18.1 General Terms

External review comment:

Speaking from the standpoint of one group of FEA practitioners, the descriptions of the various stresses in HHB-3214.1 through HHB-3214.12 are somewhat difficult to interpret and utilize in a component analysis, particularly within the context of the FEA-based stress assessment method described in the comments for Section HHB-3213. The fundamental difficulty with this section is that it appears to be written using the terminology and approaches of traditional stress analysis, whereas the preferred analysis tool is FEA, which inherently captures the different types of stresses outlined in HHB-3214.1 through HHB-3214.12 that result from the applied mechanical loads, boundary conditions, temperature field, and irradiation field. The term "stress" in this section is also confusing to some.

Specifically, in HHB-3214.2 (MLM stress), some uses of "stress" refer to loads, but in other instances, "stress" refers to the stress experienced by the composite component. Furthermore, and more generally, the definition of the MLM stress (i.e., the entire content of HHB-3214.2) is incomplete and insufficient for determining a critical loading case because it appears to consider only the stress magnitude in each mode (where "mode" seems to refer to direction) and not the corresponding allowable stress in each mode.

Some of the stress analysis guidance is somewhat unclear and notably different than the typical approach for composites. As one example, HHB-3214.1 states the following: "For example, when a component is expected to fail in bending, the appropriate allowable stress is the bending stress." In one interpretation, this sentence appears to assume that the designer can predict in advance that a given load case will induce failure in bending stress (which is typically interpreted to be an in-plane normal stress). However, for certain geometries of composite core components (and continuing with the example of bending stress from HHB-3214.1), a load case that induces bending response at the component level could actually induce interlaminar stresses at one or more locations that are sufficiently high to cause failure before bending stress failure. A simple example of such a configuration is the curved beam interlaminar tension (CBILT) test specimen, which is commonly used for laminated composites and is shown in Figure 5.

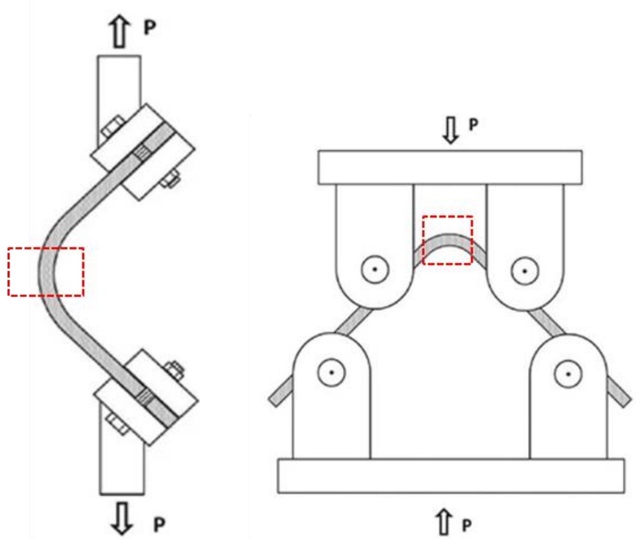


Figure 5. CBILT test setups. The red dashed boxes indicate regions of intended interlaminar tensile failure.

The CBILT test applies bending load to an L-shaped specimen, inducing significant bending (i.e., in-plane normal) stresses in the legs of the specimens while inducing interlaminar tension stress in the bend region. Although the magnitude of the peak interlaminar tensile stress in the specimen is low relative to the magnitude of the peak in-plane normal stresses, the interlaminar tensile strength of laminates is typically much lower than the in-plane normal strengths, and the specimen therefore fails in interlaminar tension. This example case considers a test specimen as opposed to an actual core component, but it illustrates that failure in composite components can occur in a stress mode that, intuitively, may not seem to be exercised by a particular loading case.

Committee response:

This particular section on terms relating to stress analysis seems to be confusing to the nonmetallic community and was also mentioned during the review of graphite analysis procedure discussed in HHA-3000.

Developers of the code rules under Subsection HH (Class SN Nonmetallic Core Components) wanted to use verbiage similar to the metals code sections as much as possible. This desire was likely for the sake of standardization. However, to accommodate this addition of terms, for the sake of alignment, additional terms or explanation were added to allow for more specific use of the nonmetallic material in question, creating more confusion for the nonmetallic community in general.

Primary stress, secondary stress, and peak stress are fundamental terms for the metallic rules. However, because the primary stress, secondary stress, and peak stress are defined (or introduced) in HHB-3000 similar to HHA-3000, the code now uses the metal verbiage to guide the designers to obtain to the "correct stress measure" to compare against design limits.

The use of metal verbiage and terms should be reconsidered because they clearly create confusion and result in stress terms that are added to the composites code that is typically not used for composite stress analysis (as mentioned in Section 5.12 on HHB-3130 on the use of combined bending stress and combined membrane stress).

This review again notes that HHB-3000 may makes a major simplification with its assumption about the calculation of the MLM stress as explained in Subsection 5.17, discussing the basis for determining stresses. With the anisotropic nature typical to CMCs, a critical failure mode that has a wide disparity in mechanical properties and failure mechanisms in different directions can be missed. To eliminate this risk, additional description must be added to the text of HHB-3214.1 on the loading mode stress, HHB-3214.2 on the maximum loading mode stress, HHB-32.14.3 for the normal stress assessment, and HHB-3214.4 on the shear stress assessment.

Action:

Review HHB-3214 and make a motion to remove the terms not appropriate for the use of composite design analysis.

5.18.2 Primary and Secondary Stresses

External review comment:

Section HHB-3214.7 reviews examples of and the differences between primary and secondary stresses but proceeds to state that, for design purposes of ceramic composite materials, no distinction is made between the two types of stress, and they must be combined when assessing stress response.

Related to this topic, for ceramic composite materials, matrix failure modes are not always catastrophic. It is worth considering whether a higher POF could be applied to interlaminar stresses if they can confidently be determined to have all of the following characteristics:

1) They are self-relieving or self-limiting.
2) They do not induce fiber-dominated failure in any mode or material direction.
3) They do not compromise the component's ability to perform its function.

Before adopting a higher POF, the designer must use subcomponent testing or advanced FEA to verify that the interlaminar response does not adversely affect the component's ability to function. An example case is summarized below in Figure 6 and Figure 7 for 2D C/C material. Work by Burchell [20] has illustrated that, when irradiated, C/C materials typically shrink in fiber-dominated directions and shrink less or expand in matrix-dominated directions, as shown in Figure 6(a). In a closed circular sample of 2D C/C, this general behavior would therefore induce radial expansion and hoop shrinkage, as shown in Figure 6(b). These conditions generally cause hoop tensile stress on the outer surface, hoop compressive stress on the inner surface, and radial compressive stress throughout. Subcomponent split-ring tests, illustrated in Figure 7, could be performed to determine whether the internal stresses are self-relieving. For this example, the radial compressive stresses may exceed the allowable without adversely affecting the performance of the component.

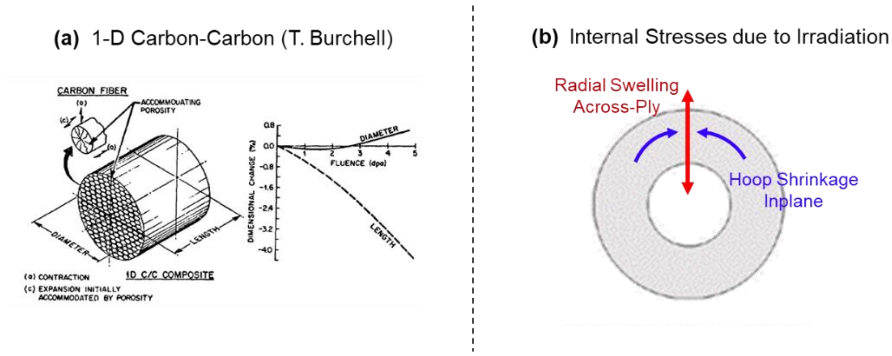


Figure 6. Irradiation dimensional changes. (a) 1D C/C composites from [20] and (b) illustration of stresses in a 1D or 2D C/C ring under irradiation.

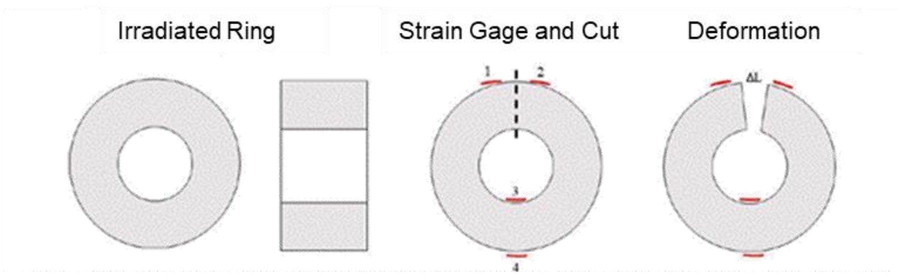


Figure 7. Illustration of the split-ring test for a C/C composite.

Committee response:

This interesting proposition could be taken under advisement. If a designer wanted to implement this approach for self-relieving stresses, then a case could be brought to the committee to assess if and how rules can be amended should this scenario be presented.

Section 5.18's response related to metallic stress terms provides more comment on primary and secondary stresses.

Action:

No action at this time, but the committee is willing to entertain such a proposal when presented.

5.19 HHB-3215 STRESS ANALYSIS

External review comment:

Overall, the finding for this section was clear, with the only exception being the third paragraph, which states the following: "For a simplified assessment (HHB-3220), only the maximum loading mode stress need be known; thus, simplifications to the stress analysis commensurate with achieving this objective are acceptable."

This statement is unclear or subject to misunderstanding, owing primarily to the use of MLM stress, the definition of which is difficult to interpret and incomplete as discussed in comments in Section 5.18 on HHB-3214. In the context of a typical analysis approach, the MLM stress is generally interpreted to mean "the load case which induces the highest stress-to-allowable ratio in any of the nine material stress modes," although it is not clear if that is the intent of the above paragraph.

Previously mentioned in Section 5.18 (on HHB-3214), the rules stipulate how to derive the MLM stress, or allowable stress, S_{gm}, for a specific failure mode. This instruction implies that the failure mode is known. This failure mode is expressed as S_{gm}(POF) and is derived by using the applicable POF value applied to material failure-mode-specific distribution curve. The applicable POF depends on the predefined SRC and the associated service level. It does not describe how to determine the MLM, nor does it give further consideration of the directional effect caused by the anisotropic nature of the material.

An advisory circular by the FAA also acknowledges this point on the subject of composite aircraft structure [21]:

> *There are factors unique to the specific composite materials and processes used for a given application. For example, the environmental sensitivity, anisotropic properties, and heterogeneous nature of composites can make the determination of structural failure loads, modes, and locations difficult. The reliability of such evaluation depends on repeatable structural details created by scaled manufacturing or repair processes. The extent of testing and/or analysis may differ for a structure depending upon the criticality to flight safety, expected service usage, the material and processes selected, the design margins, the failure criteria, the database and experience with similar structures, and on other factors affecting a particular structure.*

Section 3215.1(d) specifically cites that dynamic elastic modulus shall be used for the stress analysis. Moduli derived from quasi-static mechanical testing may also be permitted, because this method is frequently used to define moduli for ceramic composite materials.

Committee response:

As mentioned in an earlier response, all of these comments are valid and identified as potential gaps or areas of improvement in the code. A record has been created to change the simplified MLM stress to instead address the maximum loading mode orthogonal stresses.

A case analysis should be performed to support the technical basis on which the rules are based. An example case study will most likely help to address the questions on how to determine the MLM stresses and then how to apply the material POF values to determine allowable stress conditions.

In regard to the review comment on dynamic modulus, refer to the response for HHB-2230. Quasi-static mechanical testing should be included or revised in the code.

Action:

Record 23-2452 was created to support these changes. An ongoing initiative, through case study, is developing the appropriate technical basis for this work.

Record 24-1445 was created to address the revision on the means of how to obtain moduli response.

5.20 HHB-3220 STRESS LIMITS FOR COMPOSITE CORE COMPONENTS

External review comment:

The first paragraph of HHB-3220 references MLM stress and the definition provided in Section HHB-3214.2, so the previously mentioned challenges of this quantity apply here as well. The text in HHB-3220 does appear to clarify that the MLM stress is a single value of stress, which is to be compared with a corresponding allowable stress value. The allowable stress value is determined based on the appropriate

POF for the component and the strength data from the MDS for the specific ceramic composite material of interest. However, because HHB-3213 states that a stress combination method is not used, the MLM stress, as currently defined, seems to be selected from the orthotropic stress components based on their relative magnitudes but without consideration of the (generally) unique strengths corresponding to each mode. As discussed in prior Section 6.17, such an approach could result in an incomplete or incorrect assessment of the structural feasibility of the component.

With these points in mind, and as discussed previously in the content for HHB-3213, the first paragraph of this section (HHB-3220) should be revised to indicate that structural assessments should be made by comparing all nine component stresses with corresponding POF-adjusted allowable stresses, where the POF-adjusted allowable stress in each material direction is calculated from strength data in the MDS and appropriate knockdowns based on the statistical distribution of the strength data as outlined in HHB-II-3400. For clarity, this suggestion does not imply any changes to the process of calculating allowables outlined in HHB-II-3400.

As a side note related to earlier versions of the code and for the sake of completeness, the final paragraph of HHB-3220 (in the 2019 edition) cites the use of an "equivalent stress" for evaluating the MLM stress. This instruction appears to be inconsistent with the content in HHB-3213, which states that no theory for combining stresses is utilized.

Finally, HHB-3220 allows for only the Weibull distribution to be used for statistical characterization. Although allowing only one distribution does simplify the code, a Weibull distribution may not closely fit all data sets. For reference, CMH-17-5 also allows normal and log-normal distributions.

Committee response:

As previously mentioned, stresses must be determined for all the orthogonal directions to avoid an incomplete or incorrect assessment. In particular, the reference in HHB-3220 must be addressed.

The Weibull distribution was selected because nearly all kinds of distributions can be adapted with the Weibull distribution, and it is mostly appropriate for ceramic materials.

Action:

Record 23-2452 was created to support these changes.

5.21 HHB-3240 EXPERIMENTAL LIMITS—DESIGN BY TEST

External review comment:

Design by analysis (HHB-3220) seems unavoidable for larger components because the testing infrastructure does not exist to simultaneously apply all the necessary loads to properly qualify a component. Unfortunately, design by analysis requires extensive material characterization because of the added complexity of composite materials (orthotropic vs. isotropic, more strengths to measure). A combined analysis/testing approach does not appear to be explicitly outlined in the code but would be beneficial for the adoption of ceramic composite materials, as it would reduce the amount of material testing by employing supplemental subcomponent and component level testing. An example qualification plan combining elements of testing and design analyses could be outlined as follows:

1) Execute a reduced material characterization effort for critical material properties.

2) Conduct subcomponent testing to calibrate and verify design tools (FEA). An example test could be three-point flexure on small tubular geometries.

3) Correlate FEA to load–deflection, strain gage data, and strain field visualization data gathered from the tests.

4) Use subsequent FEA to size components to the in-service loads.

5) Develop a qualification test, using an environmental correction factor (ECF) to account for irradiation and temperature as outlined in the NASA report [19] and shown in Eq. (1).

   [STR0051] Structures shall be designed and tested for combined loading as specified in Table 3.3.2-1.

   <u>Rationale</u>*: The most sever combination of thermal, mechanical, and pressure loads occurring at the same time or during the same mission event should be combined in a rational manner. Test cases should consider an ECF when the flight environment cannot be replicated during testing.*

$$ECF = \frac{Strength\ Capability\ at\ Test\ Conditions}{Strenght\ Capability\ at\ Operating\ Conditions}. \qquad (Eq. 1)$$

   Eq. (1) shows the adjustment factor that is used to account for differences in the environment (thermal and chemical) in which the part is used and the environment in which it is tested.

6) Qualify the component via testing, and validate the supporting design tools (i.e., micromechanics and material models, FEA) using component-level test results.

7) Use the validated design tools for design revision work or for the design of similar components.

Committee response:

From the onset of HHB code development, it was understood that characterization and design of composite components need to be accompanied with a testing via the various building blocks defined by the CMH-17 [7] (previously MIL-HDBK-17 volume 5) community. However, the committee, and community at large, agrees that an analysis method is unavoidable for larger components because the proper testing infrastructure can be hard to come by.

Although the two design methods are introduced in the code, it does not state that a combined design by test and design by analysis approach can be allowed. The community stated that a combined analysis/test approached is desired to reduce the amount of material testing through supplemental subcomponent and component level testing.

As mentioned, the code introduces the two methods in HHB-3100:

> *A simplified assessment that provides rules to derive reliability targets from the material reliability curves or otherwise known as the Design by Analysis method, detailed in (HHB-3200).*
>
> *The other method is a Design by Test (HHB-3300) which experimental proof testing to demonstrate that the design meets its reliability targets.*

In paragraph HHB-3220, the rules state that the simplified assessment approach is conservative: if a component does not meet the prescribed criteria, then it is not necessarily unacceptable.

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.

Despite potential revision, the philosophical intent of the design by analysis method is for the code to be more conservative than the test method. In theory, analysis should be more time- and cost-effective than testing.

To continue, in HHB-3240, the rules state that not all parts and loadings may be adequately reproduced with a test; therefore, an analysis in the applicable loading mode shall be applied.

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).

The text in HHB-3200 indicates some connection between methods, but the rules do not eloquently address the iterative nature often required for composite component design. This text should be revisited to be more explicit. The outlined process discussed in the review comment nicely demonstrates how such a combined approach will work. A diagram to this extent will also be helpful.

Component design (via analysis or test) is impossible without a material characterization effort. As previously stated, the code requires the designer to determine the material properties and associated test conditions, apart from those mentioned in HHB-2200 (Section 5.4 through 5.6), to populate the material database. This basic testing is part of the materials qualification process and required input for the design.

Equation (2) from HHB-3243 shows the method specified to determine the service load rating (SLR) used in the design by test method, where LT is the mean test load, N the number of samples, S_{gm}(POF) is the failure-mode-specific stress derived from the target POF and the target material strength and S_{um} is the mean failure-mode-specific ultimate stress. This equation shows that the allowable stress POF value (a value derived from the material strength curve) is used together with the ultimate stress value of the specific failure mode.

$$SLR = LT \times \left[\frac{S_{gm}(POF)}{S_{um}}\right] \times \left(\frac{2N}{2N+1}\right). \qquad (Eq. 2)$$

The key takeaway is that the design by analysis (via simplified assessment) and design by test approaches both require the designer to first determine the allowable stress (using POF) based on the material strength properties in each of the orthogonal directions because of the material's anisotropic nature.

Action:

Record 23-2453 was created to be more explicit on the combined use of design by analysis and design by test methods.

5.22 HHB-I-1120 CERAMIC COMPOSITE MATERIAL SPECIFICATION DEVELOPMENT

External review comment:

The vast majority of content in the code related to material specifications for ceramic composite materials indicates that it must be quite detailed; for example, the content in Sections (b) and (c) of HHB-I-1120, which then reference ASTM C1783 and C1793 [8,9], provides additional depth. However, Section (a) of

HHB-I-1120 states the following: “Depending on the performance requirements in the Design Specification, the Ceramic Composite Material may require a very limited or a very complex and detailed material specification.”

A “very limited” ceramic composite material specification would likely be of significant interest to reactor designers, and the sentence above initially appears to indicate that such a material specification may be feasible for some components, depending on their expected usage. Section (h) then briefly mentions this option again and references nonmandatory appendix HHB-A along with ASTM C1835 and C1836 [22,23]. However, the content in HHB-A then appears to indicate that any limited material specifications are to be used only for initial classification and screening. If limited specifications are only intended for classification and screening, and any in-core composite component requires a fully detailed material specification, then MR&D suggest revising the sentence of HHB-I-1120 cited above to avoid potential confusion.

Committee response:

ASTM C1783 and C1793 are the guidelines to assist the designer/user/producer in developing a comprehensive and detailed materials specification on well-defined composition, structure, properties, and processing requirements for a specific CMC application/component with a particular focus on nuclear applications. These guides are critical for the completion of the MDS forms, which outline the particulars of the material qualification requirements.

The classification system presented in ASTM C1835 and C1836 are intended to serve as a top-level identification tool with limited number of composite properties for high-level classification. As indicated by the reviewer comment, the classification standards are more appropriate to be used for materials screening.

ASTM C1835 and C1836 were never intended to be substitutes for ASTM C1783 and C1793. The sentence of HHB-I-1120 should be revised as cited.

Action:

Record 24-1445 was created to address the concern regarding the use of limited material specifications.

5.23 HHB-II-2000 MATERIAL DATA SHEET FORMS

5.23.1 General comments on MDS

External review comment:

Several comments on MDS-3 and MDS-4 (which are part of HHB-II-2000) are summarized as follows.

These forms require detailed information on the composite material, and as noted in this report, CMC fabricators may consider some of the required information to be proprietary and may be unwilling to provide it.

The required temperature increment is 200°C (360°F). However, ceramic composite materials often exhibit a low degree of variation with temperature up to their processing temperature, which is typically above 800°C (~1,500°F). As such, the change in an average measured property over the temperature increment of 200°C may be lower than the amount of variability observed in the property at a given temperature and may not add appreciable value to the material characterization.

Shear properties are listed as designer-specified and not mandatory. However, as noted earlier in this report, interlaminar shear strengths are often quite low for 2D C/C materials, and in-plane shear strengths can also be low for 0°/90° or ±45° architectures. If these strengths are not gathered and compared with operational stresses, then potential failure modes may be overlooked. Shear properties should be mandatory.

Note 30 from Table HHB-II-2000-1 specifies Young's modulus by sonic resonance is a designer-specified property, but HHB-2230 appears to require dynamic modulus.

It would be beneficial (particularly for new users of the code) if mandatory quantities were noted as such in these forms or if a note was added before the forms to state the quantities that are not noted as "If Specified" are mandatory, simply to reduce the need for the user to refer to Table HHB-II-2000-1.

Committee response:

The graphite community has similar issues with the proprietary conditions associated with material production. The standard attempts to introduce quality rigor because materials are not produced to standards. This comment should also be addressed by the ASTM community, but contractual agreements between supplier and designer/owner should be able to resolve this conundrum.

The guidance on the temperature-dependent data recording is to obtain behavior response for the irradiation, oxidation (or chemical attack), and STT during the environmental condition exposure. For the as-manufactured condition, this question is understandable, but for irradiation conditions, a 200°C difference can significantly affect the material properties.

The MDS forms provide the designer with options for obtaining Young's modulus and shear modulus properties. For Young's modulus, the options include obtaining the modulus from mechanical loading in tension or compression or obtaining the modulus from sonic resonance, sonic velocity or impulse excitation. For composites, these methods are rather difficult to achieve because of the material's complex nature (also mentioned in Section 5.5 on HHB-2230). A gap exists between what the code specifies as designer specific (HHB-II-2000) vs. what is required in HHB-2230 and the standard guides ASTM C1783 and C1793 [8,9] as it relates to modulus determination and Poisson's ratio calculation.

The point on making shear strength a mandatory property is reasonable proposal, as is the note on indicating what is mandatory or not in the MDS. Mandatory properties are communicated in HHB-2200 as mentioned in Sections 5.4–5.6.

Action:

Record 24-1460 on dynamic modulus was created to address this change, and the ASTM committee will be notified about the concerns mentioned about ASTM C769 in Section 5.5 on HHB-3230.

5.23.2 Specific comments on POF-adjusted stress allowables

External review comment:

Another fundamental question is related to the conservatism of component design. The rules provide limits to be applied when calculating stresses, but the key question is whether the rules adequately describe how these limits should be applied to the various component-level designs.

For example, POF-adjusted allowable stresses for C/C materials could be challenging assuming the Weibull modulus (m^*) value is 10 or less. This assumption appears reasonable considering the typical approximate m^* value for graphite is 10. For completeness, Figure 8 summarizes the relationships between the Weibull characteristic strength (S_c^*) and the 95%-confidence Weibull characteristic strength (S_{c95}) (Figure 8 [a]), as well as the relationships between S_c^* and the allowables for POFs of 1.0×10^{-2} (i.e., the A-basis allowable, frequently used in human-rated aircraft and spacecraft design), and the bounding POFs in the code (5.0×10^{-2} and 1.0×10^{-4}).

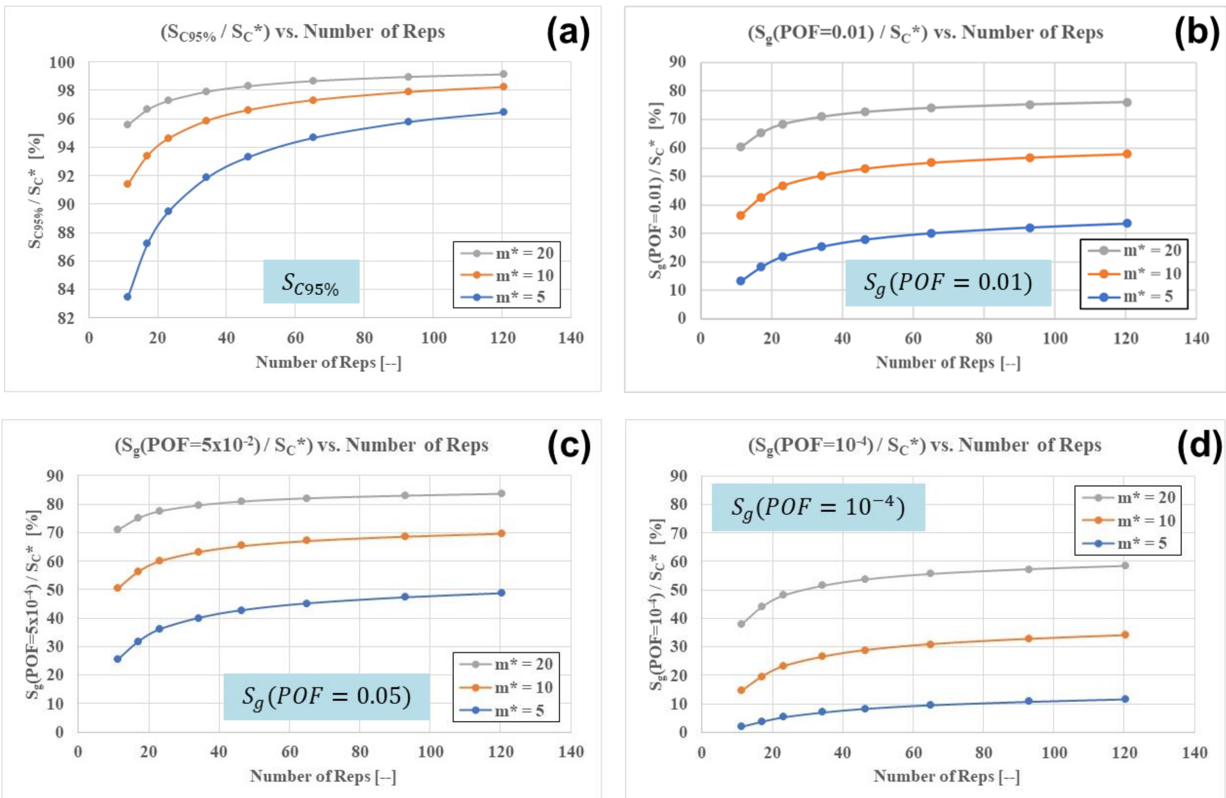


Figure 8. Statistical analysis. (a) Relationships between the Weibull characteristic strength ($\boldsymbol{S_c^*}$) and the 95%-confidence strength ($\boldsymbol{S_{c95\%}}$) and (b, c, d) POF-adjusted allowables as a function of the number of test reps.

The 95%-confidence strength can be significantly increased with a large number of testing repetitions, even for a low m^* value of 5 (Figure 8[a]). However, for any of the POFs presented here, (Figure 8[b, c, d]), the number of test repetitions clearly has very little effect on the allowable stress and that the m^* value is the primary factor for any given POF. Although the calculations shown in Figure 8 can readily be made by a designer, data of this type (in plot or tabular form) would be worthwhile to include within the code to assist designers in their initial assessments of candidate materials by facilitating estimates of allowable stresses based on Weibull characteristics.

Committee response:

The POF principles described in HHB (for CMCs) is based on those applied in HHA. Both HHA and HHB fall within the same code classification, namely, Class SN (Nonmetallic Core Components) under Sec. III-5. As mentioned in the beginning of the report, a code class is a set of rules that provide a reasonable assurance of structural integrity and quality commensurate with the relative importance assigned to the individual components of the advanced reactor plant.

The presented case study poses a valid question because the proposed design limits in HHB were adapted from HHA, and the technical basis to support that decision is lacking. However, sufficient conservatism follows the approach to be reasonably confident about the safety margins.

Because of graphite's unique nature, HHA selected Weibull statistics to define strength limits to derive allowable stresses from POF values. Weibull hypothesized that the probability of failure in structural components is influenced not only by the magnitude of local stresses but also by the stressed volume. The failure limits used in HHA was based on the proposed the Kerntechnischer Ausschuss (KTA) 3232 methodology [24]. The method introduced to determine the POF values manipulates the strength values to produce a stress distribution that is always conservative.

The problem is that the current method does not allow for a quantifiable amount (or a consistent amount) of conservatism in the allowable stress. This result is largely because the design-allowable stress is calculated from two knock downs, or safety factors, namely a modified modulus ($m_{95\%}$) and a modified characteristic strength ($Sc_{95\%}$) based on the 5% lower confidence interval.

A particular concern for composites is that the interlaminar direction are likely to have a lower Weibull modulus than graphite. As such, the assumption of the Weibull modulus (m^*) to be 10 or less is not unrealistic, implying that larger safety factors are expected. These safety factors could cause qualification challenges for components made from composites, particularly for 2D materials in interlaminar tension and interlaminar shear modes, which are typically the modes with lowest strength and highest variability.

This item requires further evaluation. The calculation of safety factors from the FAA and/or NASA guidance for human flights must be assessed. From a safety perspective, the code wants to ensure that the approach is conservative, which it is (regardless of the unquantifiable conservatism). However, if the approach is overly conservative, then it may prevent or discourage the community from using the rules because they are too restrictive, especially if other standards or guidance allow more leniency for the allowable stresses.

The A-basis and B-basis allowable criteria, which are generally accepted by the FAA [21] and specified in the CMH-17-5 [7] for various type CMCs, should be compared to discover whether the stress allowables in HHB can be less restrictive.

Action:

Conduct a parametric case study presenting a typical component with various CMC compositions applying Weibull statistics as defined in HHB with the associated criteria and comparing it to the statistical methods defined in CHM-17-5 when applying A-bases and B-basis allowable criteria. The objective of the study is to validate whether the stress allowables defined in HHB are appropriately conservative and reasonable. The results will serve as the technical basis on stress-allowable criteria to support HHB.

6. ACTIONED AND IMPLEMENTED CODE CHANGES

R22-2267—Weibull notation changes and reference update to align with HHA

Summary

Weibull notation changes were made to Sec. III-5-HHA. These changes affected the text in Sec. III-5-HHB. The purpose for the record was to realign the notational changes made in HHB with those that were made to HHA.

Status

Record was reviewed and approved and is being reviewed by the Standards Committee by the Board on Clean Energy and Facility. On course for being adopted in the 2025 edition of the ASME BPV III code.

R23-1572—Change per-lot testing requirements for as-manufactured ceramic composite materials

Summary

HHB-III-4100, “As-Manufactured Ceramic Composite Material,” revise the following: “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).” to “As-manufactured material property data shall be obtained from tests of composite components or witness coupons from, at minimum, three production lots of material meeting all of the requirements of the Designer (Mandatory Appendix HHB-I).”

Status

Record was reviewed and approved and is being reviewed by the Standards Committee by the Board on Clean Energy and Facility. On course for being adopted in the 2025 edition of the ASME BPV III code.

R23-2452—Revision on the Maximum Loading Mode Analysis approach

Summary

The use of the MLM stress should apply to all orthogonal directions in HHB-3000. The current use of the MLM stress can be somewhat misleading in that it may be interpreted that only the most severe case needs to be evaluated. Most composites are anisotropic, so all orthogonal directions in all stress modes need to be evaluated to determine the critical load case to evaluate.

Status

Record was approved by the working group and is being reviewed by the subgroup committee. On course for being adopted in the 2025 edition of the ASME BPV III code.

R23-2453—Combined Design by Test and Design by Analysis approach

Summary

The change is to elaborate on the use of design by analysis vs. design by test in HHB-3000. The nature of composite materials lends itself to the situation in which a designer may have to use both a design by analysis and a design by test approach during the course of component design. This option is not clear within the text of the code. Revise HHB-3100 General Design to (1) make wording in paragraph (a) consistent with language used throughout (i.e., design by analysis) and (2) provide guidance, literally and graphically, to the user for when each approach is useful and appropriate.

Status

Record was approved by the working group and are being reviewed by the subgroup committee. On course for being adopted in the 2025 edition of the ASME BPV III code.

From discussion mentioned in action items, additional records under development include the following:

- Record 24-1439 was created to address material properties to be measured in all three orthogonal material directions.
- Record 24-1442 was created to address revision on “highest use” definition in HHB-3112.
- Record 24-1445 was created to address the concern regarding the use of limited material specifications.
- Record 24-1460 was created 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.

7. AREAS IDENTIFIED FOR FURTHER OPTIMIZATION ALIGNED WITH INDUSTRY GOALS

7.1 IDENTIFIED OPTIMIZATION AREAS AND ONGOING EFFORTS

The review and comments on design and on material characterization define the critical questions needed to support the basis for the code, specifically, how POF values are derived to obtain stress allowables. The code will benefit from a demonstration on how to apply and execute component design through modeling and testing as stipulated by the revised rules. This process will require a completed MDS and will present opportunities to improve and/or propose testing methods (where shortcomings are identified).

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 white paper will comprise be two sections of content.

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 defined using literature data on irradiated materials (on fibers, ceramics, CMC composites) and, where needed, typical engineering assumptions for the behavior of laminate materials (e.g., to define the two interlaminar Poisson’s ratios, which are frequently not measured individually or are not measured at elevated temperatures).

Example calculations of allowable stresses that are adjusted for probability of failure (POF) will also be included. These calculations will be shown for each relevant POF cited in HHB for composite materials.

The second section will present a procedure for assessing the structural feasibility of the exemplar 2D CMC component using FEA. Specific content will include the setup of the finite element model, assignment of material properties, extraction of peak stresses, and comparison of peak stresses with POF-adjusted stress allowables.

This study started, but first emphasis was to address the critical code revision required to perform this study on the revised basis. Now that there are more-or less clarity on how the rules are revised, this will be the main focus going forward.

7.2 SUPPORTING RESEARCH AND EXPERIMENTAL STUDIES

As mentioned in Sections 5.4 and 5.5, environmental material properties are required by the code. Generally, irradiated CMC materials, specifically C/C composites, are sparse. In recent years, significant emphasis was placed on SiC/SiC composites for the use of fuel cladding in light-water reactors, so limited information on SiC/SiC materials is available. Additional research and development are needed to optimize the architecture and components of composites for nuclear applications. Some of the potential areas of research and development and areas of opportunity are described in this subsection.

A composite microstructure may deviate from the ideal design during manufacture or when exposed to the reactor environment. Whether these deviations should be considered defects, depends on the material's application and the effect of the deviation on performance. However, determining the specific type and size of the defect that must be identified for each application requires thermomechanical or microstructural tests that enhance the understanding of how such defects may develop under a service environment (e.g., oxidation, salt exposure, or irradiation damage). Developing techniques and tests that establish the acceptance criteria for manufacturing and in-service defects for composites is necessary for the deployment of these materials. New irradiation campaigns must be conducted to elucidate different aspects of the C/C composites. Moreover, several techniques can enhance the understanding of irradiation effects in these materials. Examples of the challenges related to composites are described in the following points.

Machining—Machining a composite can introduce significant damage to the surface of C/C composites or SiC/SiC composites. As shown in Figure 9, nondestructive techniques can detect defects before they are used for in-service applications. Some of the damage generated by machining can potentially reduce the local strength and properties of the composite. Moreover, the effects of defects introduced by machining on the performance of composites under irradiation remain poorly understood.

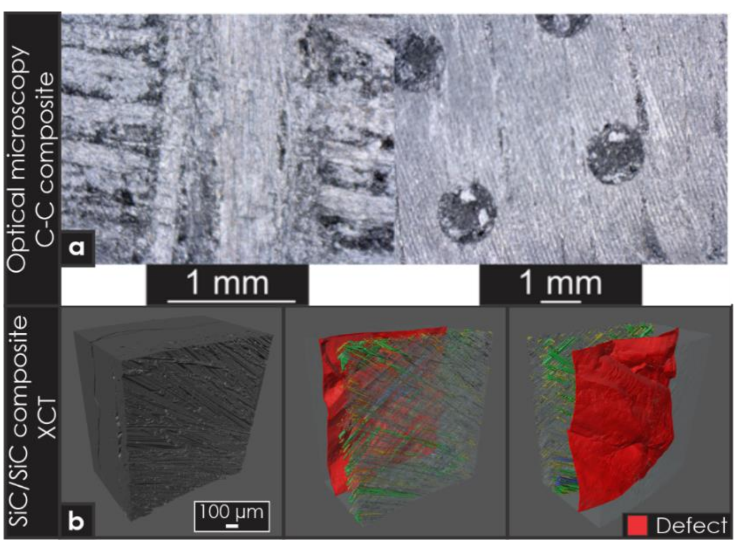


Figure 9. Defects introduced by machining in composites. (a) C/C composite surface damaged by machining detected by optical microscopy, (b) crack generated by machining in a SiC/SiC composite detected with x-ray computed tomography (XCT).

Novel nondestructive testing and characterization—Nondestructive testing is a common approach to inspect and estimate the properties of composites. Figure 10 shows the detection of a crack caused by neutron irradiation in a SiC/SiC composite. In the case of composites, x-ray computed tomography (XCT) can be a valuable technique to inspect and measure some of the geometric features of composites with complex shapes, such as the internal diameter of cylindrical components, porosity, or roughness of the samples. Moreover, pre- and postirradiation examinations via XCT can use digital volume correlation to track the displacements caused by neutron irradiation. The internal features and changes produced by neutron irradiation can be tracked to help determine the evolution of the composite microstructure under neutron irradiation. These data can also be used in conjunction with continuum mechanics models to understand the stress state of the composite.

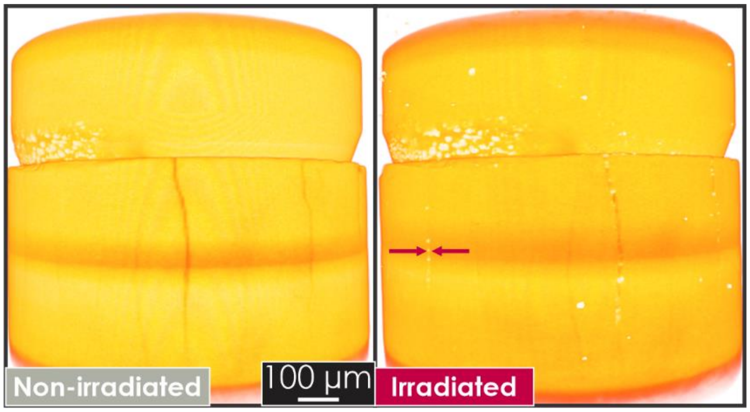


Figure 10. Neutron induced cracking in a cylindrical SiC/SiC composite tube detected via XCT.

Some composites' mechanical properties depend on the composite's fiber orientation. Cylindrical composite samples are expected to be used for some applications in the nuclear industry. Cylindrical geometries require the development of novel characterization techniques that can account for the direction of the fibers. Flash thermal diffusivity measurements are a novel approach to estimating the thermal diffusivity on curved coupons in the nuclear industry for composites [25]. This approach, illustrated in Figure 11, uses a flash camera to heat the sample and an infrared camera to track the heat dissipation from the specimen. In this way, the samples can be characterized using a nondestructive method. Moreover, this technique can be adapted to detect large defects such as pores or significant neutron irradiation-induced defects, including cracks.

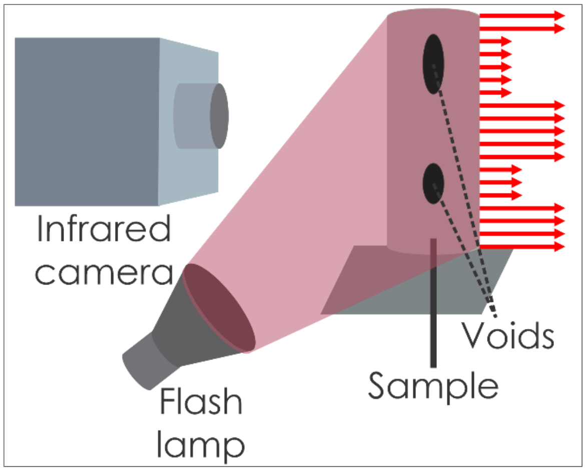


Figure 11. Flash thermal diffusivity setup for ceramic cylindrical specimens.

Choice of C/C composite fiber and neutron irradiation effects characterization—The C/C composites have unique microstructures that depend on the architecture, fiber type, binder material, and source materials. Examples of two C/C composites that have been considered for nuclear applications are shown in Figure 12. The left panel of Figure 12 shows an XCT scan of FMI-222, a balanced 3D weave composite. The right panel of Figure 12 shows an XCT scan of a specimen of the JET fusion reactor tile, a 2D woven fiber sheets composite. Depending on the architecture, the composite can have various thermomechanical responses and neutron irradiation-induced dimensional changes.

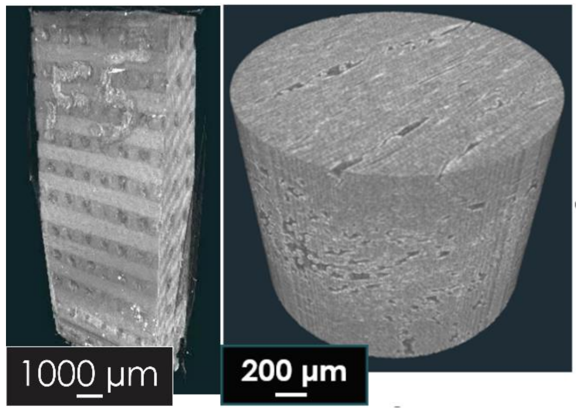


Figure 12. Examples of the architectures of two types of C/C composites. (left) FMI-222 composite and (right) JET fusion composite.

Figure 13 shows examples of carbon fibers treated via different thermal treatments. The fiber texture under neutron irradiation may influence the dimensional change rate and type of defects generated in the fibers. A more systematic understanding is required with respect to the irradiation response of the different types of fiber and binder material, as well as postirradiation dimensional stability compatibility between fiber and binder. The rate of irradiation-induced damage in fibers might be different because of carbon fibers' various sources and manufacturing processes.

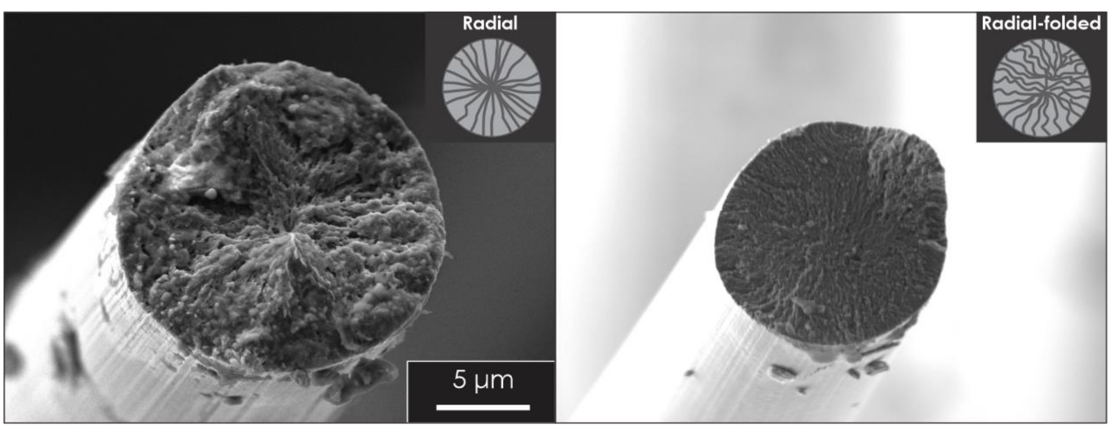


Figure 13.Observed textures of carbon fibers treated at two conditions. (right) Radial texture and (left) radial-folded texture.

Some of the neutron irradiation effects in carbon fibers are shown in Figure 14. The scanning transmission electron microscopy micrograph of Figure 14 reveals the densification and rearrangement of the texture of the fibers. The rate of defect generation and defects generated in the carbon fibers might depend on the type of fiber (e.g., PAN or pitch) and temperature treatment.

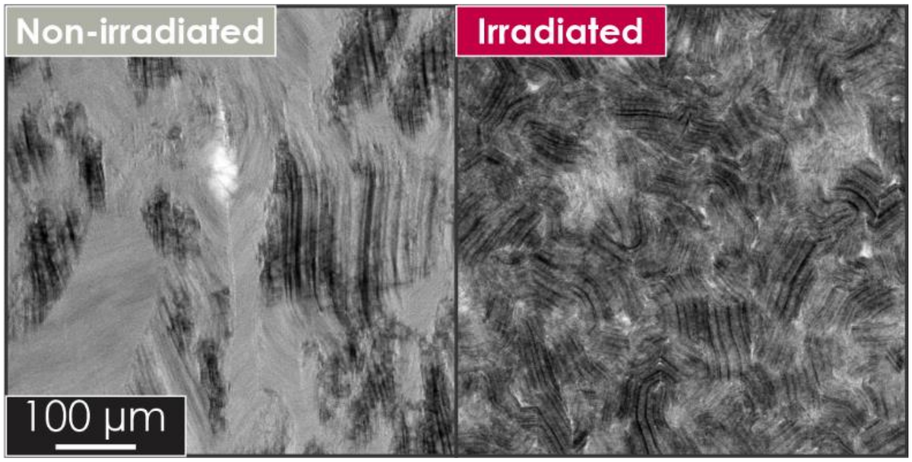


Figure 14. Bright-field scanning transmission electron microscopy micrograph taken from the center of a carbon fiber.

Developing new methodologies and creating new irradiation campaigns that focus on understanding irradiation effects in composites would enable assessments of these materials' performance, irradiation resistance, and operational window conditions.

8. CONCLUSION

To conclude, the code is written by the nuclear industry for the nuclear industry. HHB was reviewed for critical errors and/or flaws. The most critical findings were related to the structural assessment procedure, the generation of material properties, and the material specification. Several actions have been taken to revise the code for further improvement.

The code will benefit from a code case or benchmark study to demonstrate what component design would look like according to the code. Furthermore, the allowable stress knockdown factors should be validated. Component modeling is not trivial. Demonstration and a technical basis that validates the new composite code will significantly enhance its applicability and assist in its future endorsement.

Limited information on environmental material performance exists. Preliminary experimental studies, specifically for C/C materials, will be of great benefit to the community.

9. REFERENCES

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