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Design Procedure of Graphite Components by ASME HTR Codes

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) is developing a Very High Temperature Reactor (VHTR) of own design as shown in Fig. 1. The Korean VHTR has a prismatic core which is made of multiple graphite blocks, reflectors, and core supports. One of the design issues is the assessment of the structural integrity of the graphite components because the graphite is brittle and shows quite different behaviors from metals in high temperature environment. The American Society of Mechanical Engineers (ASME) issued the latest edition of the code for the high temperature reactors (HTR) in 2015[1]. In the edition, the design and structural assessment methods for the graphite components were adopted in the code for the first time. In this study, the ASME B&PV Code, Subsection HH, Subpart A, design procedure for graphite components of HTRs was reviewed and the differences from metal materials were remarked.

2. General Design Procedure of Graphite Components

2.1 Structural Reliability Class (SRC)

The subsection HH is applied to the Class A nonmetallic core support structures. However, subpart A, the graphite code requires the additional classification of the graphite structures. They are Structural Reliability Classes (SRCs) and all graphite core components should be classified to one of SRC-1, 2, or 3. There is an issue about the redundancy of this addition classification. The SRCs are classified by these rules:

(1) SRC-1: Important to safety. (Environmental degradation is possible)
(2) SRC-2: Not important to safety. Subjected to environmental degradation.
(3) SRC-3: Not important to safety. Not subjected to environmental degradation.

The allocation of SRC classification should be stated in the Design Specification. The Owner is responsible to the allocation. The failure from the lower SRC component should not be propagated to the higher SRC component.

2.2 Loading

The code proposed the essential loadings that should be considered in the design of graphite components are listed in HHA-3132. They are not a complete set of loadings and the designer should include other loadings if necessary.

The design loadings are defined as the enveloping Service Level A Loadings. They are fast flux distribution, design temperature distribution, mechanical load, and pressure distribution. Other Service Loadings are mentioned in the other part of the code, HAB-2142 and the Owner should define the loadings in the Design Specification.

2.3 Special Consideration

Graphite materials have distinct material features and theses special consideration should be included in the design procedure.

(1) Oxidation
(2) Irradiation Effects
  (a) Irradiation Fluence Limits
  (b) Stored Wigner Energy
  (c) Internal Stresses Due to Irradiation
  (d) Graphite Cohesive Life Limit
(6) Abrasion and Erosion
(7) Fatigue Damage
(8) Compressive Loading

When the irradiation effects are considered, the code requires the irradiated material properties and the viscoelastic modeling using 3-D FEM or equivalent method. The rule for the fatigue damage has not been established yet and the corresponding article is blanked in the 2015 edition of ASME code.

3. Design by Analysis of Graphite Components

Graphite is brittle which is different from conventional metals. The concept of primary and secondary stress evaluation is not applicable to graphite components. Instead, the concept of equivalent stress and combined stress was introduced.

3.1 Evaluation of Equivalent Stress

The evaluation of the design of graphite components uses equivalent stress concept. This equivalent stress is based on the maximum deformation energy theory. This equivalent stress is compared to the design limits. The equivalent stress is calculated as:

$$\sigma_v = \sqrt{\bar{\sigma}_1^2 + \bar{\sigma}_2^2 + \bar{\sigma}_3^2 - 2\nu \cdot (\bar{\sigma}_1\bar{\sigma}_2 + \bar{\sigma}_1\bar{\sigma}_3 + \bar{\sigma}_2\bar{\sigma}_3)} \qquad (1)$$

$$\bar{\sigma}_i = f \cdot \sigma_i$$

$$f = \begin{cases} 1\ , & \text{if } \sigma_i\ (i = 1,2,3) \text{ is a tensile stress} \\ \dfrac{1}{R_{tc}}\ , & \text{if } \sigma_i\ (i = 1,2,3) \text{ is a compressive stress} \end{cases}$$

Where, R_{tc} is the ratio of the mean compressive to mean tensile strength.

3.2 Combined Stress

For the graphite materials, the primary and secondary stresses are not districted clearly. The combined stress is used instead. The combined stress is the sum of all stress components at an evaluation point. The combined stress is linearized into the membrane, bending, and peak components and the only membrane component is used in the simplified assessment.

3.3 Design Approaches

The code provides three alternative design approaches:

(1) Simplified Assessment
(2) Full Assessment
(3) Design by Test

It is thought that the Design by Test should be the last approach after the failure of the other two approaches. The code does not provide the test procedure, and the method of evaluation of acceptability of the test results. The Designer is responsible of them. Also, the cost of the component test may be more expensive than the design by analysis. Therefore, the other two approaches are reviewed in this study.

3.4 Simplified Assessment

In the simplified assessment, the combined membrane stress and the peak equivalent stress are compared to the damage-tolerant strengths from the 2-parameter Weibull distribution of the graphite grade used in the design. The combined membrane stress assessment is performed along a line of interest; however, the equivalent stresses are calculated at all integration points of 3-D FEM model or equivalent and the maximum value is the peak equivalent stress of the graphite component. The allowable stress values are acquired from the corresponding probability of failure (POF) which is tabulated in Table I.

Table I: Design allowable probability of failure[1]

SRC	Design	Service Limit Level A	Level B	Level C	Level D
SRC-1	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-3}
SRC-2 [Note (1)]	10^{-4} (10^{-3})	10^{-4} (10^{-3})	10^{-4} (10^{-3})	5×10^{-3}	5×10^{-2}
SRC-3	10^{-2}	10^{-2}	10^{-2}	5×10^{-2}	5×10^{-2}

NOTE:
(1) This applies to the SRC-2 Design as well as Service Level A and B limits. The change in limits is to indicate that this Article allows for the degradation of Graphite Core Components (or increase in stresses) caused by irradiation during service. The difference between the initial allowable stress value and the allowable stress value in parentheses makes sure that there is margin for material degradation or increase of stresses in service.

3.5 Full Assessment

According to the code, the simplified method is conservative (HHA-3220) and the full assessment is recommended when the simplified assessment fails. In the Full Assessment, the establishment of 3-parameter Weibull distribution of the graphite grade used in the design is required. However, the 3-D FEM results can be shared with the Simplified Assessment.
In the Full Assessment, the equivalent stresses calculated at all integration points of the 3-D FEM model or equivalent and the POF corresponding the equivalent stress is calculated and the volume sum of POFs is compared to the allowable POF limits which is also shown in Table I. The assessment procedure is listed and explained in the article, HHA-3217. In the procedure, the integration volumes are divided into groups. There are two conditions for the allocation to groups. The designer can choose the number of the integration volume groups; however, the code does not recommend the optimal number of groups. An example of the full assessment[2] shows that the largest number of the integration volume groups results in the conservatism as shown in Fig. 1.

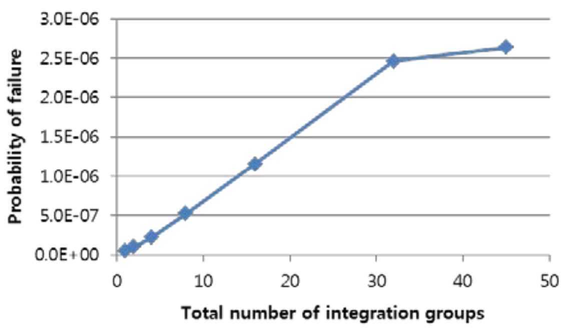

Fig. 1. Effect of number of integration groups on POF[2].

3.6 Special Stress Limits

For the special design, loadings, or configuration, the special stress limits are priority when multiple limits conflicts. The code only provides a special stress limits about the bearing stress on the contact regions between two graphite components.

3. Conclusions

In this study, the ASME B&PV Code, Subsection HH, Subpart A, Graphite Materials was reviewed and the special features were remarked. Due the brittleness of graphites, the damage-tolerant design procedures different from the conventional metals were adopted based on semi-probabilistic approaches. The unique additional classification, SRC, is allotted to the graphite components and the full 3-D FEM or equivalent stress analysis method is required. In specific conditions, the oxidation and viscoelasticity analysis of material are required. The fatigue damage rule has not been established yet. The three design assessment approaches are provided: Simplified Assessment, Full Assessment, Design by Test. The Simplified and Full Assessment procedures were reviewed and investigated.

REFERENCES

[1] 2015 ASME Boiler & Pressure Vessel Code, Section III, Division 5: High Temperature Reactors, July 1, 2015.
[2] Ji-Ho Kang, Chang Keun Jo, “Preliminary Structural Assessment of VHTR Graphite Components According to ASME Code,” High Temperature Reactor 2015, Submitted.