Nuclear Engineering and Design 240 (2010) 1–29

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Overview of statistical models of fracture for nonirradiated nuclear-graphite components☆

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ARTICLE INFO

Article history:
Received 8 January 2009
Received in revised form
24 September 2009
Accepted 5 October 2009

ABSTRACT

Nuclear-grade (low-impurity) graphite for the fuel element and moderator material for Next Generation (Gen IV) Reactors displays large scatter in strength and a nonlinear stress–strain response from damage accumulation. This response can be characterized as quasi-brittle. In this review, relevant statistical failure models for various brittle and quasi-brittle material systems are discussed with regard to strength distribution, size effect, multiaxial strength, and damage accumulation. This includes descriptions of the Weibull, Batdorf, and Burchell models as well as models that describe the strength response of composite materials, which involves distributed damage. Results from lattice simulations are included for a physics-based description of material breakdown. Consideration is given to the predicted transition between brittle and quasi-brittle damage behavior versus the density of damage (level of disorder) within the material system. The literature indicates that weakest-link-based failure modeling approaches appear to be reasonably robust in that they can be applied to materials that display distributed damage, provided that the level of disorder in the material is not too large. The Weibull distribution is argued to be the most appropriate statistical distribution to model the stochastic strength response of graphite.

Published by Elsevier B.V.

Contents

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0029-5493/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.nucengdes.2009.10.002

1. Introduction

At present, 10 countries, including the United States, have agreed to cooperate on the development of the fourth generation (Gen IV) nuclear energy system (Generation IV International Forum, 2007). The Gen IV system is expected to come into service in 2030. In the United States, Gen IV research is being conducted by the U.S. Department of Energy for development of the Very High Temperature Reactor design concept for the Next Generation Nuclear Plant (NGNP) Project (Idaho National Laboratory et al., 2005). The design will have a graphite-moderated reactor, either a prismatic graphite-block-type core or pebble-bed core that will produce process heat in a highly efficient manner, reducing the need to burn fossil fuels to produce process heat and thereby reduce green house emissions. Application of heat is essential to nearly all basic material and commodity manufacturing processes. Heating processes account for about 17% of all industrial energy use (U.S. Department of Energy Industrial Technologies Program, 2009).

The NGNP will have a projected service life of 30–60 years and be designed to ensure passive decay heat removal without fuel damage or radioactive material releases during accidents. The development of the design methods and validation of the graphite structures used in the reactor are important to the NGNP Project because large amounts of graphite (up to thousands of tons) would be required for the reactor core and the individual graphite bricks that surround the nuclear fuel may experience significant loads. Of particular concern is the potential for crack formation and even rupture in individual blocks. Therefore, failure theories – and/or effective design strategies that can predict and mitigate failure from fracture – are needed.

An important characteristic of graphite is that its strength is stochastic – an individual specimen can show a large random fluctuation in strength from a population mean. Graphite also can have a nonlinear stress–strain response because of distributed damage and damage accumulation within the material prior to rupture. This behavior can be described as “quasi-brittle” or “ductile-like”. In contrast, classically brittle materials, such as ceramics and glasses, fail abruptly without prior damage accumulation, although they similarly display large scatter in strength. Other materials, such as fiber-reinforced composites, can accumulate significant damage prior to failure and have less scatter in strength than the individual constituents of the composite have. Graphite rupture behavior seemingly falls somewhere between the behaviors of ceramics and fiber-reinforced composites.

This article reviews some statistical failure models that may be relevant for the design of nonirradiated nuclear-grade graphite. Models for various brittle and quasi-brittle material systems are discussed with regard to strength distribution, size effect, multiaxial strength, and damage accumulation. This includes descriptions of the Weibull, Batdorf, and Burchell models as well as models that describe the strength response of composite materials, which involve distributed damage. Results from lattice simulations are included for a physics-based description of material breakdown, and consideration is given to the predicted transition between brittle and quasi-brittle damage behavior versus the density of damage (level of disorder) within the material system.

More specifically, Section 2 describes the morphology and fracture characteristics of graphite, Section 2.1 describes the effects of strength distribution and results from size–effect studies, and Section 2.2 introduces the two broad classes of statistical models of fracture: weakest link series systems and parallel systems. Section 3 covers fracture models that fall under the weakest link series system category of brittle material failure, and Section 4 covers the category for parallel systems, describing fracture models that involve distributed damage.

Section 3 includes the weakest link model (Section 3), the Weibull distribution and size–effect relationship (Section 3.1), the Batdorf model for multiaxial stress states (Section 3.2), strength anisotropy models (Section 3.3), the effect of R-curve on strength distribution (Section 3.4), the Ho and Schmidt modified Weibull models for diminished size effect (Section 3.5), and the Burchell model for considering the role of graphite microstructure in fracture (Section 3.6).

Section 4 introduces the parallel system modeling category – specifically, composite material fiber-bundle models (Section 4.1) and lattice models of disordered materials (Section 4.2) – for describing fracture from distributed damage and how that is relevant to graphite. Importantly, Section 4 discusses the bounds of the applicability of weakest link theory to distributed damage modeling. It describes fiber-bundle models,