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Weibull Analysis of H-451 Nuclear-Grade Graphite

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Abstract

This paper presents the estimation of Weibull parameters by Least Square Method and Maximum Likelihood Method. Experimental data of H-451 nuclear-grade graphite have been taken for evaluation. A computer program has been developed for the analysis of two parameter Weibull distribution. It is illustrated that maximum likelihood estimator gives more accurate values of Weibull model in comparison to least square estimation. Weibull parameters estimated from two methods are match well with the results given in referred paper.

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Keywords: Weibull; maximum likelihood; nuclear-grade graphite.

1. Introduction

Next generation nuclear graphite reactor design needs gas cooling and nuclear-grade graphite for the fuel element and moderator [1]. At present, around 13 countries corporately developing the fourth generation nuclear energy system. The Gen IV systems are expected to come into service in 2030. The development of dependable design and material characterization methods for the graphite structures used in reactor are important to the Next Generation Nuclear Plant (NGNP) Project because large amount of graphite (up to thousands of tons) would be required for the reactor core and because the individual graphite bricks that surround the nuclear fuel may experience significant loads.

Graphite is a key material for forth generation (Gen IV) nuclear energy system. It is similar to the ceramic materials in some respects that it is not processed via melting [2, 3]. Some of the important characteristics of graphite are its strength at high temperature, high thermal conductivity and shock resistance, fire proof and acid and alkaline proof. It is similar to other brittle materials in some respect that it does not exhibit plastic deformation and

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show wide scatter in strength. It has a non-linear stress-strain response and this behavior is different in tension than in compression. This is because of the distributed damage and damage accumulation within the material prior to rupture. This type of material known as known as quasi-brittle material [4,5].

The fracture of graphite can be a complex process, with different grades of graphite potentially having different failure behaviors. Fracture is nominally brittle or quasi-brittle, with little or no plasticity prior to failure. This means that fracture is influenced by pre-existing flaws or inherently weak regions in the material. Porosity can also be an important factor for fracture. Tensile fracture occurs when a local concentration of micro-cracks develop and coalesce to form an unstable micro-crack of critical size. Tucker et al. [6] discussed the micro-growth tends to be trans-granular (through the grains), with the crack path within the individual grain corresponding to the crystalline cleavage plane [7,8].

The theory of statistical extremes, that is, extreme value of a random variable is used for prediction of integrity and life of individual components. One of the extreme value distributions for smallest values is the Weibull distribution. Weibull [9] developed this distribution to study fatigue and fracture of materials. The Weibull distribution is defined by a few parameters and estimation of these parameters for a given data set is necessary to describe the data set by the Weibull distribution.

In this paper, rough estimation method of Weibull parameters is extended to the more accurate methods for nuclear grade-graphite specimen data [10] for fatigue and fracture characterization of graphite claded nuclear reactor.

2. Methodology

Weibull proposed a distribution to describe the life length of materials under fatigue and fracture loads. According to this distribution, failure distribution can be described as:

$$P_f = 1 - \exp[-(\frac{x - x_u}{x_0})^m] \qquad \text{for } x \geq x_u, x_0 > 0, m > 0 \tag{1}$$

where x_0 is the scale parameter. It is the characteristic value of the distribution, such as time-to-failure or load. m is the shape parameter of the distribution or the Weibull modulus. It controls the width of the frequency distribution of the measured values of the parameters. The higher the value of the m, the narrower the distribution of the measured value and the higher its peak. x_u is called the location parameter which is the characteristic smallest value of the measured parameter. There is zero probability of failure if the applied stress or time-to-failure x is smaller than x_u.

The Weibull theory uses the weakest link approach to describe the strength of various materials where the strength of the weakest link determines the strength of the chain. Consequently, the measured value of the parameter is the minimum value (smallest value) from a set of possible values.

Eq. (1) is a three parameter Weibull distribution. When location parameter is assumed to be zero, the resulting distribution is the two parameter Weibull distribution:

$$P_f = 1 - \exp[-(\frac{x}{x_0})^m] \tag{2}$$

This two parameter Weibull distribution has been used extensively where the minimum value of random variable may be assumed to be equal to zero. The probability density function of Weibull distribution is

$$f(x) = \frac{dP_f}{dx} = \frac{m}{x_0}(\frac{x}{x_0})^{m-1}\exp\{-(\frac{x}{x_0})^m\} \tag{3}$$

Depending upon the values of m and x_0, the probability density function can take a wide variety of shapes. Rough estimation of the Weibull distribution parameters can also be made graphically by plotting Eq. (2) after taking double algorithms and a suitable transformation. More accurate values of Weibull distribution parameters for a failure data set of small sized tensile specimens are estimated by following method:

- Least square estimation (LSE)
- Maximum likelihood method (MLM)