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STUDY ON TENSILE STRENGTH OF NUCLEAR GRAPHITE BASED ON BRAZILIAN DISC TEST

Yuanyuan Ma[1], Junjie Zhou[1*], Dexin Wang[1], Tianhao Wu[1], Yunhao Luo[1], Haixiang Zhang[1], Ze Xi[1], Jiaqing Zhao[1], Libin Sun[1] and Li Shi[1]

1 Key Laboratory of Advanced Reactor Engineering and Safety of Ministry of Education, Collaborative Innovation Center of Advanced Nuclear Energy Technology, Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, China

ABSTRACT

Tensile strength is an essential parameter for evaluating the structural integrity of core support in the design of graphite components for High Temperature Gas-cooled Reactors (HTGRs). The disc split test has gradually become the major measurement of tensile strength due to small sample size and convenient operation. In this paper, the tensile strength of various graphite materials was determined according to the procedure of ASTM D 8289-20. A high-speed camera was applied to capture the fracture process of the specimens, while the DIC approach was performed to obtain strain fields. Both two and three parameter Weibull distribution models were adopted to analyze the tensile strength data of graphite specimens. Moreover, the size effect on tensile strength and Weibull parameters was discussed. The results could provide useful support performance evaluation and lifetime prediction of nuclear graphite materials.

Key words: Nuclear graphite; HGTR, Tensile strength, Brazilian disc, DIC, Weibull distribution.

INTRODUCTION

High-temperature gas-cooled reactors (HTGRs) are fourth-generation advanced reactor types that have attracted global attention because of their inherent safety. Nuclear graphite has the advantages of high moderating rate, good resistance to neutron irradiation, etc. It is widely used in high temperature gas-cooled reactors, playing multiple roles such as core structural material, fuel matrix, moderator(Taylor et al., 1967; Zhou et al., 2018). Graphite materials can exhibit typical characteristics of brittle fracture behavior(Romanoski & Burchell, 1999; Šavija et al., 2016; Yi et al., 2020). During reactor service, as the irradiation dose increases, the material properties and dimensions of graphite will change significantly, generating large internal irradiation stresses. Given that the tensile properties of graphite materials are lower than the bending and compression properties, graphite may be subject to tensile damage under complex stresses, which could affect reactor safety(Burchell & Snead, 2007; Jenkins, 1962; Karthik et al., 2015; Matsuo et al., 1981; Taylor et al., 1967).

For quasi-brittle materials such as graphite, tensile strength is usually measured using the direct tensile method, such as the U.S. standard ASTM C749(2020), the German standard DIN51914(2009), Japan standard JIS R7222(2017), the Chinese standard GB/T 8721(2019). However, due to the large size of the sample required for the direct stretching method, there is some difficulty in performing irradiation experiments on the sample. The disc splitting method using small sized specimens is just the right solution to this problem. The disc splitting test is widely used in the measurement of tensile strength of

* Corresponding author: zhoujunjie@tsinghua.edu.cn

brittle materials such as rock and concrete(Karthik et al., 2015; Liu et al., 2021; Yan et al., 2024; H. Zhang et al., 2018).

The advantages of the Brazilian disc split test lie in its simplicity and reliability. First of all, the test setup is simple and easy to operate for a variety of test chamber environments. The equipment required for the test usually consists of a loading device and a measuring instrument, eliminating the need for a complex test setup. Secondly, the test method provides direct tensile strength data, which is particularly important for assessing the mechanical properties of brittle materials. Zhang, C.(2020), Ayatollahi, M. R.(2010), Zhang, X.(2018) et al. have also made various improvements to disc splitting, such as the size of the sample and fixture. American Society for Testing and Materials (ASTM) published “Standard Test Method for Tensile Strength Estimate by Disc Compression of Manufactured Graphite” (ASTM-D8289, 2020). Meanwhile, China Society for Testing and Materials (CSTM) has also released the corresponding test method in 2025.

The digital image correlation (DIC) as a noncontact full-field displacement measurement method(Peters & Ranson, 1982). It can be combined with a high-speed camera to capture the entire process of crack extension. The DIC technique is now widely used in graphite fracture property studies. H.H.N. Chen et al. studied on the fracture properties of IG11 used banding test with single-edge notched beams. Electronic speckle pattern interferometry (ESPI) is used to measure the full-field deformation of graphite samples simultaneously(2017). Haiyan Li et al.in four-point banding test on Gilsocarbon (IM1-24) polygranular nuclear graphite， achievement of in-situ observations of the distribution of crack nucleating defects in nuclear graphite through full-field strain mapping by DIC(2013). M.Mostafavi et al. performed equi-biaxial ring-on-ring-flexural test on large disc specimens of nuclear graphite and observed crack nucleation and propagation by DIC(2011). It follows that Digital image correlation (DIC) can measure planar deformations by analyzing images of the sample's surface during an experiment, and is commonly used in the study of the mechanical properties of material(Mostafavi et al., 2010).

This study conducts Brazilian disc splitting tests on 46 specimens of two different graphite materials to obtain tensile strengths under ambient conditions. During the test, full-field surface strains were observed by DIC. The experimental results were discussed in terms of both mechanical behavior and statistical distribution of strengths. Some useful information was summarized at the conclusion to provide a scientific reference for graphite material selection in reactor design.

TEST METHOD

In this study, samples and fixtures were prepared according to ASTM D8289 and CSTM standard “Graphite Splitting Tensile Test Method”, and the specific sample dimensions are shown in Table 1.

Table 1: Specimens required for the experiment.

<table>
<tr><th rowspan="2">Grades</th><th colspan="2">Specimen Dimensions</th><th rowspan="2">Number of samples</th></tr>
<tr><th>Diameter, mm</th><th>Thickness, mm</th></tr>
<tr><td rowspan="3">DG</td><td>10</td><td>5</td><td>10</td></tr>
<tr><td>15</td><td>7.5</td><td>10</td></tr>
<tr><td rowspan="2">20</td><td rowspan="2">10</td><td>10</td></tr>
<tr><td>IG11</td><td>16</td></tr>
</table>

Figure 1 showed the test system, which consisted of a specimen, a fixture, a tester, a high-speed camera and a light source. The sample-loaded fixture was placed in the tester. Pressure was applied at a constant rate of 0.1 mm/min until the sample cracked. Images of the splitting process and load displacement curves were recorded.

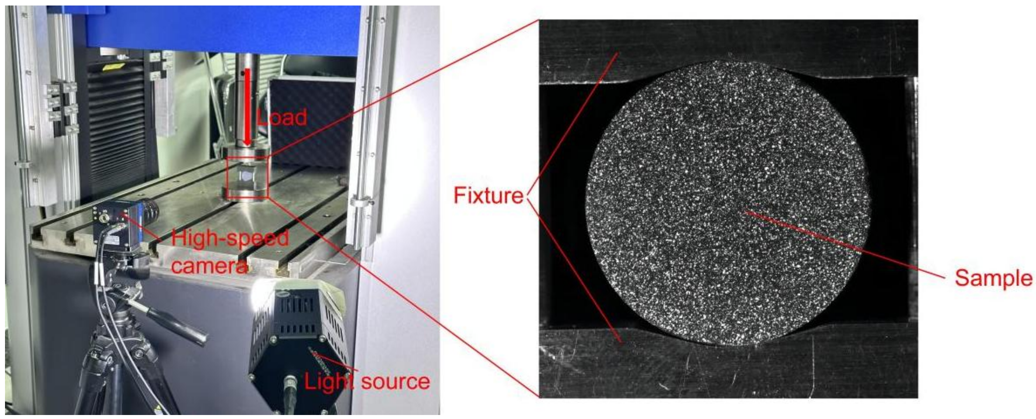
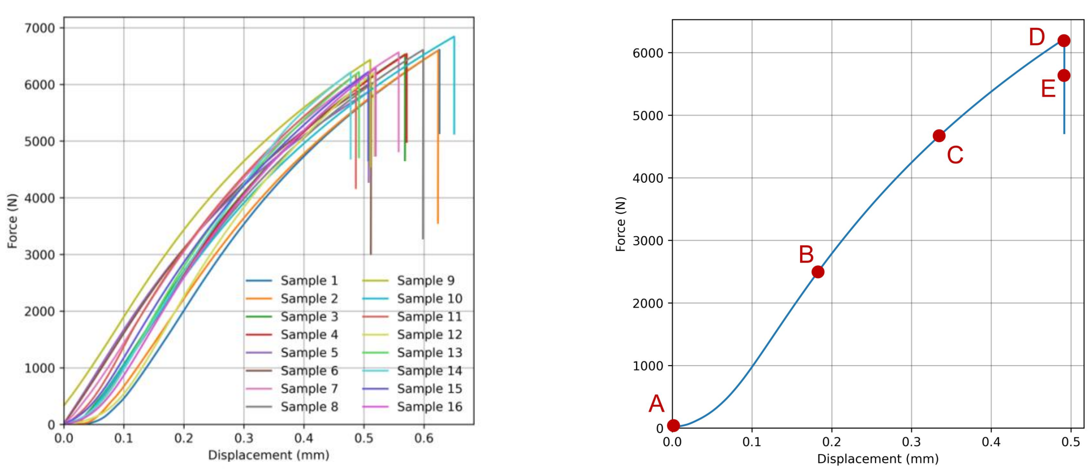


Figure 1. Test equipment and measurement system.

RESULTS

Load-displacement curves

Figure 2 (a) illustrated the load-displacement curve of the IG11 specimen. It can be seen that all the specimens ruptured between the loads of 6000N-7000N, indicating a good repeatability of the test data. Sample 13 was selected for detailed analysis, as shown in Figure 2 (b). Five points A-E were used to describe the typical compression fracture process of the specimen. As compression proceeds, the specimen and fixture were gradually contacted and stressed (A), and the load showed a nonlinear increase with displacement (B and C). When the force reached the maximum value(D), the specimen was crushed and the load dropped steeply (E). Similarly, the force-displacement curve for SD graphite had the similar trend with IG11, except that both the peak load and maximum displacement were different.



(a) (b)

Figure 2. Force-displacement curves of (a) IG11 graphite disc samples and (b) Sample 13.

DIC Strain Measurements

Digital image correlation (DIC) can measure planar deformations by analyzing images of the sample's surface during testing, which is commonly used in the study of the mechanical properties of materials. In our work, strain fields obtained by DIC were applied to analyze the graphite failure process with increasing load. The IG11 graphite disc of Sample 13 was selected for detailed analysis as follows.

Figure 3 showed a clear image of disc during the splitting process provided by DIC. In this case, point A was the strain field in the unstressed state. As the load increases, the sample started to show a stress concentration at point C from a uniform stress (point B) until point D, where a high strain region was observed clearly at the center of the specimen. The point E displayed the stress distribution after splitting, where a small crack was also observed in the upper right corner of the disc. In general, the stress in the x-direction was greatest at the center to generate the tensile cracking.

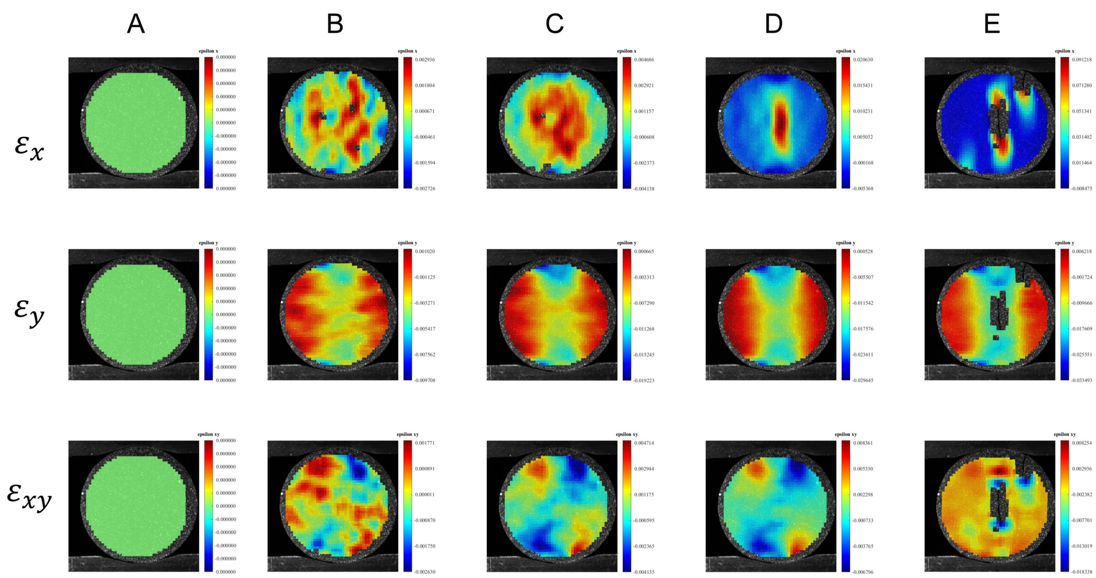


Figure 3. Strain field obtained during the test. where A, B, C, D, and E correspond to Sample 13, respectively.

DISCUSSION

Comparison of Tensile Strength

Calculation of the estimated maximum tensile stress follows Awaji(1978) and Hondros(1959):

$$\sigma_t \approx \frac{P}{\pi L R}\left[1-\left(\frac{b}{R}\right)^2\right] \tag{1}$$

where σ_t is the splitting tensile strength in MPa; *P* is the maximum loading applied by the testing machine in N; L is the thickness of the specimen in mm; *b* is the contact length in mm; *R* is the radius of the specimen in mm.

Figure 4 demonstrated the tensile strength of DG graphite and IG11 graphite. DG samples were provided in three sizes, whereas IG11 samples were made in 20 mm diameter only. Notably, the average tensile strength of DG material was higher than that of IG11. This indicated that DG has better tensile properties than IG11. Considering that graphite tensile strength was much smaller than its own compressive strength, DG graphite could be used for real reactor engineering applications in the future if its irradiated strength is excellent as well. In addition, the data showed that the DG material had outliers well above the average, which could result in an increase in the mean value of tensile strength. Outliers reflected the poor consistency. Compared with DG, IG11 exhibited the smallest standard deviation, indicating better consistency in tensile strength. It is undeniable that increasing the number of samples may optimize the current results.

Meanwhile, a clear size effect was also observed, where the tensile strength of DG material gradually decreased as increasing the sample size. This phenomenon indicated that specimen size may have an inevitable effect on the Brazilian disc splitting test. It should be noted that this outcome may also correlate with the number of microscopic defects in the graphite. Larger specimens tend to exhibit a higher number of structural defects, which could contribute to a reduction in mechanical strength.

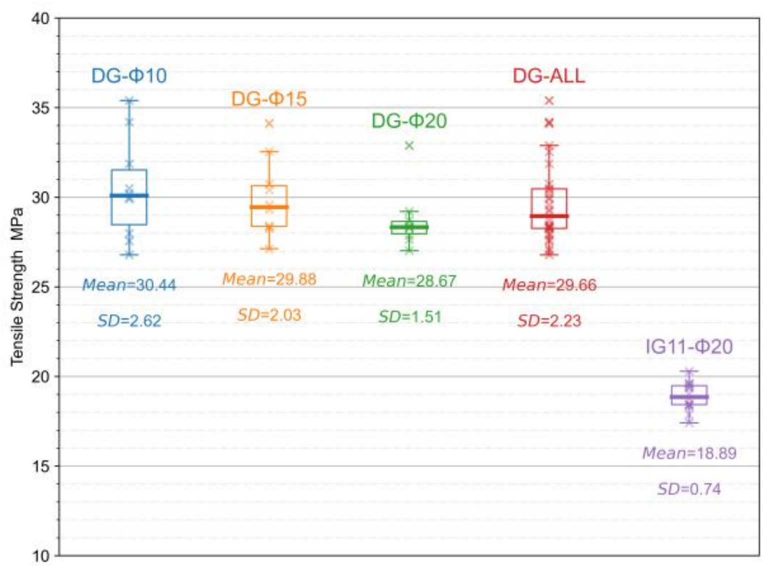


Figure 4. Average values of tensile strength of different materials.

Weibull Distributions

After W. Weibull established the distribution function, it was widely used in the failure evaluation of brittle materials(Weibull, 1939; Weibull, 2021; Zhang et al., 2011).The probability density function of the two-parameter Weibull distribution is described by the following equation:

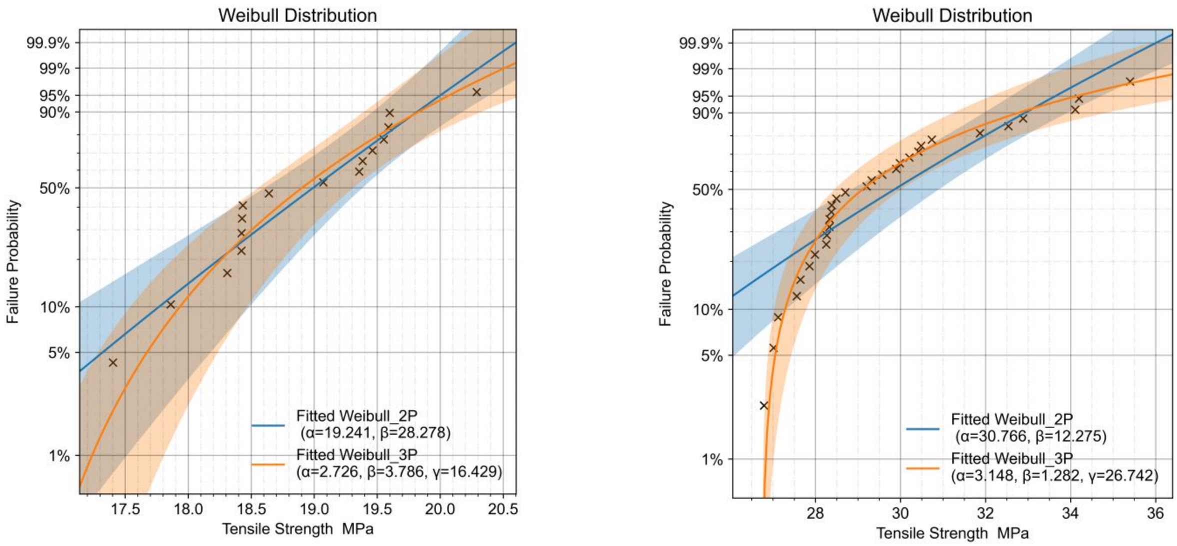
$$f(x,\alpha,\beta) = \frac{\beta}{\alpha}(\frac{x}{\alpha})^{\beta-1}e^{-(\frac{x}{\alpha})^{\beta}} \tag{2}$$

The three-parameter Weibull distribution is expressed:

$$f(x,\alpha,\beta,\gamma) = \frac{\beta}{\alpha}(\frac{x-\gamma}{\alpha})^{\beta-1}e^{-(\frac{x-\gamma}{\alpha})^{\beta}} \tag{3}$$

where α is called the scale parameter; β is called the shape parameter; γ is called the threshold paramter.

Figure 5 showed the results obtained from the Weibull analysis of all samples of DG and IG11. The blue area represented the two-parameter Weibull distribution, while the orange area represented the three-parameter Weibull distribution. As can be seen, both the two-parameter and three-parameter Weibull distributions were able to describe the graphite tensile strength data. However, in the low failure probability region, the three-parameter Weibull distribution fitted the experimental results better, which also suggested a better and more accurate prediction of the failure probability.

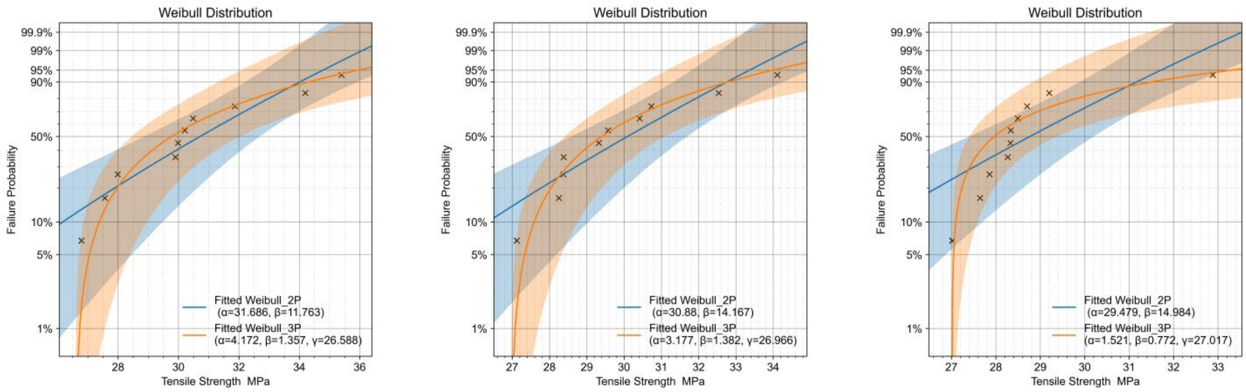


(a) (b)

Figure 5. Weibull distribution of (a) IG11 and (b) DG graphite.

Figure 6 presented the Weibull distribution results for DG specimens of varying dimensions. In the two-parameter Weibull model, the shape parameter (α) determined the shape of the curve, while the scale parameter (β) corresponded to the characteristic strength value. The smaller the scale parameter, the smaller the variation in tensile strength. As regard to the three-parameter Weibull distribution, the threshold parameter (γ) was introduced to the minimum strength. An increase in γ implied a rise in the lower limit of strength in the low failure probability region.

For the two-parameter model, α decreased from 31.686 to 29.479 with increasing specimen size, consistent with the observed strength degradation trend. Conversely, β increased from 11.763 to 14.984, representing an improvement in the dispersion of data. In the three-parameter model, γ increased marginally from 26.588 to 27.017, indicating a slight upward shift in the lower strength threshold as specimen size increased. It should be noted that Weibull parameters were influenced by the number of specimens. Generally, increased sample size enhances statistical confidence in the results. Given the limited data in this study, the observed variation in Weibull parameters with respect to size scaling was found to be statistically insignificant.



(a) (b) (c)

Figure 6. Weibull distribution of DG graphite with (a) ϕ 10 mm × 5 mm, (b) ϕ 15 mm × 7.5 mm, and (c) ϕ 20 mm × 10 mm,

CONCLUSION

This study investigated 46 graphite specimens subjected to disc split tests at rooms temperature. The measured average tensile strengths were 29.7 MPa for DG material and 18.9 MPa for IG11 material. Strain fields and loading histories were acquired using DIC equipment and a servo-hydraulic test system to investigate the relationship between forces and strains in the specimens. Statistical analysis of DG material specimens with varying dimensions revealed a negative correlation between tensile strength and specimen size, whereas specimen size had a negligible effect on Weibull parameters. Furthermore, the three-parameter Weibull distribution exhibited superior goodness-of-fit compared to the two-parameter model in the low failure probability region. These findings advance the fundamental understanding of nonlinear mechanical behavior in graphite material and provide valuable insights for performance evaluation and fracture prediction in graphite-based components.

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