1

Introduction

"By failing to design properly, you are designing to fail", Benjamin Franklin would have quoted instead of "By failing to prepare, you are preparing to fail" in all appropriateness in the context of failure analysis and design. Design concepts are peculiar and require the most particular attentions in almost all fields of science and engineering, not to mention God; the almighty is the best designer. To unearth the novel secrets uphold by nature's metamorphosis, material system has to be characterized properly from a microscopic point of view to its macroscopic complexity of structural failure modes. However, failure as an event can only be predictable under certain circumstances to a finite degree of accuracy, provided the physics of compo-mechanization is well understood, which nevertheless poses uncertainty in itself. Reconciling this, the failure strength of nuclear graphite used as moderator in Next Generation Nuclear Reactor (NGNR) is treated as a continuous random variable problem determined by the flaw population in the light of Weibull Statistical Model (Weibull 1939a, b, 1951; Mitchell et al. 2003; Smart et al. 2003). Capturing these types of uncertainty, necessary for a correct prediction of the reliability of structural components is a formidable task. This thesis deals with strength, size scaling and fracture behavior of nuclear grade graphite.

1.1 Nuclear Grade Graphite

Carbon has two natural crystalline allotropic forms: graphite and diamond. Each has its own distinct crystal structure and properties. Graphite derives its name from the Greek word "graphein", to write. The material is generally greyish-black, opaque and has a lustrous black sheen. It is unique in that it has properties of both a metal and a non-metal. It is flexible but not elastic, has a high thermal and electrical conductivity, and is highly refractory and chemically inert. Graphite has a low adsorption of X-rays and neutrons making it a particularly useful material in nuclear applications. The unusual combination of properties is due its crystal structure. The carbon atoms are arranged hexagonally in a planar condensed ring system. The layers are stacked parallel to each other. The atoms within the rings are bonded covalently, whilst the layers are loosely bonded together by van der Waals forces. The high degree of anisotropy in graphite results from the two types of bonding acting in different crystallographic directions. For example, graphite's ability to form a solid film lubricant comes from these two contrasting chemical bonds. The fact that weak Van der Waals forces govern the bonding between individual layers permits the layers to slide over one another making it an ideal lubricant.

Graphite is one of the most suitable allotrope of carbon for the use of moderator in the nuclear reactors. Apart from its high fusion temperature and high velocity neutron absorption capabilities, it has remarkable refractory and mechanical properties such as easy machinability. A moderator must be made up of highly purified graphite. Harmful impurities like Boron, Cadmium, Lithium, Germanium, the rare earth group (particularly gadolinium), Titanium, Vanadium, Manganese, Iron and other elements might be tolerated in concentration of several parts per million. The higher the specific weight of graphite, the number of nuclei per unit volume is more and hence greater is its capacity to slow down the neutrons. The specific weight of graphite is dependent on several factors related to the fabricating procedure. It is well known that the graphite in fabricated parts is a porous material; the lower the specific weight of the graphite, the higher being its porosity. This results is more significant amount of air and therefore also nitrogen in the pores. The nitrogen, having a relatively high neutron capture cross-section, is a harmful impurity. Therefore, the effort is to obtain graphite parts of maximum density. However, manufacturing limitations constrain to obtain high density graphite. Oblivion to mention that it is very difficult to prepare large fabricated graphite components having high value of specific weight (Goncharov 1958).

1.1.1 Allotropes of Carbon: Graphite, Diamond

Graphite is the softest allotrope of carbon. Carbon is originated from a Latin word ‘Carbo’ means ‘coal’. Its lavishness and unique diversity of organic compounds, and its rare capability to form polymers in the environmental condition enable this element to serve as a common element of all known life. It is the second most bountiful element in the body of a human being by mass (approx 18.5%). It is the fourth most plentiful element in the universe by mass after hydrogen, helium, and oxygen; whereas, the fifteenth most abundant element in the Earth's crust. The pure form of carbon is available in a number of different allotropes. It is one of miracle of the God that one form of carbon is diamond, which is hardest, whereas the other form is graphite, which is softest. The most common form of pure carbon is α-graphite. This is also the thermodynamically most stable form. Diamond is a second form of carbon but is much less common (Fig. 1.1). Other forms of carbon include the fullerenes. Whereas diamond and graphite are infinite lattices, fullerenes such as buckminsterfullerene, C60, is a discrete molecular species. Amorphous forms of carbon such as soot and lampblack are materials consisting of very small particles of graphite. Graphene is a semi-metal with a small overlap between the valence and the conduction bands (zero bandgap material). It is also an allotrope of carbon consisting of a single layer of carbon atoms arranged in a hexagonal lattice. It is the basic structural element of many other allotropes of carbon, such as graphite, diamond, charcoal, carbon nanotubes and fullerenes.

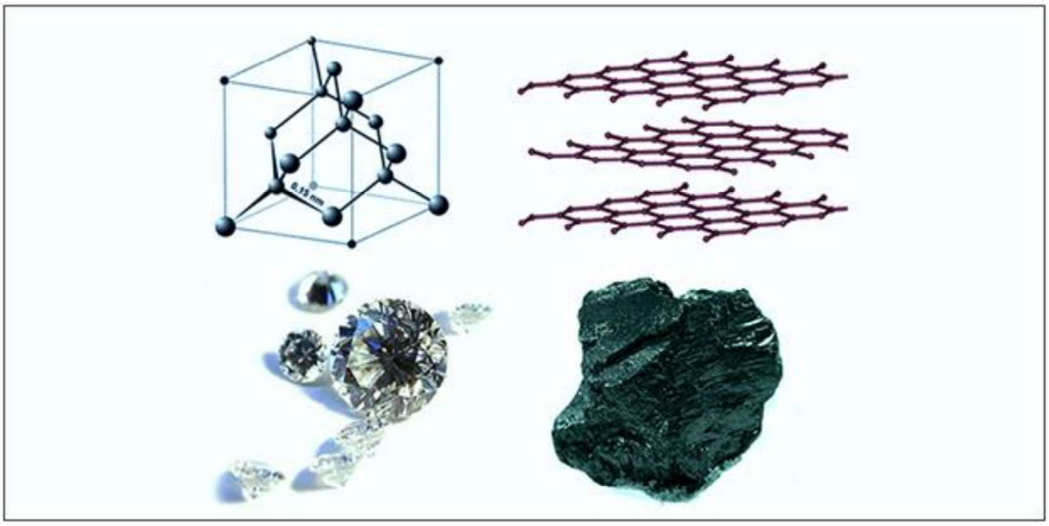

Fig. 1.1 Pictorial view of diamond and graphite.

Graphite is one of the allotropic forms of carbon and has a hexagonal crystal lattice structure (Fig. 1.2). Within the graphite crystal, atoms of carbon are closely spaced at a distance of 1.46 A at the corners of equilateral hexagons, so that each atom has only three neighboring atoms. The hexagons are distributed in basic parallel planes (layers). The distance between adjacent planes (approx. 3.345 A) is greater than the distance between atoms within the hexagon; therefore, the binding force between atoms is more significant in the horizontal plane than the binding force between planes. Adjacent parallel planes are displaced relative to each other, their positions are repeated at every additional layer. The binding force between atomic layers is maintained by easily displaced electrons. The weak attraction between atomic layers gives the graphite its characteristic unidirectional cohesive strength. The laminar structure causes the variation of graphite properties along different cross-sections.

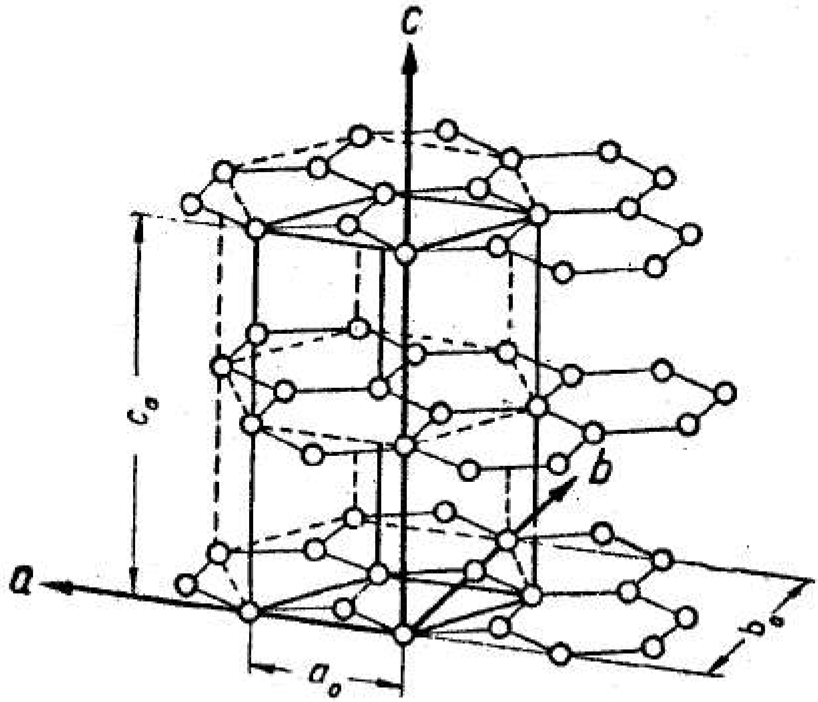

Fig. 1.2 The crystal lattice of graphite (Goncharov 1958)

The hardness of graphite on the Mohs scale is about 1, which is the result of the ease of fracture along the binding planes. In the perpendicular direction, the hardness of graphite is higher than 5.5. The firm bond between atoms of the hexagonal lattice gives rise to the very high fusion temperature of the graphite.

Depending on the grade of graphite; the range of melting temperature typically varies around 4000K to 5000K (Savvatimskiy 2005). Because of the presence in the crystal lattice of the mobile electrons, the graphite possesses heat conductivity and electrical conductivity of the same order as many metals. For this same reason, graphite exhibits metallic color and luster. The crystalline structures of natural and artificial graphite are the same; however, natural graphite crystals are considerably larger and are oriented along one direction, leading to lamination. Artificial graphite, possessing properties similar to those of natural graphite, considerably surpasses it in purity. Natural graphite contains many impurities. Usually, polycrystalline artificial graphite becomes smaller and nearer to the value for a perfect crystal, as the degree of graphitization of the synthetic material increases.

1.2 Nuclear Energy and Reactor Safety

Nuclear energy is one of the leading low carbon power generation methods of producing electricity. From the beginning of its commercialization in the 1970s, nuclear power prevented about 1.84 million air pollution-related deaths and the emission of about 64 billion tonnes of carbon dioxide equivalent that would have otherwise resulted from the burning of fossil fuels in thermal power stations (Kharecha and Hansen 2013). Civilian nuclear power supplied 2,488 terawatt hours (TWh) of electricity in 2017, equivalent to about 10% of global electricity generation. As of April 2018, there are 449 civilian fission reactors in the world, with a combined electrical capacity of 394 GW. Additionally, there are 58 reactors under construction and 154 reactors planned, with a combined capacity of 63 GW and 157 GW, respectively. Over 300 more reactors are proposed.

The six design concepts are:

1. The Gas-Cooled Fast Reactor (GFR)
2. Very-High-Temperature Reactor (VHTR)
3. Supercritical-Water-Cooled Reactor (SCWR)
4. Sodium-Cooled Fast Reactor (SFR)
5. Lead-Cooled Fast Reactor (LFR)
6. Molten Salt Reactor (MSR)

In 2002 the Gen IV International Forum (GIF) nations (Argentina, Brazil, Canada, France, Japan, Korea, South Africa, Switzerland, Russia, United Kingdom and the United States of America) proposed a long term research and development program to investigate six promising new reactor designs.

1.2.1 Next Generation Nuclear Reactor (NGNR)

The evolution of reactors since their introduction in the 1950s has been shown schematically in Fig. 1.3. At present, fourteen countries have agreed to cooperate on the development of the next generation nuclear plant. For more than a decade, Generation IV International Forum has led international collaborative efforts to develop next generation nuclear energy systems that can help meet the world's future energy needs. The Gen IV system is expected to come into service in 2030. The choice of graphite in the present work is because, apart from being a reliable refractory material having high temperature stability, its applications are manifold in critical areas of nuclear energy. Graphite is currently being used for the construction of the major core components such as the fuel block, reflector, moderator and core support critical structure in a nuclear reactor. This will be a key material in the development of Very High Temperature Reactor (VHTR) for the six next-generation nuclear reactor systems within the Generation IV International Forum (Generation IV International Forum 2019). The VHTR is considered to be the Next Generation Nuclear Reactor (NGNR) in the evolutionary development of high-temperature gas-cooled reactors with significant advantage of inherent safety, high thermal efficiency, process heat application capability, low operation and maintenance costs, and modular construction(Nemeth and Bratton 2011; Chi 2016). Fig. 1.4 shows a schematic of the Gen IV Very High Temperature Reactor gas-cooled reactor.

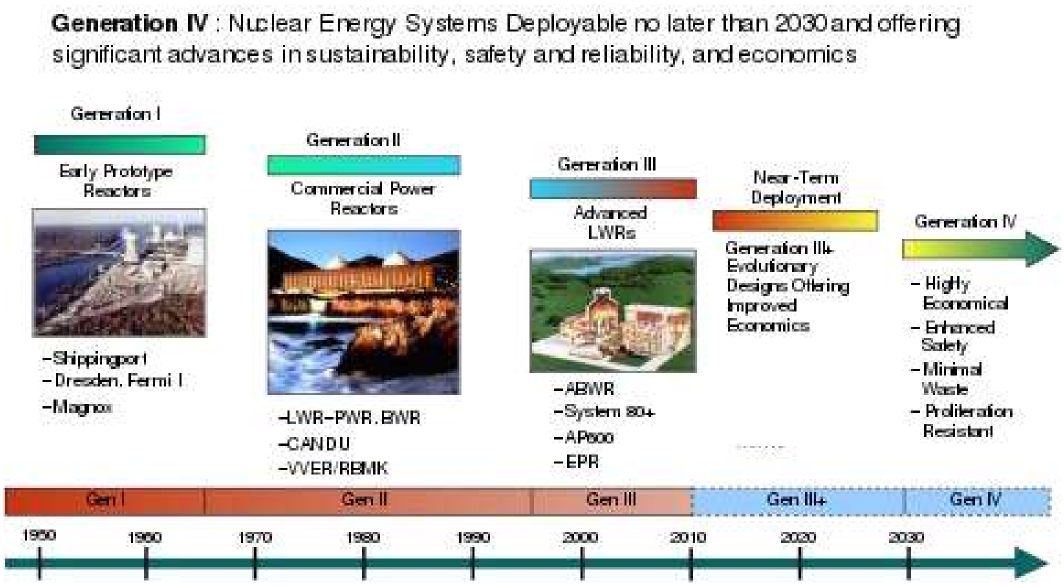

Fig.1.3. The time line of development of Generation I to IV reactors.

The next generation nuclear power plant is to be designed, which will have a projected service life of 30 to 60 years. And also it is ensured that the passive decay heat removal without fuel damage. Large amount of nuclear grade graphite is required for development of the Next generation nuclear reactor. Specifically, graphite is used for the reactor core and the individual graphite bricks that surround the nuclear fuel.

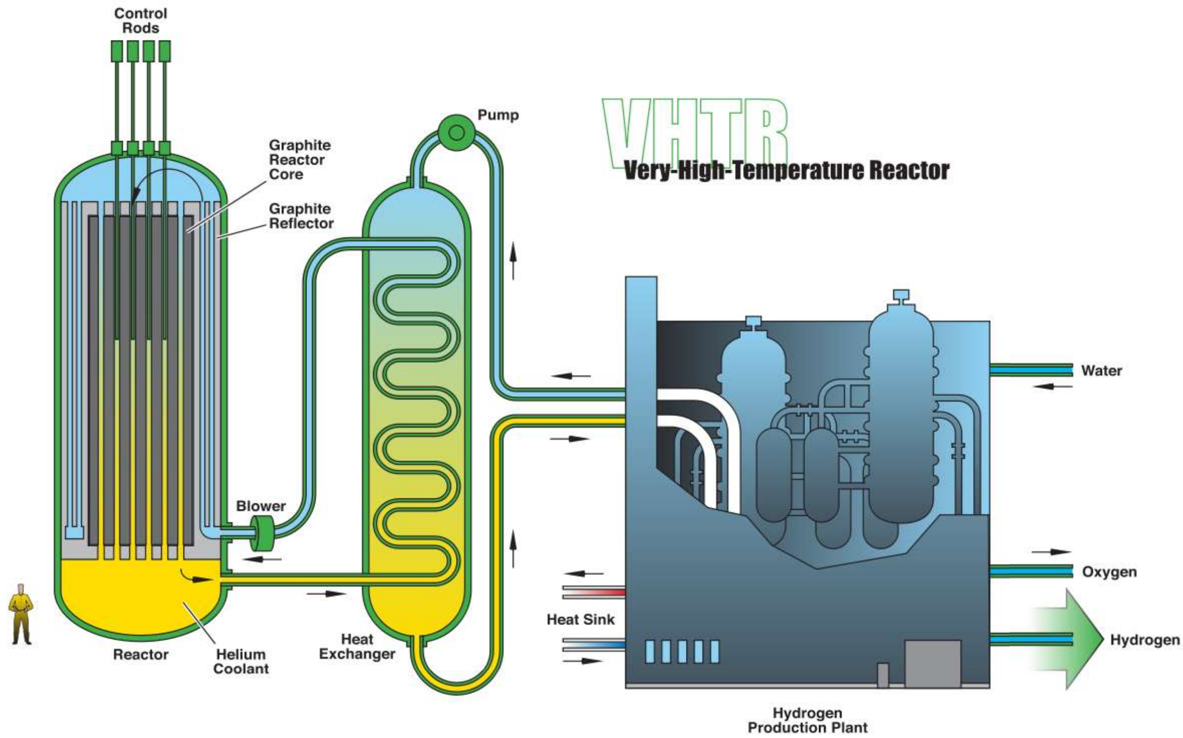

Fig 1.4 Generation IV very high temperature gas-cooled reactor using graphite for neutron reflection and moderation within the reactor core (Generation IV International Forum 2019).

The in-core graphite components for an earlier generation II reactor design has been shown in Fig. 1.5. The potential for crack formation and even rupture in individual graphite blocks are the primary issue to take care. So that the concept of failure theories, fracture mechanics, size effect and effective design strategies are needed to predict and mitigate failures from fractures are needed. The strength of nuclear grade graphite is stochastic and the strength of specimen shows a large random fluctuation from a population mean. Graphite also can have a nonlinear stress-strain response with bimodularity because of distributed damage and damage accumulation within the material prior to rupture.

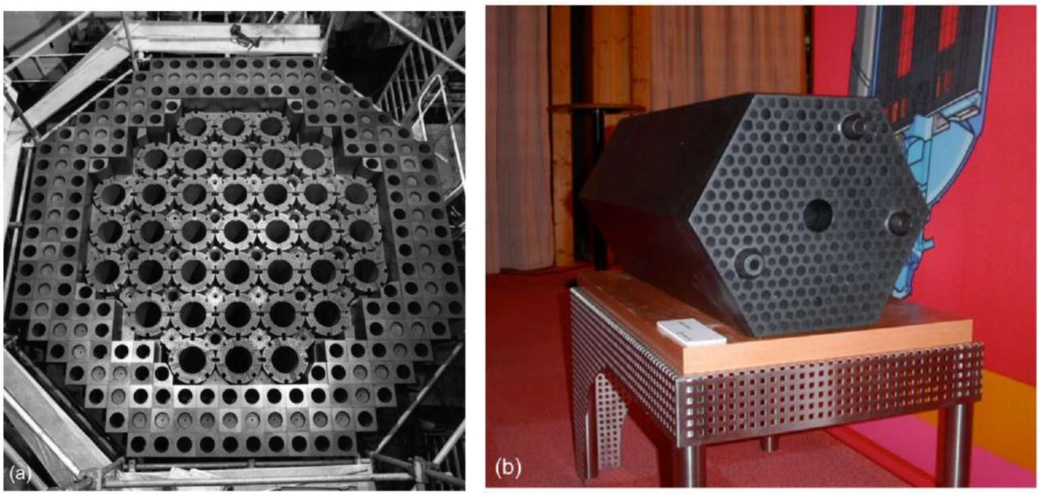

Fig. 1.5 The graphite reactor core components. (a) Advanced gas-cooled reactor (AGR) (United Kingdom) (b) Prismatic graphite fuel element from Fort St. Vrain research reactor (Nemeth and Bratton 2011).

1.2.2 Importance of Graphite for Reactor safety

Most of the nuclear power reactors are gas-cooled and graphite moderated. As well as acting as a moderator the graphite also acts as a structural component providing channels for the coolant gas and control rods. In a gas-cooled reactor the properties of the graphite components are changed by fast neutron irradiation and, in the case of air or carbon dioxide-cooled reactors, by radiolytic oxidation. These irradiation induced changes can lead to the buildup of significant stresses and deformation in the graphite components. Nuclear graphite presents such significant problems of the worst characteristics exhibited by metals and semiconductors, as demonstrated by the localization within the proximity of deep core potential of initial row element combined by the pi system delocalization in lattice structure. Throughout reactor life it is essential that the graphite core structure remains sufficiently strong and undistorted in order to maintain fuel cooling, permit loading and unloading of the fuel and allow the necessary movements of control rods, in both normal and fault conditions. In order to perform structural integrity assessments, the definition of the constitutive equation relating stress and strain in the irradiated graphite material is required. Graphite is used as a structural material as well as a moderator in nuclear reactors. In some gas-cooled reactors, the graphite components are also subjected to radiolytic oxidation which further undermines their structural integrity. Its structural integrity is important for safe operation, as irradiation-induced dimensional strains and thermal strains can cause tensile stress, and irradiation can be detrimental to strength. Crack nucleation may therefore occur with prolonged operation. The design and safety assessment of nuclear graphite components is often based on empirical rules derived from material irradiation.

The structural integrity assessments of nuclear graphite components is an essential element of reactor design for the safety and reliability of nuclear power plant, which may otherwise lead to potentially high risk and hazardous phenomena counting human lives and confidence of research community. The increasing demand for ensuring the failure-free operation of various components and systems in our technologically advanced world, within specified performance limits and for a specified length of time, has brought into play the concept of reliability. Reliability is intimately related with probability. The evolution of this probability of non-failure, or reliability, has become nowadays a critical design procedure in failure control of nuclear graphite structures.

1.3 Motivation

In order to perform graphite component stress analysis, the definition of the constitutive equation relating stress and strain for irradiated graphite is required. Apart from the usual elastic and thermal strains, irradiated graphite components are also subjected to additional strains due to fast neutron irradiation and radiolytic oxidation. Furthermore, the dimensional change strain in graphite components can lead to similar internal stress distributions to those generated by thermal loading and these additive stress distributions may be critical in design. A thermoelastic superimposed coupled field in a crack propagation problem exhibits more asymmetry than a purely mechanical kind of structural problem. Added to it, the thermoelastic anisotropy and property degradation makes the analysis inherently three-dimensional, which otherwise would have been simpler to tackle (Liu and Nairn 1999; Park et al. 2004; Takeda et al. 2004; Yilmaz and Dunand 2004; Pradhan and Panda 2006). Graphites, due to their superior high-temperature behavior and hardness result in reduced erosion rates when compared to monolithic materials. This makes them strong candidates for application in the harsh environment for nuclear power generation reactors. Enhancements in material processing and probabilistic design methodologies have prompted their large scale use in nuclear reactors. Still there are several inhibiting factors which restrict their application along with ceramics and such other high-temperature brittle materials which ascribed to characterizing a proper material model for the same (Wu et al. 1990; Zou et al. 2006; Babout et al. 2008; ASTM C1239 −13 2013). The primary limiting factors have been the inability to design around the inherent low tensile strength, large variability in the observed strength, and brittle failure. The behavior of nuclear grade graphite under flexural loading condition is of interest, since bimodular state of stress is representative of the loading in graphite components. The phenomenon of showing different mechanical properties in tension and compression is called bimodularity. It is commonly found in ceramics and composites. The bimodularity is first reported by Saint-Venant in 1864 (Saint-Venant 1864). Later on, the concept of a bimodularity was rediscovered by Timoshenko in 1941 (Timoshenko 1941) while considering the flexural stress in such a material undergoing pure bending. The probabilistic model needs to include the effects of bimodularity (Grujicic et al. 2003; Berre et al. 2006; Tsang and Marsden 2007). The widely accepted deterministic theory for fracture of graphite defines a critical maximum principal stress based on classical theory. However, due to the bimodularity of graphite, the local state of stress distribution can be noticeably different in similar specimens under identical loading condition. Linear elastic fracture mechanics has been used to assess the fracture resistance of graphite specimens. However, its validity in the assessment of graphite components is uncertain because of an inability to explain behaviors such as the dependence of the toughness on the stress state, specimen size, specimen geometry, the non-linearity observed in the tensile tests and J-resistance (fracture resistance) behavior. The nonlinear behavior of graphite can be attributed to the observed mechanisms of micro-cracking and crack bridging. In this work, a finite element analysis will be employed to predict the relationship between the strength of specimens under uniaxial and equi-biaxial loading, and comparisons will be made with the experimental results.

The design and testing of nuclear graphite components pose such an uncertainty of scattered damage accumulation patterns leading to catastrophic brittle fracture that probabilistic methods have evolved as an ultimatum to study their operational and functional transients, although highly pure graphites are the most sought after material for the fuel elements and moderator in Next Generation Nuclear Reactor (NGNR).

The qualitative and quantitative accuracy, reproducibility, and reliability of test proceedings and results when correlated with the actual real life problem of reactor components become dubious when a nuclear graphite specimen becomes excessively smaller or larger when compared to the standardized dimensions suggested by the ASTM standard Such mitigating factors give an uncertainty of proper design postulations reflecting the low level of confidence among the research community within the spectrum of nuclear graphite applications.. Such mitigating factors give an uncertainty of proper design postulations reflecting the low level of confidence among the research community within the spectrum of nuclear graphite applications. In most cases the material selections based on outstanding physical properties such as high temperature strength, erosion-corrosion, thermal shock resistance, low density and well established refractory properties for the sustainability of structural integrity of critical components leads to ceramic based materials like graphite. However, the uncertainty of stochastic fracture behavior of even near identical components, the susceptibility to sustain tensile stresses, low strain and fracture toughness arising out of the general problem of scattered flaws and brittleness results in compromising structures from the designer’s perspective rather than tackling the problem efficiently. Many a cases, the different stress strain behaviour in tension and compression for such materials are rather avoided in design than solved by efficient analytical, numerical or experimental procedures. The acumen of such hypothesis is reasoned to be simplifying the strength design, though we understand the fallacy of such assumptions shall only be magnified as we build up real structures of significantly large size than lab scale models. As the size and so the volume and/or surface area of the structure is scaled up, the probability of encountering severe flaws and their numbers are only increased and hence if the material is inherently brittle, catastrophic failure of such components are very intriguing to explain with existing classical unimodular assumptions. Therefore, there is a need for reassessment of such assumptions leading to closed form and semi-analytic solutions for an improved design. The endeavor of the present work has been to conduct a detailed analytical, numerical and experimental analysis of strength scaling of bimodular specimens with different geometry to eliminate the deficiencies associated with the existing model. Probabilistic approach based on the weakest link theory (WLT) model of Weibull distribution functions has been employed for evaluating effective volume and area by developing a semi-analytic three-dimensional numerical model. Weibull functional parameters such as Weibull modulus and characteristics strength has been evaluated from tension and compression testing of C-ring graphite specimens. The numerical estimates of the unimodular model and bimodular model have been compared with calculations obtained from existing literatures (Quinn 2003a, b; ASTM C1323-16 2016)and CARES/Weibpar respectively (WeibPar V-4.3 and CARES V-9.3).

The prime objective of this research has been to assess experimentally and numerically the failure probability of nuclear graphite reactor components based on Weibull Weakest Link Theory. This theory is restricted to the assumption that the distribution underlying the failure strengths is the two-parameter Weibull distribution with size scaling and the flaw population is stable with time.

Furthermore, experimentation is needed to test specimens (tensile, flexural, pressurized ring, fractography etc.) that are primarily subjected to uniaxial stress states. Weibull characteristic strength and Weibull modulus are the characterizing quantities to evaluate the probability of component failure in the Weibull probabilistic analysis. The Weibull modulus, or such parameter, is important for probabilistic assessments of structural integrity. Knowledge of both the size and spatial distributions of flaws in the microstructure is therefore important for probabilistic modeling of component failure (Peirce 1926; Ang and Tang 1984; Tsang and Marsden 2007; Marsden et al. 2008). One element required for evaluation of the graphite fracture behavior under realistic loading conditions is an understanding of the effect of stress state on strength. Test specimens of quasi-brittle materials, such as nuclear graphite, are well known to exhibit sensitivity to stress state and exhibit different stress strain behaviour under tension and compression. This so called bimodular behavior of nuclear grade graphite has been studied to quantify its influence on fracture behaviour of scaled up components.

1.3.1: Probabilistic Fracture Mechanics: Weibull Weakest Link Model

The stochastic nature of fracture in engineering materials can be categorized from two distinct models: series systems and parallel systems. Series systems assume that the material is composed of a set of n links connected in series such that the structure fails whenever any of the links fail. In the parallel-system model, the n links are arranged in parallel. When one link fails, load is redistributed to the remaining $n-1$ links. The remaining $n-1$ links carry higher load, but the system (structure) may still survive as in a *fail-safe design*. The structure does not fail until all n links fail. Series-systems model the abrupt failure of brittle materials such as glasses and ceramics, whereas parallel systems more appropriately model the more gradual or graceful failure of fiber-reinforced composite materials. The design of nuclear graphite components differs from that for components made of ductile metals due to its inability to redistribute the high local stresses induced by the inherent flaws. Random nature of the size and orientation of flaws and the resulting absence of a unique strength in graphites requires a probabilistic approach in the design involving these materials. As such, both the flaw size and flaw orientation, relative to the applied stress affect material strength. The failure strength of nuclear graphite is treated as a continuous random variable, determined by the flaw population. Typically, a number of test specimens with well-defined geometry will be tested for failure under isothermal, well-defined displacement and/or force-application conditions. The force at which each test specimen (ASTM standards) fails is recorded**.** The resulting failure stress data are used to obtain Weibull parameter estimates associated with the underlying flaw population distribution. Weibull first proposed that statistics be used in a probabilistic prediction method in structural design. He used a weakest link theory (WLT) and assumed a unique form for the cumulative distribution for uniaxial fracture data, which he determined by simple tension tests. Later he demonstrated that the distribution function he had assumed had wide applicability to many naturally occurring processes.

In the present work an attempt will be made to determine mechanical parameters of nuclear graphite as per ASTM standards, to evaluate the Weibull parameter as per ASTM C-1239 and thereafter to develop Finite Element Code using Weibull weakest link theory (WLT). The strength response of graphite is generally well represented using a weakest link concept within which the graphite component under consideration is modeled as a series of links as observed in a chain. The weakest link principle is readily understood by analyzing a chain which, as it is being pulled, will fail catastrophically when its weakest link breaks. The reliability of such a chain is the product of the survival probabilities of the individual links. Subsequently, attempts were being made to derive the stress volume- and stress area-integrals to predict the failure response of purely brittle materials. These integrals take into account the fact that failure is not necessarily governed by the most highly stressed location in the component but rather by its entire stress field, which takes into account the presence of potent stress-enhancing flaws/stress raisers.

Within the Weibull theory, the effect of size but not the orientation of the flaws is considered. The effect of multi-axial stress states is handled by either averaging the normal stresses or by using the principle of independent action within which each tensile stress contributes to the failure probability as if no other stress were present. Another important phenomenon captured by the weakest link theory is that the strength of a component decreases with an increase in its volume and/or surface area. Consequently, the weakest link approach is integrated with the theory of linear elastic fracture mechanics even to characterize the mixed-mode fracture in anisotropic materials. The probability of failure of graphite components will be studied based on the concepts of Weibull stochastic model.

1.3.2 Bimodularity: A Stress Dependent Elasticity Phenomena

Bimodularity has been recognized as an uncertainty in the design and development of high risk ceramic and graphite structures leading to catastrophic failure. This results in an asymmetric shifting of elastic axis and elastic surface from an otherwise neutral axis and neutral surface respectively, when the structure is mechanically loaded (Ambartsumyan 1969; Tabaddor 1972; Reddy et al. 1980; Reddy and Bert 1982; Reddy and Chao 1983; Kamiya 1987). Classical elasticity theory has limited application for these kinds of structural materials in its original form as it not only considers the elastic properties to be same in tension and compression, but also it does not take into account the material non-linearity. Early works by Saint Venant (Saint-Venant 1864) and Timoshenko (Timoshenko 1941) has postulated the concept of variation of elastic modulus for beams under flexural loading exhibiting bimodular characteristics even under simple bending. Structural integrity assessment of structures comprising of bimodular materials necessitates the evaluation of state of stress as an integral factor of tension and compression modulus following a rigorous iterative procedure, where numerical computations are very much involved even running into hundreds of thousands of steps for an acceptable convergence limit. In this regard, evaluation of only effective modulus are erroneous leading to a design handicap at the prototype stage, though it might give some initial estimate of bending and shear deformation with a unimodular constitutive relationship . Consequently, the influence of variation of structure behavior from test specimen geometry to actual structural shape becomes highly exaggerated forcing the designer to take shelter under either over designed/under-designed hypothetical safety factor. This might lead to huge material and volume loss, not to mention that the cost and reliability of the structure has been compromised. The redundancy observed in the existing literature to address those issues concentrating only on unimodular based reliability evaluation of effective volume and surface area parameters for test specimens has been the motivation of the present study. Expectedly, this has been a cause of worry in correlating the experimental observations with postulated design parameters for a bimodular based material structure. Though present endeavor to evaluate reliability parameters for analytical and numerical modeling of such real life structural behavior might be uncannily computationally exhaustive, still we feel it will be worthy to get rid of such uncertainty of scaling of size and shape from laboratory specimen to actual prototype in high risk design parts exhibiting stress dependent elasticity. The conversion of design data from one specimen configuration to another without concern of bimodularity effect and prior knowledge of flaw distribution leads to unexpected failure rendering the existing design principles very much conservative for such ceramic and graphite cladded structures in contrast to metals.

1.4 Structure of the Thesis

The present work endeavors to study the fracture behavior bimodular graphite specimens. The thesis comprises of **12 chapters**.

Chapter-1 includes the brief introduction of different form of carbon, different grade of nuclear graphite used in nuclear reactors. The introduction of size effect, Weibull weakest link theory and its applicability in nuclear grade graphite are discussed.

Chapter-2 includes the detailed literature review based on fracture behavior and Weibull strength scaling for nuclear grade graphite components. The detailed objectives of present investigation are presented.

Chapter-3 provided theoretical background for the thesis. It also includes the tensile and compressive testing on the SED 40s graphite specimen using ASTM standard. The bimodular ratio is characterized.

Chapter-4 formulates the effective volumes and effective surfaces for bimodular rectangular bars loaded in flexure. The strength scaling for specimen size is dependent on whether the flaws are volume or surface distributed. However, in this study it has been observed that the ratio of strengths from any two configurations, such as three-point flexural to four-point, is independent of whether the flaws are volume or surface distributed when the cross-sectional sizes are the same.

Chapter-5 comprises the strength distribution of bi-modular cylindrical ceramic specimen from that of another based on Weibull statistical theory. In order to do so, initially, semi analytical expression for effective volume and effective surface for the cylindrical bar loaded in flexure have been derived. Also, strength scaling ratio from one flexural loading configuration to another with various Weibull modulus have been made available. Elaborate experimentation and numerical simulations has been carried out to verify the analytical model.

Chapter-6 consists of study addresses the issues of shifting of elastic axis and elastic surface for strength scaling of bimodular C-ring specimens using Weibull statistical model. It has been endeavored to promulgate a semi-analytical weakest link theory approach for evaluating effective volume and effective area with presumed surface and volume distributed scattered defects in the specimen. Experimentation, semi-analytic and finite element based numerical procedures have been pursued to evaluate iteratively the Weibull characteristic parameters for typical loading configurations.

Chapter-7 investigates the influence of bimodularity on the crack growth behaviour employing the three-dimensional path independent integral as the characterizing parameter. The asymmetric variation of both line and the area integrals through the thickness of the specimen are found to be significant indicating the effect of the bimodular elastic moduli parameter on the average *J*-integral estimation.

Chapter-8 consist of the influence of bimodularity on fracture behaviour of graphite specimens has been studied with critical fracture toughness (K_{Ic}), 3D J-integral (J_{Ic}) and strain energy release rate (G_{Ic}) as the characterizing parameter. Bimodularity index of graphite specimens has been obtained from the normalized data of tensile and compression experimentation. Single edge notch bend testing of pre-cracked specimens from the same lot have been carried out as per ASTM standard D7779-11 to determine the peak load and critical fracture parameters K_{Ic}, G_{Ic} and J_{Ic} using digital image correlation technology of crack opening displacements. Weibull weakest link theory has been used to evaluate the mean peak load, Weibull modulus and goodness of fit employing least square method, biased and unbiased maximum likelihood estimator. And Experimental and Computational fracture parameters have been compared qualitatively to describe the significance of bimodularity.

Chapter-9 consists of computation of *J*-integral for curve crack geometry under bimodular material media. The severity of bimodular 2D curved crack progression behavior has been delineated with asymmetry of stress-distribution and distortion of neutral axis. And also the effect of bimodularity has been observed on curve cracked beam geometry subjected to the thermal gradient with fixed constraint.

The bimodular J-integral behavior is found to be path independent computationally.

Chapter-10 pronounces a universal path independent integral J^u that represents the energy release rate or flux during crack extension in a homogeneous and isotropic material, has been derived for straight crack subjected to multiple loads. This version of integral includes the effect of elastic strain, Eigen strain, thermal strain, body forces and magnetic strain. Particularly focus is made on thermo-mechanical and magnetic strains. The 3D *J*-integral expression represents the energy release rate in the combined thermoelastic field with magnetostriction characteristics

Chapter-11 provided the summary of the thesis.