2

Literature Survey

2.1 Introduction

Graphite derives its name from Abraham Gottlob Werner (1750-1817). He named the material after the Greek word meaning ‘to write’. Graphite refers to an allotrope of carbon having a particular crystalline structure. Graphite is used as moderator as well as structural material in the high-temperature gas-cooled reactors (HTGR). To have a clear view and understanding the nature and properties of nuclear graphite, a comprehensive review to present and past result will be introduced and critically present maximum possible ideas associated with nuclear graphite and its manufacturing, strength and fracture behavior. The purpose of this literature review is to assess the state of the art, analytical, experimental, statistical and numerical methodology for the analysis of fracture behavior of bimodular materials. This will adhere to the safe and reliable design of nuclear reactor core. Nuclear grade graphite has lower tensile strength and higher compressive strength. Its attractive physical and mechanical properties of like high-temperature strength, light weight, excellent erosion, corrosion and oxidation resistance, low thermal conductivity, low cost, and wide availability have made an increasingly important structural material in the nuclear reactor core. The potential of graphite in demanding structural applications as moderator inside the nuclear reactor is especially attractive when resistance to high temperatures is the main concern.

With today's needs for more energy production, without polluting the ecosystem is full-filled by nuclear thermal power-plant operating at much higher temperatures with graphite moderator, appear to be mandatory to meet economically and safely these national objectives. However, similar to graphite all other brittle materials, display linear stress-strain behavior from zero to fracture. The lack of ductility and yielding capability gives graphite materials their most undesirable characteristics such as low strain tolerance, low fracture toughness, and large variation in observed fracture strength. This wide variation of material strength of graphite is due to the nature and distribution of intrinsic microscopic flaws, which are unavoidably present as a result of materials processing operations. Failure in graphite usually initiates at a single weakest flaw when the local stress there reaches a critical value. Because of the large scatter in strength of graphite, designers today use statistics and reliability analysis for the failure prediction of graphite components, which may be subject to arbitrary loadings and multidimensional stress states. A brief review of literature available on size effect specimen size on the strength, bimodularity effect and various statistical models relevant to fracture of nuclear grade graphite has been discussed in the following sections. Some survey of literatures are presented for previous studies on fracture parameters.

2.2 Size Dependent Stress Analysis

Brittle materials like ceramics are those in which failure is caused without plastic yielding. It can be analyzed according to linear elastic fracture mechanics (LEFM). In literature, the size effect on strength in failure of structures has been explained in Weibull's (Weibull 1939b, a, 1951) statistical theory, which extended to multidimensional solids the weakest-link model for a chain proposed by (Peirce 1926). The Weibull statistical fracture theory is widely applied to the fracture of ceramic materials. This theory predicts the strength of brittle materials, which is a function of size of specimens, stress distribution, and stress state. (Petrovic 1987) provided the experimental multiaxial loading results for alumina tubes are compared to the stress state predictions of the Weibull theory. They concluded that the most cases, the Weibull theory yields reasonable predictions, although there may be some difficulties in dealing with shear stress effects on fracture. According to Weibull's theory, the failure is determined by the minimum value of the strength of the material, and the statistical size effect is due to the fact that the smaller the structure, the larger is the strength value and vice a versa (Bazant et al. 1992). The size effect on strength of ceramic materials is satisfactory correlated with the effective volume or effective surface area. The correlation is firstly established for various specimens by (Jadaan et al. 1991; Shelleman et al. 1991). Experimental validation has been also given. Further, Quinn (Quinn 2003b, a) gave the formulas are given for the effective volumes and effective surfaces for a beam with circular and rectangular cross-section with unimodular material behavior. Duffy et al. (Duffy et al. 2005) described the Weibull parameters for spatially distributed flaw populations in c-ring which is commonly applicable to ceramic gun barrels and (Wereszczak et al. 2008) derived for sectored flexural strength test specimen which is developed to measure the strength of ceramic tubes specifically for circumstances when flaws located at the tube’s outer diameter are the strength-limiter when subjected to axial tension.

2.3 Bimodularity and Stress Dependent Elasticity

The materials such as ceramics, composites also exhibiting different modulus of elasticity in tension and compression characteristics was recognized by (Saint-Venant 1864). However, the concept had not received much attention for a long time from research community. Later on, the concept of a bimodulus material was originated by (Timoshenko 1941) while considering the flexural stress in such a material undergoing pure bending. The effective modulus for stiffness of such a beam in pure bending was given by(Marin 1962). The bimodulus concept was extended to two-dimensional materials by (Ambartsumyan and Khachatryan 1966b; Ambartsumyan 1969). The a generalized constitutive relation based on stress dependent elasticity model for bimodular materials has been developed by (Tabaddor 1972). The bimodular beams were numerically analyzed with the aid of the developed formulation and the predicted deformations are compared with experimental results (Tabaddor 1976, 1981). An exact solution is derived by (Jones 1971a) for buckling of circular cylindrical shells with different elastic moduli in tension and compression under arbitrary combinations of axial and lateral pressure. The stress-strain relationship and improved weighted compliance matrix material model for bimodulus material is given by (Jones 1977a). A mixed finite-element analysis is presented for static behavior of rectangular plates laminated of composite materials having finite transverse shear moduli and different elastic properties depending upon whether the fiber-direction strains are tensile or compressive(Bert et al. 1981). Bending of Thick Rectangular Plates Laminated of Bimodulus Composite Materials (Tran and Bert 1982). Analytical and finite element solutions are presented for thermal bending and stretching of laminated composite plates(Reddy et al. 1980). A new approach is given to the theory of non-linear elastic materials which have different behaviour in tension and compression(Green and Mkrtichian 1977). Dynamic stability of bimodulus beam subjected to a periodic axial load is investigated by using the Timoshenko beam theory (Jzeng et al. 1992). Flexural analysis of laminated composite plates of bimodulus materials subjected to thermal load is studied by(Patel et al. 2004). Also the free flexural vibration behavior and transient response of bimodular material angle-ply laminated composite plates has been carried out by (Patel et al. 2005a, b). Within the last few decades several attempts have been made to establish constitutive relationships and numerical validation in various loading conditions for bimodular materials by several researchers.

This thesis contributes the bimodular effect of specimen size on the strength of ceramics especially nuclear grade graphite specimens for better core design which has been not studied by any researcher.

2.4 Stochastic Fracture Model

A number of theories of nuclear graphite failure have been proposed by several researchers. Some of the more commonly employed theories, which describes some loading situations well. The variation in strength and complexity of the microstructures found in graphite are studied. Because of this complexity it would be expected that the most versatile theories of failure are those which take most account of microstructures. Some of the stochastic fracture models are relevant in studying failure of the graphite. The frequency distribution of Limiting forms of the frequency distribution of the largest or smallest member of a sample is given by(Fisher and Tippett 1928) is an example of extreme value distribution. The Weakest Link Theory concept introduced in determining the strength of cotton yarn of different length by (Peirce 1926). Further, the concept is used in different material volume. Weibull developed the very famous and widely applicable distribution called Weibull distribution (Weibull 1939b, a, 1951). Further, Weibull distribution is found good in analysis of strength distribution and specimen size effect of quasi-brittle material. The Weibull distribution is obtained if the defect size distribution is described by a power law, and the Gumbel distribution is obtained if the defect size is exponentially distributed (Gumbel 1958). The specimen size effect has been investigated for graphite in several researchers. Brocklehurst studied the weakest link Weibull theory, which is based upon a statistical distribution of flaw sizes in the specimens and offers a qualitative explanation for the observed results, has been explored in an attempt to explain the volume dependence of strength, or the strength distribution at constant volume (Brocklehurst and Darby 1974). Price tested more than 2000 tensile and four-point bend experiments at ambient temperature on specimens from one log of extruded near-isotropic petroleum coke- based nuclear graphite (Price 1976). It is found that the mean strengths showed the expected systematic dependence on orientation and location, with axial specimens stronger than radial specimens and material near the edge of the log stronger than material near the centerline, There were additional local fluctuations in strength which, in some cases, corresponded to local variations in density. Price didn't conclude that the cumulative failure strength distribution could be better fitted by a normal distribution or by Weibull distribution. Further, the same experimental results are re-analyzed by (Nemeth et al. 2013). Strength variation versus specimen location, size, and orientation relative to the parent body were compared. The data were progressively and extensively pooled into larger data sets to discriminate overall trends from local variations and investigate the strength distribution. Issues regarding size effect, Weibull parameter consistency, and nonlinear stress-strain response were investigated using the Ceramics Analysis and Reliability Evaluation of Structures Life Prediction Program (CARES/Life) and WeibPar codes (WeibPar V-4.3 and CARES V-9.3). Overall, the Weibull distribution described the behavior of the pooled data very well.

A failure model is associated with a failure probability with each grain and determines the probability of sufficient grains failing such that they form a contiguous array of a size which satisfies the Griffith failure criterion(Buch 1976). (Rose and Tucker 1982) developed the fracture criterion for nuclear graphite. In this The measurements of tensile and flexural strength of nuclear graphite using small bar specimens are reported. The critical flaws are defined on the basis of linear elastic fracture mechanics. Failures criteria are described by critical defects associated with cleaved large coke particles. Another study is directed towards establishing an improved an improved understanding of the mechanism which control fracture in nuclear graphite by (Burchell 1986; Burchell et al. 1986). The graphite fracture is studied in dynamically by straining graphite specimen on the stage of optical microscope. Semi-quantitative fracture data were obtained by monitoring the acoustic emission (AE) response of a wide range of poly-granular graphite. Further, this model is used with the finite element code to study failure probability of a graphite side reflector design in the pebble-bed HTR during its entire service life from the microstructural view by (Yu et al. 2012). The physical basis of, and assumptions behind, the Burchell fracture model for graphites are reported by(Burchell 1996). The model combines a fracture mechanics failure criteria and a microstructurally based description of fracture. The excellent performance and versatility of the Burchell fracture model was attributed to its sound physical basis. The potential for applying the Burchell fracture model to irradiated graphites was explored and the model was shown to qualitatively predict the influence of neutron damage on the strength of a nuclear graphite. (Joyce et al. 2008) worked on microstructure deformation and damage in nuclear graphite. A full field strain mapping technique is employed to obtain in situ, load resolved, strain fields from the surface of disc compression and tensile test specimens of Gilsocarbon IM1-24 nuclear graphite. Cracks are detected to nucleate at porosity, and to propagate by coalescence.

Weibull parameter estimates of the strength distribution also provide detail information regarding the survival probability or the reliability under stress & also provide the analysis of reliability of the nuclear grade graphite using mechanical properties as specified in the ASTM specification D7219-05(Srinivasan 2008).

The size effect on the compressive strength and flexural strength are studied for nuclear graphite of different coke particle size (Chi 2013, 2015).

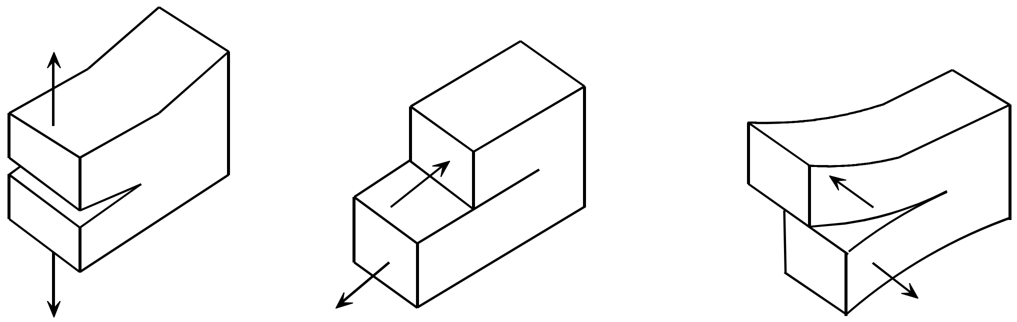
Hindley et al. (Hindley et al. 2013) has presented a methodology that can be used for calculating the probability of failure of graphite core components in a nuclear core design, such as that of pebble bed modular reactor. The proposed methodology is shown is shown to calculate the failure of multiple geometries using the parameters obtained from tensile specimen test data. Experimental testing of various geometries is undertaken to verify the results. The observed experimental behavior of graphite exhibits failure strength is higher in compression than tension whereas failure strength is higher in flexural than tension with similar size. Weibull's weakest link theory anticipates that the larger volume of material the greater the chance that a defect exists within the volume. Further, the selection of a statistical distribution has been chosen to represent the experimental material strength of NBG-18 nuclear graphite in (Hindley et al. 2012). A relevant statistical fit is determined and the goodness of fit is also evaluated for different data set of failure strength. The process for approximating the optimal size of a link volume required for weakest link failure calculation in nuclear graphite, with NBG-18 used as an example (Hindley et al. 2014) . As part of the failure methodology, the link volume is defined in terms of two grouping criteria. The first criterion is a factor of the maximum grain size and the second criterion is a function of an equivalent stress limit. Further, the prediction of the failure of a full-size nuclear graphite reactor component made up of NBG-18 based on experiment obtained from standard tensile test specimens (Hindley et al. 2015). A full-size specimen structural test was developed to simulate the same failure conditions expected during a normal operation of the reactor in order to validate the failure prediction.

2.5 Fracture Characterization and 3D J integral

In this section, an attempt has been made to provide an insight into the use of classical fracture mechanics approach and deterministic methods for estimating the various fracture parameters, a central problem in computational fracture analyses. With respect to the state of the art to solve complex linear or nonlinear crack phenomena under mechanical, thermo-mechanical or electro-mechanical loads along with advanced damage model, the field of fracture mechanics has become sufficiently matured. The advent of fracture mechanics is generally attributed to the pioneering work of (Inglis 1913) when he observed the infinite nature of stresses at the vertex of a degenerate ellipsoidal cavity. Consequent studies by other research workers have since then led to a better and deeper understanding of fracture phenomena. This in turn has led to the development of theories to explain and quantify the observed physical behavior of engineering structures during failure. Among the earliest fracture theories developed was Linear Elastic Fracture Mechanics (LEFM), which was ultimately extended to take care of the more practical situation in terms of load, loading rate, material response etc. The early development can be traced back to the work of (Griffith 1921) when he formulated an energy equation to describe the propagation of cracks using the concept of critical energy release rate G_c. This fracture criterion, which is essentially a statement of the energy balance principle, indicates that crack propagation initiates when the gain in surface energy due to the increase in surface area equals the reduction in strain energy due to the displacement of the boundaries and the change in the stored elastic energy. This theory, however, is limited only to the failure analysis of homogeneous brittle materials such as glass, ceramics etc.

2.5.1 Linear Elastic Fracture Mechanics

Realizing this limitation, Orowan and Irwin proposed a modification of the theory, which can be used for engineering materials exhibiting limited ductility(Orowan 1949; Irwin 1957). The model is an extension of the energy formulation used by Griffith where plastic strain energy rate for crack propagation was added in the energy equation. Both of them recognized that the energy required to produce plastic strain at the crack tip is much greater than the surface energy needed to create new surfaces. It is through this work that the foundation of LEFM was established.



(a) (b) (c)

Fig. 2.1 Various basic loading modes in fracture mechanics (a) opening mode (b) sliding mode (c) tearing mode

Large magnitudes of stresses and their steeper gradients near the tip of a crack are of serious importance. The material near these areas become weak and fail to sustain the intense local stresses and as a result, further nucleation of micro-cracks occur which subsequently grow to attain critical dimensions. The investigation of near tip stress field and their intensity is of prime concern for fracture analyses. The stress field near the tip may be grouped into three basic types, each associated with a local mode of deformation, namely the opening mode (mode I), the sliding mode (mode II) and the tearing mode (mode III), Fig.. Two important fracture parameters in LEFM are Stress Intensity Factor (SIF) and Energy Release Rate (G).

2.5.2 Elastic Plastic Fracture Mechanics (EPFM)

Undeniably, plastic deformation is a fact that occurs at the crack tip in all engineering materials and their alloys. The importance of the area of EPFM was appreciated when it was recognized that considerable amount of plastic deformation occurs in most of the materials prior to fracture except the brittle material. The crack growth in these materials involves plastic strain fields near the crack tip and fracture occurs after a critical amount of plastic strain is reached at certain locations. As one moves away from the crack tip, the stresses decay rapidly and reach the nominal value. This implies that the plastic deformation is confined to a region near the tip, which is thus enclosed by the surrounding material remaining in the elastic state. Therefore, large stress gradients near the tip regions produce a sizeable plastic zone rendering the elastic solution inadmissible for accurate representation of crack tip parameters. The characterization of the crack tip stress fields by a parameter estimated without the direct use of stresses within the uncertain yielded region will naturally provide a more practical and accurate fracture criterion.

Interests in the fracture mechanics of ductile materials arose out of the research conducted by (Dugdale 1960; Barenblatt 1962). Dugdale proposed a simple model, the strip yield model, to deal with plasticity at the crack tip, A key assumption in the model states that stress values at the crack tip are limited by the yield strength of the material and the yielding is confined to a narrow band along the crack line.

2.5.3 Path Independent J integral

Of the various concepts developed over the years, the J integral and the crack opening displacement (COD) etc. have drawn the attention of yielding fracture mechanics. They form the main stream of fracture parameters when plastic deformations are considered in the analyses. However, among the various accepted ductile fracture criteria, the path independent J integral has become most attractive and is being widely used in computational fracture mechanics.

During the analysis of lattice defects, Eshelby (Eshelby 1956) deduced a surface integral representing the force on an elastic singularity or inhomogeneity giving rise to conservation law in regular elasto-static fields in the presence of infinitesimal deformation. The path independent J integral introduced by (Rice 1968) is such a parameter for linear or nonlinear elastic material. For two-dimensional stress field, the expression for J is

$$J = \int_{\Gamma} (W n_1 - T_i \frac{\partial u_i}{\partial x}) d\Gamma$$

where, Γ is the contour enclosing the crack tip, W *is* the strain energy density, n is the unit outward normal on Γ,c T_i is the traction vector on Γ and u_i is the displacement vector. The value of J is independent of the choice of contour taken.

Rice has shown that the J integral may be interpreted as the potential energy difference between two identically loaded bodies with slightly differing in crack sizes and may be equated to

$$J = -\frac{\partial U}{\partial a}.$$

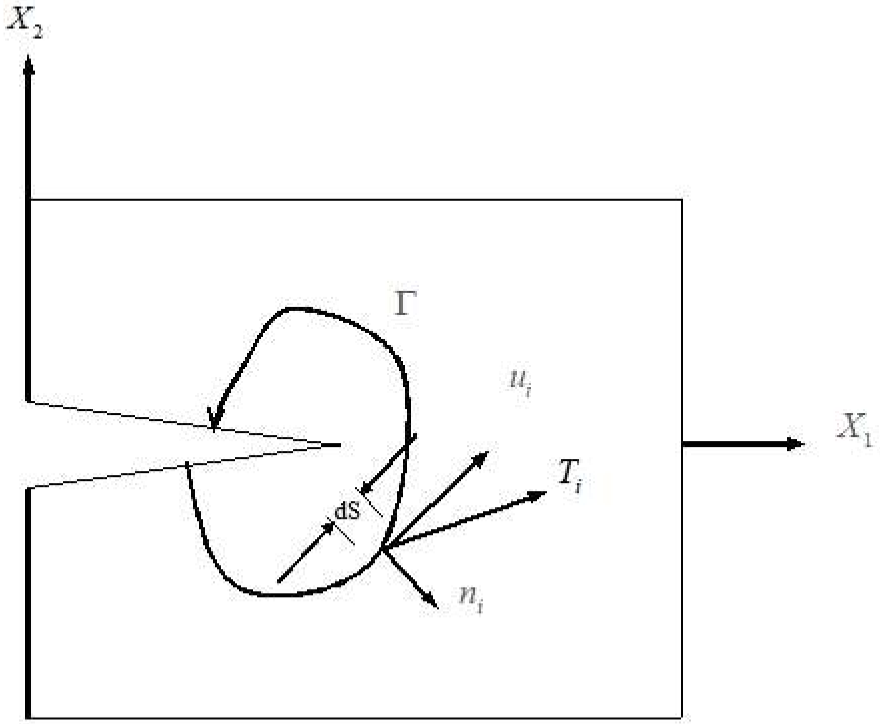


Fig. 2.2 2D J-integral around a notch

Hence, J is equal to G for linear elastic material and may be correlated to the K_I by

$$J = \frac{K_I^2}{E} \qquad \text{for plane stress}$$

$$J = \frac{(1-\upsilon^2)}{E} K_I^2 \qquad \text{for plane strain.}$$

Quantitative fracture mechanics has made impressive advances in extending Rice's J-integral to complicated problems incorporating correction terms to preserve the path independent character. Many such integrals with the common property of path independence received considerable attention in computational fracture mechanics. Such extensions are mainly restricted to straight crack geometry or an arbitrarily kinked crack. It is established the total of three conservation laws and for a 3-D deformation field these integrals generalize to(Knowles and Sternberg 1972):

$$J_k = \int_S (Wn_k - T_i u_{i,k}) dS$$

In the absence of body force and when the notch edges are traction free, the path independent integral for a notch is given by as (Chang and Kang 2002)

$$J_{kR} = \int_{\Gamma_0} [Wn_k - \sigma_{ij} n_j (-\frac{\partial u_i}{\partial x_k})] ds + \int_{C_1 + C_2} Wn_k ds$$

Where, Γ_0 is an arbitrary counter clockwise contour, C_1 and C_2 are the portions of line segments along the notch edges and *R* is the cut off radius.

The crack geometry is one of the major factors that influence the overall resistance against fracture for many engineering structures. The fracture behavior associated with such cracks thus depends on the crack radius, crack front curvature and crack surface curvature etc. Even though a few solutions are available, more detailed investigations on the near tip singular behavior of cracks of general curved shapes are still necessary. Some analytical studies on description of the stress behavior, derivation of SIF for planar as well as non-planar cracks of curved shapes have been performed. One of the earlier works in this area is reported in (Cotterell and Rice 1980).

2.5.4 Extension of J Integral from 2D to 3D

In literature, there are some research papers that discussed the J integral in unimodular material whether it is 2D or 3D. The effect of bi-modularity had not been discussed in the literature for the evaluation of J integral in 3D. But the rapid technology evolution and applications in aeronautic, civil, mechanical fields lead to the study of bi-modular property of the material. Moreover, some ceramics, some composite materials exhibit a phenomenon known as bi-modularity in which the elastic properties in tension differ from those in compression. The Evaluation of the 3D crack parameters over a bimodular material media is one of the objectives of present work.

Traditionally, the behavior of cracked elastic solids has been considered mainly in 2D situations. Although there are some seminal works on the analysis of three-dimensional cracks in linear elastic fracture mechanics, LEFM, (Sih 1971) the main practical developments still rely on concepts and results obtained from 2D solutions. However, it is commonly accepted that many of these concepts may not always be generalized to 3D. The analysis of a through-thickness crack in a finite thickness plate is one of such cases. It is well known that the apparent fracture toughness of a cracked plate increases for decreasing thicknesses 't' given a certain crack length 'a'. This increase is due to the loss of constraint as compared to the constraint existing in a thick plate, often assimilated to a plane strain condition. A proper study of this constraint effect can only be addressed considering the three-dimensional stress fields around the crack front. In previous works a tensor description has been introduced to characterize the singular stress field in the vicinity of the crack front in accordance to the Williams' series expansion (Williams 1952b). In these studies, it is concluded that the existence of second order terms (i.e. terms that do not depend on the radial distance to the crack front) cannot in general be neglected. In addition to the in-plane stress often considered in 2D problems, the out of plane component of the so-called constraint tensor σ_{ij} plays an important role in the constraint effects due to the thickness.

2.5.5 Computation of J in 3D

The *J* integral is an alternative way to compute the point-wise value *J*. It is defined as the combination of a path integral and an area integral (Blackburn et al. 1977; Dodds 1987; Chiarelli and Frediani 1993; Huber et al. 1993). In order to characterize 3D elastic crack problems, it is customary to compute the point-wise value of *J* along a 3D crack front. This point-wise value is usually denoted as *J(s)*, where s is a parametric coordinate that defines the crack front position, as shown in figure. 2.3.

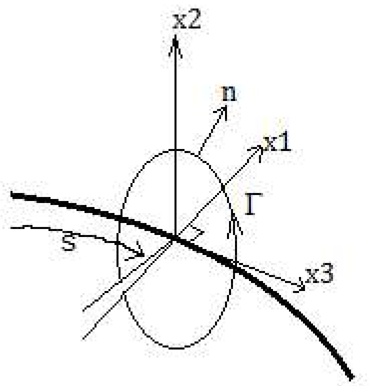


Fig. 2.3: local cartesian coordinate system at a point s of the crack front.

A local Cartesian coordinate system is conventionally defined as follows: the x2 axis is perpendicular to the plane tangential to the crack at s and the x1 and x3 axes lie in that tangential plane, being normal and tangent to the crack front, respectively. Many works regarding the computation of *J* can be found in the literature and we do not intend to make a thorough review of them (Omer and Yosibash 2005). For the sake of completeness, we introduce below the definitions and nomenclature that will be used in the rest of the study. (Carpenter et al. 1986) had given the expression for the *J* integral of local crack extension for 3D geometries.

2.5.6 Extension of J Integral in magneto-thermo-elastic field

A path independent integral is presented by (Kishimoto et al. 1980a) as the rate of energy flux during crack extension. This integral is an extension of the J-integral proposed by Rice and includes the existence of a fracture process region and the effect of plastic deformations, body forces, thermal strains and inertial of material. A formula is derived for determining the SIF from the path independent *J* integral by taking the effect of inertia into account (Kishimoto et al. 1980b). The development of magneto-thermo-elastic field is also one of the objectives of the present work in straight crack and curved crack geometry.

2.5.7 Some Fracture Studies Related to Nuclear Grade Graphite

Nuclear grade Graphite used in a Very High Temperature Reactors may fracture in working condition. Measurement of the fracture properties of graphite is therefore essential in the design and structural integrity assessment of reactor cores. The various studies are performed to evaluate the fracture toughness and energy release rate by various methods. Crack growth in nuclear graphite using R-curve analysis is studied by (Ouagne et al. 2002). The moderator core bricks are subject to neutron irradiation and radiolytic oxidation, which induce dimensional changes internal stresses and reduce strength, respectively. The R curve for AGR moderator graphite has been determined using two independent methods. Both methods show similar results which differ from other carbon materials in that a relatively high resistance to crack initiation is observed followed by a slightly decreasing crack propagation and crack termination.

Double Torsion (DT) is a powerful testing technique is used to evaluate the fracture parameters of brittle materials. (Becker et al. 2011a) presented a critical review of the DT technique, followed by proposed corrections through an experimental analysis using the proposed corrections, a Finite Element model of the geometry and the use of Digital Image Correlation to measure out-of-plane surface deformations. Reliable and accurate data can be achieved with a DT testing configuration using an optimum specimen. The crack initiation and propagation characteristics of two medium grained polygranular graphites, nuclear block graphite (NBG10) and Gilsocarbon (GCMB grade) graphite, have been studied using the Double Torsion (DT) technique by (Becker et al. 2011b). The DT technique allows stable crack propagation and easy crack tip observation of such brittle materials. The R-curve behavior was measured to determine the critical J-integral for crack propagation in both graphites and crack bridging and distributed micro-cracks are responsible for the increase in fracture resistance. The linear elastic fracture mechanics (LEFM) methodology of the DT technique was adapted for elastic–plastic fracture mechanics (EPFM) in conjunction with a methodology for directly calculating the J-integral. Further, the combined experimental-numerical technique for the calculation of the J-integral as an area integral in cracked specimens is presented by (Becker et al. 2012). The technique is based on full-field measurement using digital image correlation (DIC) and the

finite element method. The fracture behaviour of a short-bar chevron notch crack propagation specimen fabricated from polygranular nuclear graphite by (Mostafavi et al. 2013b). Also a three-dimensional linear elastic finite element simulation of the specimen obtained the relations between crack length, opening displacement and stress intensity factor along the crack front. In the next analysis, the fracture behaviour of polygranular graphite crack propagation in a short bar chevron notched specimen was studied by synchrotron X-ray computed tomography combined with digital volume correlation by (Mostafavi et al. 2013a). Furthermore, a very high-resolution post-test examination of the same sample by Serial Block Face Scanning Electron Microscopy (SBFSEM) provided three-dimensional fractographs to investigate the influence of microstructural features on the measured crack propagation rates (Marrow et al. 2014). The dimensional and physical property change data for irradiated nuclear grade graphite (PCEA) at 900 ◦C to support the design of graphite creep capsule and further evaluated the fracture toughness data on irradiated graphite by (Burchell and Strizak 2014).
The comparison of fracture toughness (KIC) and strain energy release rate (G) for different grades of nuclear graphite using ASTM D 7779-11 is performed by (Chi 2016).

2.6 Objectives of the Thesis

Though graphite is the most sought after material for nuclear reactor application as found in state-of the art literature and proposed NGNR vision documents, its strength characteristics are remarkable to fathom for large scale appreciation. It is imperative to state that the catastrophic accidents leading to irreparable damage to human life, society, greenery and its prolonged after effects has to be at least minimized although nuclear energy might seem to be the best alternative to compensate ever increasing demand for electricity of the urbanization. The inherent flaws and defects found in graphite castings and slabs influence the strength and structural integrity of graphite components and structures. It is well conceived that those defect distribution and orientation are random to map into any existing established strength postulations. From the literature survey it is concluded that in most of the cases, failure of such components occur due to defects or flaws much before the characterized strength. Basically, the types of defects that cause mechanical failure of graphite like ceramic materials can be divided into three broad categories namely processing defect, machining defect and handling defect. Most of the analyses so far in this direction are failure characterization with simplified unimodular assumptions, which lacks explaining the bimodular behavior in such material under any general state of flexural loading conditions.

Ascribed to the published works in literature, it is also observed that systematic studies on the subject of characteristic tensile, compressive and flexural strength, size effect, fracture behavior of nuclear grade graphite consider unimodular material properties as a classical simplification. The reality being bimodularity should not necessarily be avoided for the safety and reliability of high risk components. How much difference it might cause to the existing design principles though debatable in the context of analytical, experimental and numerical complications, it dwarfs when we consider the danger it might possess. When bimodular behaviour of material is considered, the state of stress in a loaded member also is modified. Bimodular fracture mechanics models need to be developed for studying the crack growth behaviour in such components. This might necessitate three dimensional analyses to quantify crack propagation leading to fracture. Therefore, with a belief that even a miniature effort from the researchers might enhance the safety of the society has been the prime motivation to study the influence of bimodularity on fracture characteristics of graphite components. The investigation carried out in the present thesis can be suitably divided into three groups.

1. Analytical expressions have been derived to size scale strength from laboratory models to real components or prototypes.

2. Tension, compression, flexure and fracture experimentations have been conducted to quantify bimodularity, strength and fracture characteristics and also for the development of Weibull model.

3. Numerical simulations for specific cases have been carried out and compared with published results.

ASTM experimentation for standard geometry of specimens have been conducted for manufactured graphite (with and without gravity orientations) for understanding the material behaviour. Weibull model has been developed for estimating the Weibull shape and scale parameter considering bimodular effect. Strain energy release rate (SERR) procedures based on the concepts of linear elastic fracture mechanics are employed to assess the severity of crack progression due to mechanical loadings.

The present study endeavors to investigate the bimodular effects on the strength and fracture behavior of nuclear grade graphite under various kinds of loadings using fracture mechanics approach in the light of Weibull weakest link theory.

Some of the major aims and procedures of this research work has been delineated as follows.

- Formulation of Weibull effective volume and surface area for beam of rectangular, square and cylindrical cross section possessing bimodularity for size effect analysis.
- Estimation of shift in neutral axis and surface for bimodular cylindrical flexural beam and derivation of Weibull effective volume and effective surface area to characterizing strength controlling flaws in bimodular materials.
- Tensile and compressive tests for determination of the bimodular ratio for nuclear grade graphite. Evaluation of Weibull characteristics design strength from experimental failure strength data sets.
- Formulations of effective volume and effective area for C-ring specimen considering bimodularity. Estimation of Size Effect of nuclear grade graphite specimens. Characterization of Weibull modulus and the characteristic strength for nuclear grade graphite specimens.
- Analytical, Experimental and Numerical analogy of the effective volume and surface area for bimodular nuclear grade graphite specimens.
- Bimodular 2D J-integral and 3D J-integral derivations for SENB (Single edge notch bend) specimens. Critical Stress intensity factor and Critical strain energy release rate determination for graphite specimens. Comparison of unimodular and bimodular fracture parameters K_{Ic} and J_{Ic} and G_{Ic} and J_{Ic} value are the mean values which represent the properties of material. Analytical expressions for magneto elastic problems.