Contents

CERTIFICATE iii

ACKNOWLEDGEMENT vi

ABSTRACT viii

Contents **x**

List of Figures xvii

List of Tables xxx

Abbreviations xxxv

Nomenclature xxxvi

Preface v

Chapter 1 Introduction 1-23

1.1 Nuclear Grade Graphite 2

1.1.1 Allotropes of Carbon: Graphite, Diamond 3

1.2 Nuclear Energy and Reactor Safety 6

1.2.1 Next Generation Nuclear Reactor (NGNR) 7

1.2.2 Importance of Graphite for Reactor safety 10

1.3 Motivation 12

1.3.1: Probabilistic Fracture Mechanics: Weibull Weakest Link Model 16

1.3.2 Bimodularity: A Stress Dependent Elasticity Phenomena 18

1.4 Structure of the Thesis 20

Chapter 2 Literature Survey 24-46

2.1 Introduction....24

2.2 Size Dependent Stress Analysis....25

2.3 Bimodularity and Stress Dependent Elasticity....26

2.4 Stochastic Fracture Model....28

2.5 Fracture Characterization and 3D J integral....32

2.5.1 Linear Elastic Fracture Mechanics....33

2.5.2 Elastic Plastic Fracture Mechanics (EPFM)....35

2.5.3 Path Independent J integral.....39

2.5.5 Computation of J in 3D....40

2.5.6 Extension of J Integral in magneto-thermo-elastic field....41

2.5.7 Some Fracture Studies Related to Nuclear Grade Graphite....41

2.6 Objectives of the Thesis....43

Chapter 3 Theoretical Foundation and Experimentation 47-72

3.1 Introduction....47

3.2 Weakest Link Theory....47

3.3 Size Effect on Strength....52

3.4 Weibull effective volume and effective surface area....54

3.5 Numerical Evaluation of Effective Volume and Effective Surface Area....54

3.6 Finite Element Implementation of Bimodularity....57

3.7 Experimental Characterization of Bimodularity....63

3.7.1. Bimodularity Index from Tension Compression Data Set....69

3.8 Probabilistic Fracture Mechanics....72

Chapter 4 Weibull Weakest Link Theory Model for of Bimodular Rectangular Flexural Specimens 73-138

4.1 Introduction 73

4.2 Weibull Effective Volume and Surface Area for Bimodular Material 80

4.2.1 Effective Volume for Four-Point Flexural Beam with Bimodular Property 84

4.2.2 *Effective Volume for Beam Subjected to Uniform Bending with Bimodular Property* 85

4.2.3 Effective Surface Area for Four-Point Flexural Beam with Bimodular Property 87

4.2.4 Effective Surface Area for Beam Subjected to Uniform Bending with Bimodular Property 88

4.3 Strength Scaling 91

4.4. Weibull Analysis of Unimodular and Bimodular Flexural Graphite Specimens 94

4.4.1 Estimation of Weibull Parameters 104

4.5 Analytical and Numerical Evaluation of Unimodular and Bimodular Effective Volume 127

4.5.1 Finite Element Model of Bimodular Flexural Specimen 129

4.6. Conclusions 137

Chapter 5 Weibull Model for Bimodular Cylindrical Specimen 139-188

5.1 Introduction 139

5.2 Weibull Statistical Failure Analysis 142

5.3 Weibull Effective Volume and Surface Area for Bimodular

Material 145

5.3.1 Effective Volume for Four Point Flexural Beam with Bimodular property 153

5.3.2 *Effective Volume for Beam Subjected to Uniform Bending with Bimodular property* 157

5.3.3 Effective Surface Area for Four Point Flexural Beam with Bimodular Property 160

5.3.4 Effective Surface Area for Beam Subjected to Uniform Bending with Bimodular property 163

5.4 Strength Scaling 166

5.5 Experimental Validation 169

5.5.1 Evaluation of Weibull Parameters 172

5.6 Conclusions 187

Chapter 6 Effective Volume and Effective Surface of Bimodular C-ring Specimens 189-250

6.1 Introduction 189

6.2 Weibull Effective Volume and Effective Surface Area for Bimodular Specimen 192

6.3 Evaluation of Neutral Surface Shift 200

6.4 Evaluation of Weibull Effective Volume 205

6.5 Evaluation of Weibull Effective Surface 212

6.6 Experimental Validation 216

6.6.1 Evaluation of Weibull parameters 221

6.7. Conclusion 249

Chapter 7 Experimental and Computational Correlation of Fracture Parameters K_{Ic}, J_{Ic}, and G_{Ic} for Unimodular and Bimodular Nuclear Grade Graphite Components 251-306

7.1 Introduction....251

7.2 Experiments....259

7.2.1 Specimen Preparation....259

7.2.2 Three Point Single Edge Notch Bend (SENB) Test....260

7.2.3 Evaluation of Fracture Toughness and Strain Energy Release Rate....262

7.3 Results and Discussion....263

7.3.1. Bimodularity Ratio....264

7.3.2 Evaluation of K_{Ic} , G_{Ic} and J_{Ic}....265

7.3.3 Weibull Model of Fracture Experimentation....271

7.3.4. Formulation of Path Independent Bimodular J-Integral...279

7.3.5. Computational Analysis....296

7.4 Conclusions....303

Chapter 8 Stress Dependent Elasticity Problem of 3D J-integral with thickness effect in Bimodulus Material 307-334

8.1 Introduction....307

8.2 Computational Evaluation of Three-dimensional Bimodular Path Independent Integral....313

8.2.1 Element Description and Convergence Studies....317

8.3 Results and Discussion....320

8.5 Conclusions....332

Chapter 9 3D Path Independent Integral for Thermo-elastic and Magnetostriction Environment for Reactor Application 335-350

9.1 Introduction....335

9.2 Formulation of Path Independent Integral....337

9.3 Numerical Results....347

9.4 Conclusion....349

Chapter 10 3D Conservation Integral for Curved Crack for Thermo-magneto-elasticity for Reactor Applications 351-372

10.1 Introduction....351

10.2 Energy Balance....354

10.2.1 Energy Balance during Crack Extension....357

10.3 Various Integral Terms and Transformation....360

10.3.1 Transformation of the tensor components....361

10.3.2 Correction for Body Force....361

10.3.3 Transformation of the Integrals for Elastic Strain....*361*

10.3.4 Transformation of the Integrals for Plastic Strain....362

10.3.5 Correction for Thermal strain....362

10.3.6 Correction for Pre-strain....363

10.3.7 Correction for Magnetostriction....363

10. 3.8 Correction for Crack Curvature....363

10.3.9 Correction for Inertia....364

10.4 The Overall 2D Integral in form of Energy Release Rate.....364

10.5 Conversion of Integral Terms from Polar to Cartesian Form....366

10.5.1 Mechanical Energy Density Expression....366

10.5.2 The Integral Term Associated with Traction....367

10.5.3 The Conversion of Integral Term for Curved Curvature Correction 367

10.5. 4 The Conversion of Inertia Integral Term 368

10.5.5 The Conversion of Integral Associated with Body Forces 368

10.5.6 Thermal Strain Term Conversion 369

10.5.7 Initial Strain term conversion 369

10.5.8 Magnetic Strain Term Conversion 370

10.6 The Overall 3D Integral in form of Energy Release Rate 370

10.7 Conclusion 372

Chapter 11 Summary 373-377

11.1 General Conclusions 373

11.2 Future Scopes 377

References 378

Appendix I 390

List of Publications 394