Preface

Several spectacular failures in the early part of the twentieth century have triggered the need to look into the conventional failure theories and modes critically and this search for answers led to the birth of Fracture Mechanics. Ever since the work of Griffith in 1921, several researchers across the world have contributed immensely to the development of the field and fracture mechanics has matured into an established discipline now. Most universities with an engineering program offer a course in fracture mechanics at the graduate and senior undergraduate levels.

Fracture mechanics is a broad area covering several disciplines and it is a challenge to teach it with a balanced outlook of experimental information, mathematical derivations, numerical methodologies, and material behaviour. The usual audience for a first level course in fracture mechanics comes from several disciplines such as aerospace, civil, mechanical and materials/metallurgy backgrounds. To hold their attention and to carry them with the class requires a need to provide some basic information on stress analysis, material behaviour etc.

Although several textbooks are available on fracture mechanics, this is the first e-book on fracture mechanics. It has come about from teaching the course to graduate and undergraduate students for the last 15 years at IIT Kanpur and at IIT Madras. At Kanpur the course was taught conventionally using chalk and board but at IIT Madras the course has transformed into a multimedia course with critical inputs from at least five batches of students. The student response has greatly influenced the development of the course in many ways. The questionnaire used to get the student's response is enclosed in the CD.

As of now there is no one-way of developing an e-book. One finds in the web a set of .pdf slides or power point presentations available in the name of e-books. In some others, text is given as html pages and wherever animation is required, a link is provided to see it. The textual information given in such e-books are more formal and use of multimedia is used to show a few animations. In this e-book, a novel attempt is made to mimic the classroom environment of developing the concepts through a series of careful steps. Text and animations are juxtaposed on a single screen for convenient learning. The textual matter is in the form of points and in many cases it synchronizes with the diagram or animation. This form of presentation is hoped to provide a semblance of classroom teaching while viewing it on one's PC. The mathematical derivations are developed such that the slides pause at predefined steps allowing the learner to think and answer or help the teacher to make the class participate while using the e-book for teaching. One of the important aspects of a classroom teaching is to introduce intentional errors on

mathematical derivations so that the alertness of the class is tested and it also helps to learn the subject matter thoroughly. This feature is also tried in a few slides in this e-book – the mathematical derivation has intentional error, which is corrected later for the learner's convenience.

The animations are designed to impart an understanding of the concepts. The famous dictum that a figure is worth a thousand words is extended in this e-book to a carefully designed animation replaces several pages of explanation in a conventional book! Thus, while using the e-book the user has to participate in the learning process. It is suggested that the learner sits with a pen and paper and view the e-book on his/her computer to learn the course.

Voice is intentionally not recorded, so that any one can provide additional explanations based on the material provided. Thus, the e-book can be used by teachers to deliver their lectures. If a teacher uses the e-book, a recommendation on what can constitute a lecture hour is provided as a separate file. This may be used as a guideline to prepare his/her lecture. A self-learner can also use these guidelines to phase his/her learning from the CD. Apart from the mandatory clicks, most slides have a pause option to stop/interrupt the animation. This feature could be used by the teacher to give additional information on the subject matter than what is given in the book or use this option for innovatively involving the class in the learning process. Although, voice is not recorded, sound is provided at places where it is required – look for a click sound in the animation on pop-in behavior.

The e-book has fourteen chapters. In each chapter, the contents page has an animation, which indicates the learning goals for that chapter. Being an experimentalist, a conscious effort has been made to provide experimental justification for the many concepts presented in the e-book. Each concept of the subject matter is labeled as a slide heading. A detailed course content indicating all the slide headings are included in the e-book for easy reference. The slide headings in the detailed course content are searchable and one can search the full course. This feature helps to use the e-book as a reference source for an experienced practitioner. The first time users of this e-book are advised to go through the section on 'First time users' to understand the usage of various buttons and also learn how to navigate through the course. A link for troubleshooting is also provided to answer any problems the user may face while using this e-book.

The first chapter provides an overview of fracture mechanics. Several spectacular failures that triggered the birth of fracture mechanics are discussed. The various conventional failure modes are reviewed and how these are inadequate is highlighted. What is fracture mechanics and what questions one need to answer and what tests that are

additionally needed to answer these questions are presented. Classifications of modes of loading, examples of failure initiated by a crack(s) etc. are discussed. Photoelastic visualization of crack-tip stress fields is then presented. A brief overview on the application of photoelastic techniques to address interfacial fracture and crack-tip stress fields in fibre composites is presented. The chapter ends with a list of text and reference books for further study. Chapter 2 deals with crack growth and fracture mechanisms. The various crack growth mechanisms such as fatigue, stress corrosion, hydrogen embrittlement, liquid metal embrittlement, creep and corrosion fatigue are discussed. Brittle fracture and ductile rupture mechanisms are then discussed.

The basic concepts of fracture can be easily understood through energy approach and the third chapter deals with energy release rate. The chapter starts with basic information on what is strain energy and how this can be calculated for various types of loadings. The criterion of fracture initiated by Griffith is discussed in detail with supportive experimental results. Evaluation of energy release rate from strain energy, compliance method and potential energy are presented. The extension of fracture mechanics to ductile solids by Irwin and Orowan is then discussed. Interrelationship between stress intensity factor and energy release rate are derived. The chapter also discusses what causes crack branching and presents a simplified model.

Chapter 4 deals with an overview on mechanics of solids. It gives information on what is strength of materials and how theory of elasticity is different. Forms of Airy's stress functions in Cartesian and polar co-ordinates are presented. Stress field equations for a plate with a circular hole are derived using the principle of superposition. How the study of an elliptical hole in a plate has indicated the severity of a crack is brought out in this chapter.

Chapter 5 deals with the development of stress and displacement field equations for very near-tip, near-tip cases for various modes of loading existing at the crack-tip. Stress field equations are obtained using both Westergaard stress functions and William's eigen functions. The chapter also presents a mathematical definition of stress intensity factor (SIF). In many first level courses, one stops at singular stress field equations. This chapter goes a step further in systematically introducing the genesis of multi-parameter stress field equations. The technique of photoelasticity has greatly influenced the development of the stress field equations in fracture mechanics. The necessary background to know what photoelastic fringes are and how their geometrical features have influenced the need to look and arrive at multi-parameter stress field equations is presented in a lucid manner in this chapter.

Analytical methods for evaluating the SIF for various simple geometries and loading conditions are presented in Chapter 6. Use of Green's functions and the principle of superposition in evaluating the SIF are discussed. The relative assessment on the severity of through, edge and surface cracks are highlighted.

Chapter 7 deals with the SIF evaluation by experimental and numerical methods. Experimental evaluation of SIF by photoelasticity, method of caustics, holography, moiré and strain gauges are presented with sufficient background information. The influence of the sign of the second term in the series solution viz., σ_{ox} for photoelasticians and T – stress for the numerical analysts is also presented. The advantage of caustics to evaluate J-integral in a simple manner is highlighted. Use of strain gauge type sensors to detect the presence of a crack at pre-defined locations and the method to estimate its speed is discussed. Among the various numerical methods, the use of finite elements for solving fracture mechanics problems is presented. The focus of this section is to provide information on well developed and time-tested methodologies to get fracture parameters using FEM. Information on quarter point elements (QPE) and how do they represent crack-tip singularity in elastic and plastic fields are presented. Recommendations on the design of the mesh pattern, choice on the size of QPE are also discussed. SIF evaluation methods such as quarter point displacement, displacement extrapolation, virtual crack extension, virtual crack closure integral and J-integral are discussed. Comparison of FEM results with photoelasticity for a single edge notched specimen has also been done in this chapter. The chapter is kept intentionally exhaustive and in a first level course one may not have time to do everything in this chapter but one may choose only a relevant portion depending on the nature of the class and particular flavor of the teacher.

Chapter 8 deals with the modeling of plastic deformation at the crack-tip. Various methods to evaluate the size and shape of the plastic zone for various loading conditions are presented. Variations of plastic zone across the specimen thickness and along the failure direction are discussed with suitable animations and supportive experimental information. Plane strain fracture toughness testing evaluation is presented in detail in Chapter 9. The role of Chevron notch in controlling the fatigue crack growth is illustrated. Pop-in behavior exhibited by intermediate thickness plates is illustrated with a nice animation, which also mimics the click sound when the crack jumps in a thumb nail fashion. Brief introduction to plane stress fracture toughness testing and Feddersen's approach for getting residual strength diagrams for thin panels is then discussed.

Crack initiation and life estimation is presented in Chapter 10. Simplicity of Paris's law and various zones of the sigmoidal curve are presented in sufficient detail. Supportive information such as striations and beachmarks are provided as links. The phenomenon of crack closure and how this is handled by designers while using Paris law

is presented. The role of stress ratio, overload and environment on modifying the sigmoidal curve and issues related to crack initiation are presented briefly. Recent experimental information relating to modification of surface texture due to fatigue loading is also presented. The chapter ends with a discussion on damage tolerance approach to design. Various crack arrest methodologies such as use of a patch or drilling of holes at the crack tip are presented in Chapter 11. Supportive experimental information from photoelasticity is presented. Repair technologies such as the use of a novel concept of self healing composite and metal stitching for repairing castings are also presented in this chapter.

Brief overview of *J*-integral is presented in Chapter 12. Graphical interpretation of *J*-integral, experimental evaluation of *J*-integral by a single specimen approach is presented. Introduction to HRR field and use of *J* as a stress intensity parameter are then discussed. The modern approach of two-parameter characterization of the plastic stress field by *J*-Q approach is indicated. Chapter 13 deals with the conditions under which fracture may occur in the presence of combined modes of loading at the crack tip. It also presents the methods to estimate the direction of crack propagation. Chapter 14 gives a set of thirteen assignment sheets covering the various concepts of fracture mechanics. I will be grateful if the readers bring to my attention any errors and omissions. Suggestions for improving the animation sequence are also welcome.

To completely cover the material provided, one would require a minimum of sixty hours. An experimentalist teaching the course may want to dwell more on experimental aspects of fracture. On the other hand, a numerical person may want to say more on numerical evaluation of fracture parameters. If the students do not have a background on Mechanics of Solids, one may have to spend some time on reviewing these concepts. Keeping these issues in mind, sufficient background information is included in the course on stress analysis, experimental and numerical methods. Thus, depending on the nature of the class / teacher one can choose to emphasis relevant aspects and the e-book as available now is comfortable for a 42 hr first level course on Fracture Mechanics.

If the users welcome this concept of the e-book, it is proposed to include advanced topics such as elasto-plastic fracture, dynamic fracture, fracture of composites etc. in future editions.

Many good books already available on fracture mechanics have directly or indirectly influenced the subject matter presented in this e-book. My sincere thanks to all those authors. All the photoelastic fringe patterns appear in the e-book are specially commissioned to give a visual experience to the reader and are done at the Digital Photomechanics Laboratory, IIT Madras. To emphasis the emergence of fracture

mechanics, photographs of spectacular failures are presented and my thanks are to the Royal Air force Museum, London, Project Liberty Ship S. S. Brown and Boston Public Library for having permitted me to use the material available in their websites. Apart from this, many actual failures of components and experimental results from various sources are included in this book. My thanks are to the authors and copyright holders for permitting me to use such information in this book and wherever such materials appear a courtesy statement acknowledges their contribution. Every effort has been made to get copyright permission for the material used from other sources in this book. However, if inadvertently any mistake has been made kindly bring it to the attention of the author for suitable modification/correction.

This e-book is innovative in many ways. I have been allowed to experiment on various models before zeroing in on to the current one. All this has been possible through the innovative ambience provided by Prof. M. S. Ananth, Director IIT Madras and Prof. K. Mangala Sunder, who has shaped up a nice Web studio single handedly! I do hope that this e-book sets a new paradigm in the development of multimedia based educational material.

This e-book would not have been possible without the active support of my project associates Mr. Mathews Oommen, Mr. Ramji, Ms. Lisha and Mr. K. Srinivasan and my students Mr. M. Ravichandran, Mr. K. R. Madhu, Mr. R. Rajaguruprasad, Mr. P. R. D. Karthick Babu, Mr. R. Senthil Gurunathan and Mr. R. Manivasagam. My thanks are due to them. My thanks are also due to the five batches of students from various branches of Engineering at IIT Madras for their inputs at various stages of development of this e-book. I am thankful to Prof. S. Santhakumar, Dean, Academic Courses and Prof. K. Ramamurthy, Chairman, Centre for Continuing Education for having taken special steps to publish this book under the “Multimedia Book Series” of IIT Madras. My thanks are also due to the reviewers of the e-book viz., Prof. B. Dattaguru, Emeritus Professor, Department of Aerospace Engineering IISc Bangalore, Prof. Yogendra Simha, Department of Mechanical Engineering, IISc Bangalore and Prof. Prashant Kumar, Department of Mechanical Engineering, IIT Kanpur for their helpful comments to make the e-book more valuable to the users. Last but not the least my thanks are to my family for their understanding and support.

I dedicate this book to my father Sri. M. Krishnamurthi who was a teacher and a keen learner all his life.

Chennai K. Ramesh
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