Engineering Fracture Mechanics

By

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1. Course Outline The course covers the basic aspects of Engineering Fracture Mechanics. Spectacular failures that triggered the birth of fracture mechanics, Modes of loading, Classification as LEFM and EPFM, Crack growth and fracture mechanisms, Energy release rate, Resistance, Griffith Theory of fracture, Extension of Griffith Theory by Irwin and Orowan, R-Curve, Pop-in phenomena, Crack branching. Necessary and sufficient conditions for fracture, Stress and Displacement fields in the very near and near-tip fields, Westergaard, Williams and Generalised Westergaard solutions, Influence of the *T*-stress and higher order terms, Role of photoelasticity on the development of stress field equations in fracture mechanics, Equivalence between SIF and *G*, Various methods for evaluating Stress Intensity Factors, Modeling plastic zone at the crack-tip, Irwin and Dugdale models, Fracture toughness testing, Fedderson's residual strength diagram, Paris law, *J*-integral, HRR field, Mixed-mode fracture, Crack arrest methodologies

Prerequisite Strength of Materials, Theory of Elasticity (Desirable).

Text/References

1. K. Ramesh, e-Book on Engineering Fracture Mechanics, IIT Madras, 2007. URL: http://apm.iitm.ac.in/smlab/kramesh/book_4.htm
2. Prashant Kumar, Elements of Fracture Mechanics, Tata McGraw Hill, New Delhi, India, 2009.
3. K. R.Y. Simha, Fracture Mechanics for Modern Engineering Design, Universities Press (India) Limited, 2001
4. D. Broek, Elementary Engineering Fracture Mechanics, Kluwer Academic Publishers, Dordrecht, 1986.
5. T.L. Anderson, Fracture Mechanics – Fundamentals and Applications, 3rd Edition, Taylor and Francis Group, 2005.

Suggested Additional Reading

Articles from the journals: Engineering Fracture Mechanics, International Journal of Fracture, Experimental Mechanics, Journal of Mechanics and Physics of Solids, Journal of Applied Mechanics, Strain, Journal of Strain Analysis for Engineering Analysis and Design, Engineering Failure Analysis etc.

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Course Organisation

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Module – 1. Overview of Engineering Fracture Mechanics

Lecture	Concepts Covered
1 EFM Course Outline	List of chapters and the concepts that would be covered in the course. Review of tension test, bending and torsion. Method of handling combined stresses, principal stresses. Definition of failure, yield criteria, buckling as a failure mode. Need for fatigue test and focus on what data being collected.
2 Spectacular Failures	Further details on Fatigue test, Review on conventional design methodologies. List of spectacular failures. Discussion on Boston molasses failure, Liberty ship failure, Ductile-brittle transition temperature and its relevance.
3 Lessons from Spectacular Failures	Comet disaster, Aloha Airline failure. Lessons from spectacular failures. Fracture – Bane or boon? Common applications of fracture/fracture prevention, Brief introduction to photoelasticity, Photoelastic appreciation of severity of a crack.
4 LEFM and EPFM	Historical development, Contributions of Inglis, Griffith and Irwin. Extremum cases of an elliptical hole, Various results of fracture in glass, Classification of LEFM and EPFM – based on plastic deformation, materials and applications. Modes of Loading – Mode-I, Mode-II and Mode-III.

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5 Fracture Mechanics is Holistic	New test for fracture mechanics, Crack-growth curves, Residual strength diagram, Summary of fracture parameters. Practical examples of fracture, Typical photoelastic fringes for Mode-I, Mode-II and Mixed mode loadings.
6 Fatigue Crack Growth Model	Geometric features of photoelastic fringes observed near the crack-tip. Multiple radial cracks in annular plates – its engineering relevance. Books and references. Crack growth and fracture mechanisms. Shear-lip in necking. Fatigue crack growth model. Striations and Beachmarks.
7 Crack Growth and Fracture Mechanisms	Clarifications on fatigue crack growth model. Stress corrosion cracking (SCC) – Active path dissolution, Hydrogen embrittlement, Film induced cleavage. Creep, Corrosion fatigue, Liquid metal embrittlement. Fracture mechanisms – Brittle fracture, Ductile fracture.

Module – 2. Energy Release Rate

Lecture	Concepts Covered
8 Elastic Strain Energy	Surface energy, Elastic strain energy stored in terms of stress components, in terms of axial, torsion and bending loads for slender members. Strain energy change in the presence of a crack under constant loading and constant displacement.
9 Fracture Strength by Griffith	Strain energy in the presence of a crack by relaxation analogy, Fracture strength, Validation of Griffith's approach, Estimation of Theoretical strength based on lattice properties, Size effect, Crack-size effect.
10 Energy Release Rate	Definition of energy release rate (G) and Resistance (R), G as a function of Potential energy by energy balance. Expression of G in terms of compliance, Design of constant G specimen, Evaluation of G for two examples.
11 Utility of Energy Release Rate	Difficulties in Griffith's theory, Necessary and sufficient conditions for fracture, Crack branching in brittle materials, Irwin and Orowan extension of Griffth's theory to ductile solids, R-curve in plane strain and plane stress. Specimen specification for class experiment.
12 Pop-in Phenomenon	Need for energy release rate being non-linear, Pop-in phenomenon, Class experiment demonstrating the influence of crack configuration on fracture behavior, Review of Strength of Materials, Deformation of a plane section due to constant shear in a beam, Definition of a *free surface* and its utility.

Module – 3. Review of Theory of Elasticity

13 Displacement and Stress Formulations	Simply connected and multiply connected domains, Displacement and stress formulations, Compatibility conditions, Plane stress and plane strain situations, Airy's stress function, Semi-inverse method, Forms of stress functions in Cartesian co-ordinates.
14 Forms of Stress Functions	Solution to the problem of a beam under uniformly distributed loading, Forms of stress function in polar co-ordinates, List of problems that could be solved, Illustration of principle of superposition, Analytic functions.

Module – 4. Crack-tip Stress and Displacement Field Equations

15 Airy's Stress Function for Mode-I	Cauchy-Riemann conditions, Airy's stress function for Mode-I, Satisfaction of bi-harmonic equation, Boundary conditions.
16 Westergaard Solution of Stress Field for Mode-I	Westergaard stress function for Mode-I, Origin shifting, Very-near tip stress field, Definition of SIF, Comparison of photoelastic fringes with Westergaard solution, Irwin's modification of Westergaard's solution, T-stress, Work of Tada, Paris and Irwin.
17 Displacement Field for Mode-I	Review of Westergaard and modified Westergaard stress field equations, Stress field near a blunted crack-tip by Creager and Paris, Displacement field in plane stress and plane strain in the form of stress functions as well as in terms of polar co-ordinates, Definition of COD.
18 Relation between K_{I} and G_{I}	Evaluation of COD from displacement field referred with crack centre as origin, Crack opens like an ellipse, Evaluation of G from displacement of crack faces, Interrelationship between K_{I} and G_{I} by closing an incremental crack extension.
19 Stress Field in Mode-II	Westergaard solution for near-tip stress field in Mode-II, Photoelastic fringes in Mode-II, Comparison of fringes plotted from Westergaard's solution, Discussion on influence of T-stress on fringe patterns in Mode-I, Mixed Mode (Mode-I+ Mode-II), Displacement formulation for Mode-III.
20 Generalised Westergaard Approach	Stress and displacement field in Mode-III, Need for improvement to Westergaard solution for Mode-I, Kolosov-Muskhelishvili approach, Forms of stress functions in complex potentials, Comprehensive Airy's stress function for Mode-I, Generalised Westergaard equations.
21 William's Eigen Function Approach	Generalised Westergaard equations, Forms of Z and Y, Series stress field, Variation of maximum shear along crack axis, William's eigen function approach, Boundary conditions, Characteristic equation, Discussion on admissible roots.

22 [Multi-parameter Stress Field Equations]	Stress function ϕ as a series solution, William's singular solution and six term series solution of stress field, Airy's stress function for Generalised Westergaard Mode-II situation, Series solution of stress field by Atluri and Kobayashi, Photoelastic and holographic fringe patterns for Mode-I.
23 [Validation of Multi-parameter Field Equations]	Multi-parameter stress field equations, Equivalence of them, Photoelastic and holographic fringe patterns for Mode-I and combination of Mode-I and Mode-II, Multi-parameter displacement field equations, Multi-parameter displacement fringe field, Evaluation of SIF for various geometries.

Module – 5. Discussion Session – I

24 [Discussion Session-I]	A few questions from the course raised by the students were answered. The list of questions is available as a .pdf file from the Downloadable section.

Module – 6. SIF's, Modeling of Plastic Zone, Fracture Toughness Testing

Lecture	Concepts Covered
25 [Evaluation of SIF for Various Geometries]	Evaluation of SIF from stress functions using the mathematical definition: Crack faces loaded with concentrated load, Symmetric load and asymmetric load, SIF for collinear cracks evenly spaced, SIF for finite strips.
26 [SIF for Embedded Cracks]	Verification of class experiment on multiple cracks, SIF by method of superposition, SIF for embedded circular flaw, SIF for embedded elliptical flaw, Parametric representation, Extension of the result to non-elliptical embedded flaws, Modeling of surface flaws.
27 [SIF for Surface Cracks]	Idealisation of surface cracks, Irwin's approach for SIF of a surface crack, Leak before break – possibility, Plastic zone correction, Flaw shape parameter, Front-free surface correction, SIF for corner cracks, Direct analysis of surface cracks, Empirical relations of Newman and Raju.
28 [Modeling of Plastic Deformation]	Empirical relations of Newman and Raju – continued, Triaxiality at the crack-tip – pictorial explanation, Selection of fracture toughness for various types of cracks, Insights of SIF for various cracks, Principal stresses at the crack-tip, Triaxiality – mathematical definition, Simplistic model to get plastic zone length and shape for Mode-I using Tresca and von Mises yield criteria.
29 [Irwin's Model]	Approximate plastic zone shapes in plane strain and plane stress for Mode-I and Mode-II loadings, plastic zone shape in Mode-III, Accounting for redistribution of load, Irwin's model, Plastic zone length in plane stress and plane strain, Small scale yielding approximations, Motivation of Dugdale model.

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30 Dugdale Model	Dugdale model, Experimental result of Hahn and Rosenfield, Plastic zone lengths and correction to crack lengths – summary, Plasticity corrected SIF, Variation of plastic zone shape over the thickness of the specimen, Slip planes in plane strain and plane stress, Transition of plane strain to plane stress along the length of the specimen.
31 Fracture Toughness Testing	Variation of plastic zone over the thickness, Slip planes in plane strain and plane stress, Experimental evidence, Minimum thickness for fracture toughness specimen based on plastic zone, Fracture testing – early attempts, Fracture toughness as a function of specimen thickness, Requirements of the test, Candidate fracture toughness, Compact tension and three point bend specimens, Chevron notch – visualization exercise.
32 Plane Strain Fracture Toughness Testing	Specimens for the test, Constraints on specimen dimensions, Chevron notch, Fatigue pre-cracking restrictions, Experimental procedure, Measurement of load, Measurement and acceptance criteria of crack length, Selection of specimen from stock, Some important standards and practices: E399-06, B 645-07, E 1820-99, and E 1823-96.
33 Plane Stress Fracture Toughness Testing	Material anisotropy in fracture toughness testing, Fracture toughness values for selected materials, Plane stress fracture toughness testing, Anti-buckling guide, Influence of panel width, Stable fracture followed by catastrophic fracture, Residual strength diagram, Apparent toughness, Feddersen's approach, Experimental validation, Conventional fatigue test, Questions to be answered in fracture mechanics.

Module – 7. Crack Initiation and Life Estimation

Lecture	Concepts Covered
34 Paris Law and Sigmoidal Curve	Lacuna of fatigue test, Crack growth curve, Paris law, Validation of Paris law, Threshold stress intensity factor, Definition of stress ratio, Sigmoidal curve: Region I, Region II and Region III, Donahue Law, Forman Law, Complete Sigmoidal curve, Mean stress influence and environmental effects on crack growth rate.
35 Crack Closure	Review of Paris law, Crack closure: Designer's approach, Empirical relations of ΔK_{eff}, Current focus. Residual stress ahead of a crack in a cycle, Plasticity induced crack closure, Plastic wake, Different crack closure types: Phase deformation induced, Oxide induced, Roughness induced. Influence of overload on crack growth.
36 Crack Growth Models	Residual stress in a cycle, Influence of overload on crack growth, Wheeler's model, Issues on fatigue crack growth calculations, NASGRO, AFGROW, Summary of empirical fatigue crack growth models, Crack initiation, Intrusion and extrusion, Evidence of slip bands.

Module – 8. Advanced Topics

37 *J*-Integral	Eshelby's line integrals, *J*-integral, Path independence of *J*-integral, Analytical evaluation of *J*-integral for the DCB specimen, Graphical interpretation of *J*, Importance of strain history in elasto-plastic analysis, Extension of NLEFM to EPFM, Proportional loading.
38 HRR Field and CTOD	Review of elasto-plastic material behaviour, *J* as stress intensity parameter, Cherepanov-HRR field, *J*-Q approach, Limitation of HRR field, Work of Begley and Landes, Application areas of EPFM, CTOD: Definition, Estimation of CTOD from: Irwin's result; Dugdale's work, *J* and CTOD, Interrelationship between fracture parameters.
39 FAD and Mixed Mode Fracture	Relationship between *J* and CTOD, COD design curve, Failure Assessment Diagram (FAD): Motivation, Historical development, FAD curve definition, Definition of K_r and L_r. Mixed mode fracture: Self-similar crack growth, Crack growth direction in Mode II, Criteria based on energy release rate, Maximum tangential stress criterion, Calculation of crack growth angle, Condition for fracture instability.
40 Crack Arrest and Repair Methodologies	Mixed-mode fracture continued, Strain energy density criterion, Comparison of crack growth and critical value of K_{II} by MTS and SED, Experimental work of Wu, Empirical relations in mixed-mode fracture, Crack arrest principle, Use of patches, Photoelastic demonstration of usefulness of a patch, Hole drilling to delay crack re-initiation, Self healing polymers, Metallic stitching.

Module – 9. Discussion Session – II

41 Discussion Session – II	A few questions raised by the students from the whole course were discussed. The list of questions is available as a .pdf file from the Downloadable section.

Please Note The naming of each lecture indicates only the major thrust in that lecture.

Guideline to use the Lectures:

Please note that these are lectures given in a regular class in which students were taking notes. They are not seminars – where you try to get the basic idea and one just listens to them may be take down some short notes. The listeners are advised to take down their own notes from the lectures. If necessary use the pause option. The media player also allows one to either increase the speed or decrease the speed of content delivery as well. Use these features effectively to get the maximum benefit from the lectures.

About the Author: **K. Ramesh** is currently a Professor at the Department of Applied Mechanics, IIT Madras; as it's Chairman during (2005-2009) and formerly a Professor at the Department of Mechanical Engineering, IIT Kanpur. He received his undergraduate degree from the Regional Engineering College, Trichy (now NIT, Trichy), Postgraduate degree from the Indian Institute of Science, Bangalore and the Doctoral Degree from the Indian Institute of Technology Madras. He has made significant contributions to the advancement of *Digital Photoelasticity*. This has resulted in a Monograph on *Digital Photoelasticity- advanced Techniques and Applications,* Springer and a chapter on *Photoelasticity* in the *Springer Handbook of Experimental Solid Mechanics.* Organizations such as ARDB, ISRO, DST, and NSF have funded his research. He has pioneered a new paradigm in Engineering Education by writing innovative e-Books on *Engineering Fracture Mechanics* and *Experimental Stress Analysis* published by IIT Madras. These books are first of their kind in the world and can be truly called as e-Teachers. He has over 120 publications to date of which two have been reproduced in the *Milestone Series* of SPIE, co-authored a book on *Mechanical Sciences*, Narosa Publishing House, India and has contributed a chapter on *Experimental Stress Analysis – An Overview*, in the book on *Optical Methods for Solid Mechanics*, Wiley-VCH Verlag. He has also given Video lectures of 40 hrs. each on *Experimental Stress Analysis* and *Engineering Fracture Mechanics* as part of the National Program for Technology Enhanced Learning (NPTEL), India. He has received several recognitions: Zandman Award of Society for Experimental Mechanics (SEM), U.S.A (2012), Distinguished Alumnus Award of NIT, Trichy (2008), Fellow of the Indian National Academy of Engineering (2006), President of India Cash Prize (1984). Member of the Editorial Boards of the International Journals: Strain (since 2001), Journal of Strain Analysis for Engineering Design (2009-10), Optics and Lasers in Engineering, and Steering committee member of ASEM.

For details see : http://apm.iitm.ac.in/smlab/kramesh/index.html