EXPERIMENTAL STRESS ANALYSIS

Chapter 1: Overview of Mechanics of Solids

Slide No

1. Strength of Materials	1
2. Theory of Elasticity	3
3. Governing Equations for Three-dimensional Elasticity Problem	5 5 7
3.1 Displacement formulation	5
3.2 Compatibility conditions	7
3.3 Stress formulation	10
4. Solution to Plane Elastic Problems	12
4.1 Plane stress	13
4.2 Plane strain	14
5. Stress Formulation in Solving Plane Elasticity Problems	15
5.1 Airy's stress function	17
5.2 Inverse approach	19
6. Forms of phi in Cartesian Co-ordinates	20
7. Beam Under Uniformly Distributed Load	21
7.1 Boundary conditions	22
7.2 Stress field	23
7.3 Variation of stress components over the depth of the beam	24
8. Bi-harmonic Equation in Polar Co-ordinates	25
9. Forms of Stress Function in Polar Co-ordinates	26
10. Stress Concentration at a Circular Hole in a Tension Field	29
10.1 Simplification of the given problem	30
11. Principle of Superposition	32
11.1 Problem I	33
11.1.1 Boundary conditions	34
11.1.2 Solution	35
11.2 Problem II	36
11.2.1 Boundary conditions	37
11.2.2 Solution	38
12. Closed Form Stress Field for the Problem of a Large Plate in	
Uniaxial Tension with a Small Circular Hole	39
12.1 Variation of normal stress along the boundary of the hole	40
12.2 Variation of normal stress across the plate in a section	
containing the hole	41
13. Stress Field in a Plate with an Elliptical Hole	42
13.1 Elliptic co-ordinates	43
13.2 Expression for circumferential stress components	44
13.3 Variation of normal stress components across the plate	45
13.4 Normal stress as a function of the radius of curvature	46
14. Extremum Cases of the Elliptical Hole	47

The contents list shows the slide numbers chapter wise. When the content is in blue font, it indicates that a link is attached to this. The contents of the links are given at the end. The whole book is searchable with the contents mentioned in this list.

1. Introduction	1
2. Analytical Methods	3
3. Numerical Methods	7
4. Experimental Methods	8
5. Optical Methods Work as Optical Computers	12
6. Direct Information Provided by Various Experimental Methods	17
7. Typical Results for Various Problems	19a
7.1 Beam under pure bending – Analytical solution	20
7.2 Beam under pure bending – Fringe contours from various	
experimental techniques	21
7.3 Cantilever beam with an end load – Analytical solution	22
7.4 Cantilever beam with an end load – Fringe contours from	
various experimental techniques	22a
7.5 Disc under diametral compression – Analytical solution	23
7.6 Disc under diametral compression – Fringe contours from	
various experimental techniques	23d
7.7 Clamped circular plate under a central load – Analytical	
solution	24
7.8 Clamped circular plate under a central load – Fringe	
contours from various experimental techniques	24a
7.9 Spanner tightening a nut	26
7.10 Spanner tightening a nut – Numerical solution and results from	
Photoelasticity	27
8. Strain Gauge	30
9. Photoelasticity	32
10. Moiré	36
11. Brittle Coatings	41
12. Holography	43
13. Speckle Methods	47
14. Thermoelastic Stress Analysis (TSA)	51
15. Digital Image Correlation (DIC)	53
16. Caustics	56
17. Coherent Gradient Sensor	58
18. Naming of Experimental Methods	61
19. Fringe Patterns – Richness of Qualitative Information	64
20. Key Technologies that has Influenced Experimental Mechanics	68
21. Multi-scale Analysis in Experimental Mechanics	70
22. Trends in Experimental Mechanics	72
23. Selection of an Experimental Technique	76
24. References	86

Chapter 2: Overview of Experimental Stress Analysis

Chapter 3: Transmission Photoelasticity

1. Introduction to Photoelasticity	1
1.1 Visualisation of stress field in a beam	2
2. Physical Principle	3
2.1 Birefringence	4
3. Various Branches of Photoelasticity	5
4. Nature of Light	8
4.1 Polarization	11
4.2 Methods to get polarised light	12a
4.3 Understanding polarization	12b
4.4 Passage of light through isotropic media	13
4.5 Snell's laws	14
4.6 Passage of light through a crystalline medium	15
4.7 Birefringence effect of calcite prism	17
5. Refractive Indices of Various Crystals	18
6. Nature of Light Refraction in a Crystal for Various Orientations of	
the Incident light with the Optic Axis	19
6.1 Existence of two light rays in a crystal by laser experiment	20
7. Light Ellipse	21
8. Various States of Polarization	23a
9. Retardation Plates and Wave Plates	24
10. Stress Optic Law	27
11. Stress Information Obtainable by Photoelasticity	30
12. Plane Polariscope	31
12.1 Formation of fringes – A logical explanation	32
12.2 Trigonometric resolution	34
13. Jones Calculus	37
13.1 Representation of a retarder	40
13.2 Polarizer	41
13.3 Quarterwave plate	42
14. Analysis of Plane Polariscope by Jones Calculus	43
15. Circular Polariscope	44
15.1 Jones calculus analysis of circular polariscope	45
16. Various Optical Arrangements	47
17. Use of White Light	48
17.1 Colour code	49
18. Summary of Photoelastic Fringes	50
19. Determination of N and θ for an Arbitrary Point	50a
19.1 Determination of θ	50b
19.2 Determination of N	50c
20. Compensation Techniques	51
20.1 Babinet-Soleil compensator	51a
20.2 Tardy's method of compensation	51b

21. Jones Calculus Analysis of Tardy's Method	53
22. Calibration of Photoelastic Model Materials	55
22.1 Stress field in a circular disc under diametral compression	56
22.2 Conventional method for calibration	57
23. Use of Whole-Field Data to Evaluate Material Fringe Value	59
23.1 Sampled least squares analysis	64
23.2 Experimental evaluation	65
23.3 Fringe thinning, data collection and verification	66
24. Theoretical Reconstruction of Fringe Patterns	67
25. Comments on Fringe Ordering	69
25.1 Properties of isochromatic fringe field	72
25.2 Properties of isoclinic fringe field	73
25.3 Positive and negative isotropic points	74
25.4 Role of principles of solid mechanics in fringe ordering	75
26. Resolving the Ambiguity on the Principal Stress Direction	76
27. Determination of the Sign of the Boundary Stresses	77a
28. Model to Prototype Relations	78
28.1 Compatibility condition	79
28.2 Beltrami and Mitchell equation	80
28.3 Similitude equations	81
29. Three-dimensional Photoelasticity and Integrated Photoelasticity	83
30. Three-dimensional Photoelasticity	87
30.1 Stress freezing	88
31. Integrated Photoelasticity	91
31.1 Principle of optical equivalence	92

Chapter 4: Photoelastic Coatings

1. Historical Development	1
2. Photoelastic Coating – An Overview	3
3. Optical Arrangements	4
3.1 Optical arrangement for commercial reflection polariscopes	5
3.2 Photoelastic strain gauges	6
4. Stress-optic Relation for Coating	7
5. Strain-optic Relation for Coating	8
6. Strain Coefficient K	9
7. Evaluation of Coating and Specimen Stresses	11
7.1 Coating stresses	13
7.2 Specimen stresses	14
8. Correction Factors for Photoelastic Coatings	15
8.1 Correction factor for plane stress	17
8.2 Correction factor for bending	19
8.3 Correction factor for bending of plates	24
8.4 Combined in-plane and bending loads	26
8.5 Correction factor for torsion	28

8.6 Correction factor for pressure vessel	29
8.7 Correction factors – Summary	31a
9. Poisson's Ratio Mismatch	32
9.1 SCF evaluation by photoelastic coatings	37
10. Coating Materials	38
10.1 Properties of photoelastic coating materials	39
11. Selection of the Coating Thickness	41
11.1 Maximum fringe order obtainable	42
11.2 Thickness selection philosophies	45
11.2.1 Thickness evaluation for bending of plates	47
11.3 Thickness evaluation based on precision	49
12. Calibration of the Coating Material	51

Chapter 5: Digital Photoelasticity

1. Introduction	1
2. Uniform Sampling and Quantization	2
3. Digital Techniques	4 5
4. Digital Fringe Multiplication	5
5. DIP Methods for Fringe Thinning	6
5.1 Fringe thinning methods	6 7 8
5.2 Binary based algorithm	
5.2.1 Chen and Taylor algorithm	9
5.3 Intensity based algorithms	12
5.3.1 Global method	13
5.3.2 Edge detection	14
5.3.3 Fringe skeletonization	17
5.3.4 Fringe skeleton extraction for arbitrarily shaped fringes	20
5.4 Global fringe thinning algorithm	21
5.5 Fringe thinning – An example	22
5.5.1 0 deg OR 90 deg	22a
5.5.2 45 deg OR 135 deg	22b
5.5.3 AND operator	22c
5.5.4 Data collection for calibration	22d
5.6 Data collection for SIF evaluation	23
6. Paradigm Shift in Data Processing	24
6.1 Generic expressions for intensity of light transmitted	26
6.2 New challenges	27
6.3 Classification of digital photoelastic techniques	29
6.4 Digital photoelasticity – An overview	32
7. Features of the Ten-step Method	33
8. Ten-step Method	34
8.1 Summary of optical arrangements	34
8.2 Expressions of photoelastic parameters in terms of intensities	35
8.3 Nuances in the evaluation of parameters	36
9. Method of Plotting Phasemaps	38

9.1 Isoclinic phasemap	38
9.2 Isochromatic phasemap	39
10. Understanding Phasemaps	40
10.1 Tardy's method of compensation	41
10.2 Issues in isoclinic phasemap	42
10.3 Isochromatic – isoclinic interaction	44
10.4 Issues in isochromatic phasemap	45
10.5 Inter-dependence of inconsistent and ambiguous zones	46
11. What is Isochromatic Phase Unwrapping	47
11.1 How ambiguous zones affect phase unwrapping	48
11.2 Invisible ambiguous zones	49
11.2.1 Plate with a circular hole	51
12. What is Isoclinic Phasemap Unwrapping	52
13. Isochromatic Phasemap Free of Ambiguous Zones	53
14. Need for Smoothing Isoclinics	54
15. Phase Unwrapping and Smoothing	55
16. Phase Unwrapping	60
16.1 Phase unwrapping of simple model geometries	61
16.2 Need for non-rectangular tiles	62
16.3 Phase unwrapping by auto seeding	63
16.4 Phase unwrapping of multiply connected objects	64
17. Raster Scanning and Isoclinic Phasemap Unwrapping	66
17.1 Checking conditions along different scanning directions	67
17.2 Unwrapping process	68
17.3 Limitations of the raster scanning approach	69
18. Autonomous Phase Unwrapping Algorithms	70
18.1 Quality maps	71
18.2 Mathematical expressions of different quality measures	72
18.2.1 Pseudo correlation map	72
18.2.2 Phase derivative variance map	73
18.2.3 Maximum phase gradient map	74
18.3 Plotting of quality maps	75
18.4 How a quality guided algorithm does operate	76
18.5 Comparison on the use of different quality maps	77
19. Isoclinic Unwrapping	80
19.1 Domain delimiting along pi jumps	81
19.2 Checking conditions based on pixel positions	82
19.3 Adaptive quality guided phase unwrapping algorithm (AQGPU)	83
19.4 Need for smoothing isoclinics	85
20. Isochromatic Phasemap Unwrapping by QGPU	86
21. Whole Field Data Estimation by Quality Guided Algorithms	87
21.1 Basic procedure	88
22. Data Smoothing	89
22.1 Robust outlier smoothing	90
22.2 Need for domain delimiting	91
22.3 Comparison of various smoothing techniques	92

22.4 Comparison of binary plots	93
22.5 Ring subjected to internal pressure	94
22.6 Effectiveness of robust outlier	95
23. Photoelastic Parameter Estimation for Various Problems	96
23.1 Ring subjected to internal pressure	97
23.2 Beam under 3-point bending	98
23.3 Circular disc under three radial loads	99
23.4 Cantilever beam with central cavity	100
23.5 Complex aero-components – Strap-on joint	101
23.5.1 Strap-on joint	102
23.5.2 Model fabrication and loading	103
23.5.3 Central slice	104
23.5.4 Aft-ball insert	105
23.6 Coupled dual-beam spring element	106
24. Intensity of Light Transmitted with White Light as Source	107
25. Three Fringe Photoelasticity	111
25.1 Preparation of the calibration table	113
25.2 Basic methodology	115
25.3 Representation of total fringe order as grey scale image	116
25.4 Error due to repetition of colour	117
26. Refined TFP	118
26.1 Disc under diametral compression	119
26.2 Beam under four point bending	120
26.3 Ring under diametral compression	121
27. Colour Adaptation in TFP	122
27.1 Construction of equivalent table	126
27.2 Beam under four point bending	128
27.3 Epoxy disc under diametral compression	130
27.4 Bi-material Brazilian disc	131
27.5 Plate with a circular hole	133
27.6 Colour adaptation in TFP – Summary	134
28. Application to RP Built Models	135
28.1 Minimising shrinkage stresses	136
28.2 Choice of build styles	138
28.3 PST applied to RP models	139
28.4 Noise removal in stereolithography built models	140
29. Digital Polariscopes	141
29.1 Calibration of the polariscope	143
29.2 First generation of digital polariscopes	144
29.3 Second generation of digital polariscopes	145
29.4 Third generation of digital polariscopes	147
29.4.1 Multi-polar imager	149
29.4.2 Poleidoscope	151
29.5 Discussion on the choice of the four-step method	152
29.6 RTFP for time varying problems	154a
29.6.1 Transient dark-field isochromatics	154b

29.6.2 Total fringe order evaluation using RTFP	154c
29.6.3 Typical SIF evaluation and summary of stress field	
parameters	154d
29.6.4 Fringe order variation along a line parallel to the interface	154e
29.6.5 Transient SIF's as a function of time	154g
29.7 Tricolour light source	155
30. Photoelasticity & Finite Elements (FE)	156
31. Plotting Isochromatics from 2D FE Results	157
31.1 Modeling concentrated load	158
31.2 Plotting scheme	162
31.3 Binary plot	163
31.4 Grey scale plot	164
31.5 Colour plot	165
31.6 Choice of increments	166
31.7 Brazilian disc with a central crack	167
32. Fringe Contours from 3D FE Results	168
32.1 The issues	169
32.2 Calculation of fringe order for a slice	170
32.3 Cantilever beam example	171
32.4 Integration scheme	172
32.5 Fringe plot for the whole model	173
32.6 Fringe contours of slices	174
32.7 General case	175
32.8 Sphere under diametral compression	176
33. Fusion of Rapid Prototyping, Photoelasticity & Finite Elements	177
33.1 Fusion of Rapid Prototyping, Photoelasticity &	
Finite Elements – Summary	179
33.2 Evolving the slicing plan	180
33.2.1 Crane hook – CAD modeling & meshing	181
33.2.2 Slicing plan	182
34. Stress Separation	184
34.1 Oblique incidence method	187
34.2 Shear difference method	194
34.3 Shear difference method – Summary	196
34.4 Improvement by Tesar	197
35. Digital Implementation of the Shear Difference Method	199
35.1 Various cases of boundary orientations in digital domain	200
35.2 Modified boundary structure (*. <i>mbn</i>)	201
35.3 Digital implementation of stress difference equation	202
35.3.1 Central zone	202
35.3.2 Top-most grid	203
35.3.3 Bottom-most grid	204
35.4 Plotting of pseudo stress contours	205
35.5 Verification of the shear difference algorithm	206
35.5.1 Photoelastic data obtained analytically	207
35.5.2 Photoelastic data obtained experimentally	208

35.5.3 Reason for streak formation	209
35.5.4 Improvement by smoothed experimental data	210
35.5.5 Quantitative comparison	211
35.6 Disc under diametral compression	212
35.6.1 Photoelastic data obtained analytically	212
35.6.2 Photoelastic data obtained experimentally	213
35.6.3 Improvement by smoothed experimental data	214
35.7 Ring under diametral compression	215
35.7.1 Photoelastic data obtained analytically	215
35.7.2 Photoelastic data obtained experimentally	216
35.7.3 Improvement by smoothed experimental data	217
36. Stress Smoothing	219
36.1 Dual-beam spring element	219
36.1.1 Smoothed pseudo stress contours	220
36.1.2 Quantitative comparison	221
37. Adaptive Scanning Scheme – The Need	222
38. Adaptive Scanning Scheme	223
38.1 Ring subjected to internal pressure	224
38.2 Circular disc under three radial loads	225
38.3 Influence on the choice of seed point	226
39. Colour Ten-step Phase Shifting Method	228
39.1 Summary of optical arrangements – Colour ten-step	231
39.2 Expression of photoelastic parameters in terms of intensities	232
39.3 Disc under diametral compression	233
39.4 Choice of green plane image for isochromatic data reduction	234
39.5 Different smoothing strategies	236
39.6 Individual stress components – Method 1	237
39.7 After stress smoothing (Method 1)	237a
39.8 Smoothing isoclinic data(Method 2)	238
39.8.1 Individual stress components	238
39.8.2 Matlab plot	239
39.9 Comparison of the two strategies	240

Chapter 6: Strain Gauges

1. Historical Development	1
2. Strain Sensitivity of a Wire	3
3. Gauge Construction	6
4. Gauge Length	8
4.1 Definition	8
4.2 Error in measurement	8a
4.3 Thumb rule in selection of gauge length	10
5. Commonly Used Strain Gauge Material	11
6. Strain Sensitivity of a Strain Gauge	12
7. Transverse Sensitivity Factor, Gauge Factor – Definitions	13

8. Experimental Determination of Gauge Factor Sg	14
9. Wheatstone Bridge	15
10. Strain Measurement Options	17
11. Bridge Sensitivity	18
11.1 Bridge factor 1	19
11.2 Bridge factor 2	20
11.3 Bridge factor 4	21
12. Foil Strain Gauges – Accuracy Achievable	22a
13. Strain Gauge Linearity, Hysteresis and Zero Shift – Definitions	22b
14. Determination of Strain at a Point	23
14.1 Three element rectangular rosette	25
14.2 Delta rosette	26
15. Metallic Alloys Commonly Employed in Commercial Strain Gauges	27
15.1 Advance or constantan alloy	28
15.2 Isoelastic alloy	31
15.3 Karma alloy	32
15.4 Thermally induced apparent strain	33
15.5 Nichrome V, Armour D, and Platinum Tungsten alloy	34
16. Strain Gauge Carriers – Its need	35
16.1 Types of carriers	36
17. Cements Used for Bonding	38
17.1 Cyano acrylate cement	39
17.2 Epoxy cements	41
17.3 Polyester adhesives	45
17.4 Ceramic cements	46
17.5 High temperature strain gauge	48
17.5.1 Flame spraying Rokide process	49
18. Issues Influencing the Performance of Strain Gauges	50
18.1 Strain gauge linearity, hysteresis and zero shift	52
18.2 Stability	55
18.3 Heat dissipation	59
18.3.1 Allowable power density	60
18.3.2 Selection of bridge voltage	61
19. Temperature Compensation	65
19.1 Sensitivity of gauge to temperature	65
19.2 Strain sensitivity as a function of temperature	66
19.3 Temperature compensation – Principles	67
19.4 Self-temperature Compensated (STC) gauges	68
19.5 STC numbers to go with different specimen materials	69
19.6 STC gauges – Summary	70
20. Measurement Techniques	72
20.1 P3500 measuring circuit	73
20.2 Two-wire circuit	74
20.3 Gauge factor desensitisation	75
20.4 Role of change in temperature	78
20.5 Three-wire circuit	80

20.6 Benefits of three-wire circuits	85
20.7Applications of two-wire circuits	86
21. Transverse Sensitivity	87
21.1 Actual and apparent strains	89
21.2 Error in measurement	90
21.3 $K_{\rm t}$ for various gauge types	91
21.4 Corrections for transverse strain effects	92
21.4.1 T-rosette	95
21.4.2 Rectangular rosette	96
21.4.3 Delta rosette	97
22. Correction Factors for Special Applications	98
22.1 Effects of hydrostatic pressure	99
22.2 Effects of nuclear radiation	105
22.3 Effects of high temperature	109
22.4 Effects of cryogenic temperature	114
22.5 Effects of strain cycling	116
23. Environmental Effects	118
23.1 Effect of moisture and humidity	118
24. Special Gauges	121
25. Plane-Shear or Torque Gauge	121
25.1 Torque gauge configurations	124
26. Stress Gauge – Principle	125
26.1 Stress gauge construction	128
26.2 Stress gauge – Summary	133
26.3 Single element strain gauge as a stress gauge	134
27. Stress Intensity Factor	135
28. Strain Field in the Vicinity of a Crack (Mode I)	136
29. SIF Evaluation by Strain Gauges	137
30. SIF Evaluation Using a Single Strain Gauge	138
30.1 Strain field	139
30.2 Selection of alpha and theta	140
30.3 SIF Evaluation using a single strain gauge – Summary	143

Chapter 7: Strain Gauge Selection and Installation

1. Introduction	1
2. Selection Compromises	5
3. Strain Gauge Designation System	8
4. Guidelines for Strain Gauge Selection	11
5. Temperature Effects Guiding the Selection of Certain Parameters	13
6. Importance of Following a Bonding Procedure	17
7. Strain Gauge Installation	20
8. Surface Preparation	31
8.1 Strain gauge installation kit	34
8.2 Specimen	35

8.3 Solvent degreasing	36
8.4 Surface abrading	38
8.5 Layout lines	41
8.6 Surface conditioning	42
8.7 Neutralizing	44
9. Strain Gauge Bonding	46
9.1 Strain gauge handling	47
9.2 Strain gauge alignment	49
9.3 Catalyst application	52
9.4 Bonding with adhesive	55
9.5 Tape removal	58
10. Soldering	59
10.1 Masking the gauge	59
10.2 Tinning tabs and terminals	60
10.3 Tinning the leadwire	63
10.4 Leadwire attachment	65
10.5 Cleanup and inspection	67
11. Protective coating	68
12. Characteristics of a Good Installation	69
13. Tests for Voids in the Bonding System	70
14. Tests for Complete Curing of Adhesive	71

Chapter 8: Strain Gauge Based Transducers

1. Introduction	1
2. Strain Gauge Load Cells	3
2.1 Bending elements	5
2.2 Shear elements	6
2.3 Compression elements	7
3. Commercially Available Load Cells	8
4. Strain Gauge as a Transducer Element	9
4.1 Favourable factors of bonded strain gauge for use in transducer	10
4.2 Limiting factors	11
5. Design Considerations of a Load Cell Spring Element	13
6. Bending Element Load Cells	19
6.1 Design refinements of cantilever beam transducers	22
6.2 Importance of higher order effects	24
6.3 Multiple bending element	25
6.4 Wheel-shaped spring element	26
6.5 Evolution of a dual beam transducer	27
7. Load Cell for Weighing Applications	31
8. Transducers Based on Rings	33
9. High Capacity Load Cells	36
9.1 Shear web load cells	37
9.2 Wheel type shear web spring element	39
10. Column Load Cell	40

11. Torque Transducers	43
12. Pressure Transducers	45
12.1 Diaphragm gauge	46
12.2 Pressure transducer using a thinned pipe wall	48
13. Load Cell Installation	49

Chapter 9 Brittle Coatings

1. Introduction	1
2. Historical Development	4
3. Methodology of Brittle Coatings	6
4. Crack Patterns Produced by Direct Loading	10
4.1 Uniaxial stress field	10
4.2 Biaxial stress field	10
4.3 Isotropic stress field	11
5. Steps in a Brittle Coating Test	12
6. Evaluation of Coating and Specimen Stresses	20
	20 21
6.1 Coating stresses	21
6.2 Failure theory	
7. Quantitative Evaluation of Specimen Stresses	23a
7.1 Determination of failure strain/stress	24
7.2 Nature of coating stresses	24c
7.3 Uniaxial specimen stress	25
7.4 Biaxial specimen stress	26
7.4.1 Conditions for the formation of first set of cracks	27
7.4.2 Conditions for the formation of second set of cracks	29
8. Analysis of Isoentatic Data	33a
9. Determination of Principle Stress Direction in Low Stress Region	34
9.1 Crack patterns produced by refrigeration	35
10. Brittle Coating to Reveal Compressive Stresses	37
10.1 Crack patterns produced by relaxation	37
10.2 Double crack patterns for compressive loads	39
11. Stresscoat	40
12. Physical Evidence that the Direction of Principal Stresses at a Point are	
Mutually Perpendicular	41

Chapter 10: Caustics

1. Introduction	1
2. Formation of Caustics	2
3. Caustic Curve	3
4. Initial Curve	4
5. General Mapping Equations	5
5.1 Transmission and reflection parameters	6

5.2 Change in thickness	7
5.3 Change in refractive index	8
5.4 Change in path length of ordinary and extraordinary rays	9
6. Shadow Optical Constant – Definition	10
7. Problems Considered	11
7.1 Specific mapping equations	12
7.2 Caustics as an envelope of family of curves	14
7.3 Experimental caustics	15
7.4 Expressions for initial curve	16
7.5 Stress concentration measure from caustics	17
8. Crack-tip caustics for Mode I, Mode II and Mode III Loadings	18
9. Crack-tip Stress Field Equations	19
10. Minimum Size of Initial Curve for Accurate Determination of SIF	20
11. Mixed Mode Caustics (Mode I + Mode II)	21
11.1 Determination of SIF ratio	22
11.2 Geometry factor <i>f</i>	23
12. Caustics in Optically Birefringent Material	26
13. Elastic-plastic Caustics	27
14. J-integral from Caustics	29

Chapter 11: Brief Introduction to Selected Techniques

1. Introduction	1
2. Moiré	2
	3 3 5
2.1 Moiré phenomena	5
2.2 Undesirable effects of moiré	2
2.3 Various methods of moiré for stress analysis	7
2.4 Geometric moiré	9
2.5 Moire interferometry	13
2.6 Shadow moiré	16
2.7 Projection moiré	16b
2.8 Reflection moiré	17
3. Holography	18
3.1 Hologram interferometry	24
3.2 Double-exposure hologram interferometry	26
3.2.1 Data interpretation on hologram interferometry	28
3.2.2 Sensitivity vector	29
3.2.3 Measurement of in-plane displacements	31
3.2.4 Measurement of complete displacement vector	34
3.2.5 Method to obtain isopachics	35
3.3 Real-time hologram interferometry	38
3.4 Time-average hologram interferometry	42
3.4.1 Stroboscopic time-average hologram interferometry	45
4. Speckle Methods	46
4.1 Introduction	46

4.2 Formation of speckles	47
4.2.1 Objective speckle	47
4.2.2 Subjective speckle	47a
4.3 Characteristics of speckles	48
4.3.1 Motion of speckles	48
4.3.2 Influence of aperture on the size of speckles	49
4.3.3 Intensity change of speckle	50
4.4 Speckle photography/speckle correlation	50a
4.4.1 Point by point analysis	50b
4.4.2 Digital speckle correlation	50c
4.5 Speckle interferometry	50e
4.5.1 Digital speckle pattern interferometry	50f
4.5.2 Digital speckle shearography	50g
5. Thermoelastic Stress Analysis (TSA)	51
5.1 Thermoelastic response	54
5.2 Maintaining adiabatic conditions	56
5.3 Measurement scheme	58
5.4 Equipments for thermoelastic analysis	60
5.5 Technical issues that need to be accounted	63
5.5.1 Image distortion	63
5.5.2 Sources of noise	64
5.5.3 Motion compensation	65
5.6 Surface preparation	67
6. Digital Image Correlation	72
6.1 Methodology	74
6.2 Theory of deformation	76
6.3 Deformation analysis using digital image correlation	78
6.4 The challenges	85
6.5 Speckle pattern of different sizes	86a
6.5.1 Identification of suitability of speckle pattern	87
6.5.2 Limitations of 2D-DIC	89
7. Coherent Gradient Sensor	91
7.1 Optical scheme of Hareesh Tippur et. al	93
7.2 Caustics and CGS	96
8. Biblography	98
8.1 Moiré	98
8.2 Holography	100
8.3 Speckle methods	102
8.4 Thermoelasticity	103
8.5 DIC	104
8.6 CGS	105

Chapter 12: Experimental Evaluation of Fracture Parameters

1. Introduction	1
2. Photoelastic Appreciation of Severity of a Crack	1b
3. Fracture Mechanics is a Broad Area Covering Several Disciplines	1c
4. Modes of Loading	1e
4.1 Mode I or opening mode	1e
4.2 Mode II or sliding mode	1f
4.3 Mode III or tearing mode	1g
4.4 Summary	1h
5. Simplistic Model of Fracture	1i
6. Photoelastic Visualisation of Crack-tip Stress Fields	
6.1 Mode I	1j
6.2 Mode II	1k
6.3 Mixed-mode	11
6.4 Multiple radial cracks	1m
6.4.1 Cracks emanating from inner boundary	1n
6.4.2 Cracks emanating from outer boundary	10
7. Experimental Methods to Evaluate SIF	1p
8. Numerical Methods to Evaluate SIF	2
9. SIF Evaluation by Photoelasticity	3 3
9.1 Irwin's two parameter method – Methodology	
9.1.1 Expressions for SIF	4
9.1.2 Zone of validity	5
9.2 SIF evaluation for practical problems	6
9.3 Overdeterministic multi-parameter evaluation of stress field	7
9.3.1 Convergence criteria	12
9.3.2 Crack emanating from the outer boundary of an internally	
pressurised thick ring	13
9.3.3 Crack emanating from the inner boundary of an internally	
pressurised thick ring	14
9.3.4 Crack in the tensile root fillet of a spur gear	15
9.3.5 Isochromatics-mixed-mode	16
10. SIF Evaluation by Holography	16a
10.1 Isopachics in Mode I	17
10.2 Isopachics in mixed-mode	18
11. SIF Evaluation by Moiré	18a
11.1 Multi-parameter displacement field (Mode I + Mode II)	19
11.2 Displacement field as a function of parameters (Mode I)	20
11.3 Displacement field as a function of parameters (Mode I + Mode II)	21
12. SIF Evaluation by the Method of Caustics	22
12.1 Introduction	23
12.2 Formation of caustics	24
12.3 Caustic curve	25
12.4 Initial curve	26

27
28
29
30
31
32
33
35
37
38
39
40
41
44
45
46

Chapter 13: Exercise Problems

Assignment No.1: Review of Mechanics of Solids
Assignment No.2: Overview of Experimental Mechanics
Assignment No.3: Transmission Photoelasticity
Assignment No.4: Ordering of Photoelastic Fringes
Assignment No.5: Photoelastic Data Reduction by Least Squares Method
Assignment No.6: Photoelastic Coatings
Assignment No.7: Strain Gauges – I
Assignment No.8: Strain Gauges – II
Assignment No.9: Strain Gauges – III
Assignment No.10: Brittle Coatings
Assignment No.11: Digital Photoelasticity – I
Assignment No.12: Digital Photoelasticity – II
Assignment No.13: Digital Photoelasticity – III
Assignment No.14: Method of Caustics
Assignment No.15: Brief Introduction to Selected Techniques

Assignment No.16: Experimental Evaluation of Fracture Parameters

Search Feature

The search feature accepts any of the word/phrases appearing in the detailed course content including the Links for searching the course.

Links in Chapter 1: Overview of Mechanics of Solids

	1
1	
2	
3	
4	
5	
6	
	5
1	
2	
3	
4	
5	
	29
1	
	5 6 1 2

Links in Chapter 2: Overview of Experimental Stress Analysis

1. Variants of Photoelasticity	35
• Variants of Photoelasticity	al
• Transmission photoelasticity	1
• Reflection photoelasticity	3
• Three-dimensional photoelasticity	4
 Scattered light photoelasticity 	6
 Integrated photoelasticity 	7
• Dynamic photoelasticity	9
• Photo-orthotropic elasticity	10
Photoplasticity	11
• Utility of Variants of Photoelasticity	13

2. What is Phase?	43
• What is phase?	1

The labels in blue indicate the name of the Link and the number in blue font is the slide number in the main chapter to which this link is attached. Green font indicates that a sub-link is attached to this link.

 Sub-Links to Variants of Photoelasticity Scattered light photoelasticity Scattered light photoelasticity 	1	6
 Dynamic photoelasticity Dynamic photoelasticity 	1	9
 Photo-orthotropic elasticity Photo-orthotropic elasticity Calibration of model material Shrinkage stresses/ residual birefringence 	1 5 6	10
 Photoplasticity Photoplasticity 	1	11
Links in Chapter 3: Transmission Photoelasticity		
 Production of Polarised Light Historical Development Polarizers in Sheet Form Prism Polarizers Polarization by Reflection Polarization by Scattering 	1 3 7 12 14	12a
2. Calcite PrismCalcite prism	1	17
 3. Production of Polarised light Historical Development Polarizers in Sheet Form Prism Polarizers Polarization by Reflection Polarization by Scattering 	1 3 7 12 14	23a
 4. Understanding Isoclinics & Isochromatics Understanding Isoclinics and Isochromatics 	1	33
5. Determination of θ • Determination of θ	1	51b
 6. Photoelastic Sheet Casting Steps in Casting a Photoelastic Sheet Preparation of the Casting Mould Surface cleaning 	1 3 4	55

• Cleaning the separator pieces	6
• Forming the mould cavity	7
 Spraying mould release agent 	8
 Casting mould assembly 	9
Casting Calculation	12
 Resin and hardener for casting 	13
 Mixing of resin and hardener 	16
• Pouring	19
• Curing	20
 Taking the Cast Sheet from the Mould 	21
 Checking the Quality of the Cast Sheet 	23
7. Fringe Thinning	
• DIP Methods for Fringe Thinning	1
Fringe Thinning Methods	2 3
Binary Based Algorithm	
• Chen and Taylor Algorithm	4
 Intensity Based Algorithms 	9
• Global method	10
• Edge detection	11
 Fringe skeletonization 	14
• Fringe skeleton extraction for arbitrarily shaped fringes	16
 Global Fringe Thinning Algorithm 	18
 Fringe Thinning for Calibration 	19
• 0 deg OR 90 deg	20
• 45 deg OR 135 deg	21
• AND operator	22

Links in Chapter 5: Digital Photoelasticity

 Mask Based Methods Mask based methods Mask based method – Yatagai et al Mask based method – Umezaki et al Other Mask based methods 	1 2 4 9	12
2. PST – Historical Development		24
• Phase Shifting Techniques(PST)	1	
 Transmission photoelasticity – Isochromatics/ both 		
isochromatics and isoclinics using Monochromatic		
light source	2	
• Four-step methods	7	
• Ambiguity/Phase unwrapping	8	
 Transmission photoelasticity – Isochromatics/ both 		

isochromatics and isoclinics using white light source	11
 Transmission photoelasticity – Isoclinics 	12
• Three fringe photoelasticity	14
• Digital polariscopes	15
• Dynamic photoelasticity	16
• Reflection photoelasticity	17
• Integrated photoelasticity	18
 Plotting contours from FE 	19
 Stereolithography built models 	21
 Stress separation 	22
Fourier transform	22
Genesis of the Ten-Step Method	23
 References 	24 30
 Reviews/Books 	
	30
 Isochromatics/Isoclinics and Isochromatics – 	21
Monochromatic source	31
• Four-step methods	40
 Ambiguity/phase unwrapping 	41
• Multi wave length	44
 Isoclinics 	46
 Three-fringe photoelasticity 	50
 Digital polariscopes 	52
 Dynamic photoelasticity 	54
 Reflection photoelasticity 	55
 Integrated photoelasticity 	56
 Plotting contours from FE 	57
• Stereolithography	59
• Stress separation	60
• FFT	63
3. Jones Calculus – Details	
• Generic expression for intensity of light transmitted in a	
plane polariscope	1
 Generic expression for intensity of light transmitted in a 	Ĩ
circular polariscope	4
 Generic expression for intensity of light transmitted in a 	Т
mixed polariscope	7
inixed polariscope	1
4. Fourier Transform Approach	
• Frequency Domain Methods – Up to 90 images!	1
• Frequency Domain Memous – Op to 90 images!	1
5. PST Algorithms	
PST Algorithms	1
Role of Background Light Intensity	1 1a
• Role of Dackground Light Intensity	1 a

26

29

• Paradigm Shift in Data Acquisition – Hecker and Morche [1986]	2
• Kihara [1990]	4
• Sarma et al. [1992]	6
• Dupré et al. [1993]	8
• Performance of the Early Attempts	10
 Total Fringe Order along Isoclinics – Asundi [1993] 	11
• Six-step Methods	13
 Patterson and Wang (six-step) [1991] 	14
 Ajovalasit et al. (six-step) [1998] 	15
 Parameter Estimation in Six-step Methods 	16
• Improvement in parameter estimation by	
Quiroga and Cano	17
• Four-step Methods	18
• Barone et al (four-step)[1997]	19
 Patterson and Wang (four-step)[1998] 	21
• Asundi et al. (4-step)[1999]	23
• Ajovalasit et al. (four-step) [2002]	25
 Improved evaluation scheme for four-step algorithms 	27
 Comparison of Isochromatic Phasemaps 	28
 Poor Quality of Isoclinics from Six-step Circular Polariscope 	
based PST Methods	29
 Multiple Optical Arrangement 	30
 Multiple optical arrangement to obtain intensity equation 	S
of six-step algorithm	31
• Quarterwave Plate Error	32
• Choice of optical arrangements to minimise quarterwave	
plate mismatch	33
 Isoclinics from Plane Polariscope Based Methods 	34
 Ramesh and Mangal [1999] 	35
 Brown & Sullivan algorithm [1990] 	38
• Petrucci [1997]	39
 Comparison of plane polariscope methods in 	
evaluating isoclinics	40
 Composite Methods 	41
• Barone & Petrucci [2002]	42
 Ramji and Ramesh [2006] 	44
• Barone & Petrucci (Results from theoretically	
simulated images	46
• Ramji and Ramesh (Results from theoretically	
simulated images)	47
• Robustness of the Ten-step method (Results from	-
theoretically simulated images)	48

6. Contribution by QuirogaImprovement in parameter estimation by Quiroga and Cano

7. Other Image Representations		39
• Binary representation of isoclinics	1	
• Dark and bright field isochromatics	2	
8. Basic Data from Conventional Photoelasticity		46
 Basic data from conventional photoelasticity 		
9. Methods to Remove Ambiguity		53
Methods to Remove Ambiguity	1	
• Influence of the orientation of the model	2	
• Interactive Approach to Obtain a Good Phasemap	4	
Various Class of Ambiguous Zones	7	
• Simulated Dark Field Approach	8	
• Disc under diametral compression	10	
 New Methodology for Solving Subtle Ambiguous Zones 	11	
• Theta tolerance and delta threshold	12	
• Ambiguity Removal by Negation Algorithm	14	
• Ambiguity Removal for a Complex Problem	15	
• Use of Finite Elements in Identifying Inconsistent and		
Ambiguous zones	16	
Isoclinic evaluation	17	
• Isochromatic estimation	18	
• Angle bracket subjected to compression	19	
• Cantilever beam with central cavity under bending	21	
• Load Stepping to Get Phasemaps Free of Ambiguity	23	
• Mechanism of finding phasemap from dark field		
images	25	
10. Definition of <i>xbn</i> and <i>ybn</i>		55
Boundary Identification	1	00
Geometric Primitives	2	
Maintaining Continuity in Boundary definition	3	
• Straight line	4	
• Curved line	5	
• Role of the Boundary Definition	6	
• Definition of xbn and ybn	7	
• Extraction of XBN information – Simply connected bodies	8	
Multiply connected bodies	9	
11. Complete Set of Conditions		83
• Checking conditions for Adaptive Quality Guided Phase Unv	wrapping	
Algorithm	1	
12. Marking Outliers		90
Marking Outliers	1	-
e e e e e e e e e e e e e e e e e e e		

13. Introduction to Rapid Prototyping		135
Rapid Prototyping	1	
 Model Fabrication in Stereolithography 	3	
Scanning schemes	4	
• Curing over the depth of the layer	5	
 Minimising model distortion 	6	
 Minimising shrinkage stresses 	7	
• Choice of build styles	8	
• Approximate properties of some stereolithographic resins	9	
14. Robustness of the Ten-step Method		96
• Robustness of the Ten-step Method (Results from theoretically		
simulated images)	1	
15. Discretisation Examples		158
 Ring Under Diametral Compression 	1	
Disc Under Diametral Compression	3	
Sub-Link to PST Algorithms		
Quarterwave Plate Error		32
• Jones matrix of quarterwave plate with error ε	1	52
 Intensity of light transmitted by considering quarterwave 	1	
plate error	2	
• Intensity equation I_1 considering quarterwave plate error		
• Graphical representation of error $-I_1$	5	
• Intensity equation I_2 considering quarterwave plate error		
• Graphical representation of error $-I_2$	8	
Certain observations	9	
• Preferred optical arrangement for setting dark and		
bright fields	10	
• Intensity equation I ₃ considering quarterwave plate error	11	
• Graphical representation of error $-I_3$	12	
• Intensity equation <i>I</i> ₄ considering quarterwave plate error	13	
• Intensity equation I ₅ considering quarterwave plate error		
 Intensity equation I₆ considering quarterwave plate error Expressions for photoelastic parameters if only left or 	15	
 Expressions for photoelastic parameters if only left of right circularly polarized light is used 	17	
 Isoclinic and isochromatics parameters with judicious 	1 /	
combination of left and right circularly polarized lights	18	
 Variable quarterwave plate error distribution 	19	
• • • unable quarter wave place enter distribution	17	

Links in Chapter 6: Strain Gauges

 1. Kelvin Lord Kelvin (1824 – 1907) 	1	1
 2. Development of SR-4 Gauge Development of SR-4 gauge 	1	2
 2. Wheatstone Bridge Sir Charles Wheatstone (1802 – 1875) 	1	15
 3. Hysteresis, Zero Shift – Definitions • Strain Gauge Linearity, Hysteresis and Zero Shift – Definitions 	1	50
4. Proof • Proof	1	128

Links in Chapter 7: Strain Gauge Selection and Installation

 1. Carrier Matrix (Backing) Carrier Matrix (Backing) 	1	9
2. Foil AlloyFoil Alloy	1	9
 3. Self-Temperature Compensation • S-T-C Number 	1	9
 4. Grid or Tab Geometry Grid or Tab Geometry Linear Patterns T Rosettes Rectangular rosettes 	1 2 3 4	9
5. Options (If any)• Standard Options	1	9
 6. Number of Measuring Grids and their Relative Position to Each Other Number of Measuring Grids 	1	10
7. Strain Gauge SeriesStrain Gauge Series	1	10

 8. STC Number Self Temperature Compensation Number as used by HBM 	1	10
 9. Strain Gauge Training – BSSM • Strain Gauge Training – BSSM (pdf) 	1	18
 10. Code of Practice – BSSM Code of Practice – BSSM (pdf) 	1	20
Links in Chapter 10: Caustics		
 Values of c and λ Values of c and λ 	1	18
 2. Initial curve and caustic curve Initial curve for Mode I 	1	19
 Equation of caustic curve (Mode I) Crack-tip stress field equations (Mode II) Initial curve for Mode II 	2 3 4	
 Initial curve for Mode II Equation of caustic curve (Mode II) Crack-tip stress field equations (Mode III) 	4 5 6	
• Unitial august for Made III	07	

•	Equation of caustic curve (Mode II)	5
•	Crack-tip stress field equations (Mode III)	6
•	Initial curve for Mode III	7
•	Equation of caustic curve (Mode III)	8
•	Summary of initial curve radii	9

3. Values of *c* and λ

3. Values of <i>c</i> and λ		24
• Values of c and λ	1	
4. Details of J-integral from caustics		29
• Details of <i>J</i> -integral from caustics	1	
• Mapping equations of caustics using J	2	
• <i>J</i> -integral from caustics – Summary	4	

Links in Chapter 11: Brief Introduction to Selected Techniques

 1. Historical development Historical development – Holography 	1	18
2. Rainbow hologramsRainbow holograms	1	21

3. Historical development		51
 Historical development – TSA 	1	

27

Links in Chapter 12: Experimental Evaluation of Fracture Parameters

1. Background information		3
 Plot of theoretical isochromatics 	1	
• Experimental isochromatics – for short cracks	2	
• Modified Westergaard equations (Irwin's modification)	3	
2. Influence of sign of σ_{ox}		5
• Influence of sign of σ_{ox} on Mode I isochromatics	1	
• Influence of sign of σ_{ax} on Mode I isopachics	2	
• Geometrical features of Mode II isochromatics and isopachics	3	
• Geometrical features of Mixed-mode isochromatics and		
isopachics	4	
3. Values of c and λ		27
• Values of <i>c</i> and λ	1	
4. Initial curve and caustic curve		28
• Initial curve for Mode I	1	
• Equation of caustic curve (Mode I)	2	
• Crack-tip stress field equations (Mode II)	3	
• Initial curve for Mode II	4	
• Equation of caustic curve (Mode II)	5	
• Crack-tip stress field equations (Mode III)	6	
• Initial curve for Mode III	7	
• Equation of caustic curve (Mode III)	8	
• Summary of initial curve radii	9	
5. Values of c and λ		33
• Values of c and λ	1	00
6. Details of <i>J</i> -integral from caustics		37
• Details of <i>J</i> -integral from caustics	1	
• Mapping equations of caustics using J	2	
• <i>J</i> -integral from caustics – Summary	4	
7. Strain Field at the Crack-tip (Mode I)		38
• Strain field at the crack-tip (Mode I)	1	