Plenary Lecture

Fifty Years of Experimental Mechanics -A personal Perspective

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F.ASME, F.SEM, F.OSA, F.SPIE

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Stony Brook University

Chronology

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Major Full Field Optical Techniques	Major Development Period
Birefringence Techniques: •Photoelasticity •Photoviscoelasticity •Photoplasticity	Before 1950's
Moiré Methods: •In-plane Moiré •Shadow Moiré & Projection moiré •Reflection Moiré •Refraction Moiré & Moiré Deflectometry	1960's – 1970's
Holographic Interferometry:	1960's – 1970's
Moiré Interferometry & Two-Beam Interferometry:	1980's – 1990's

Chronology

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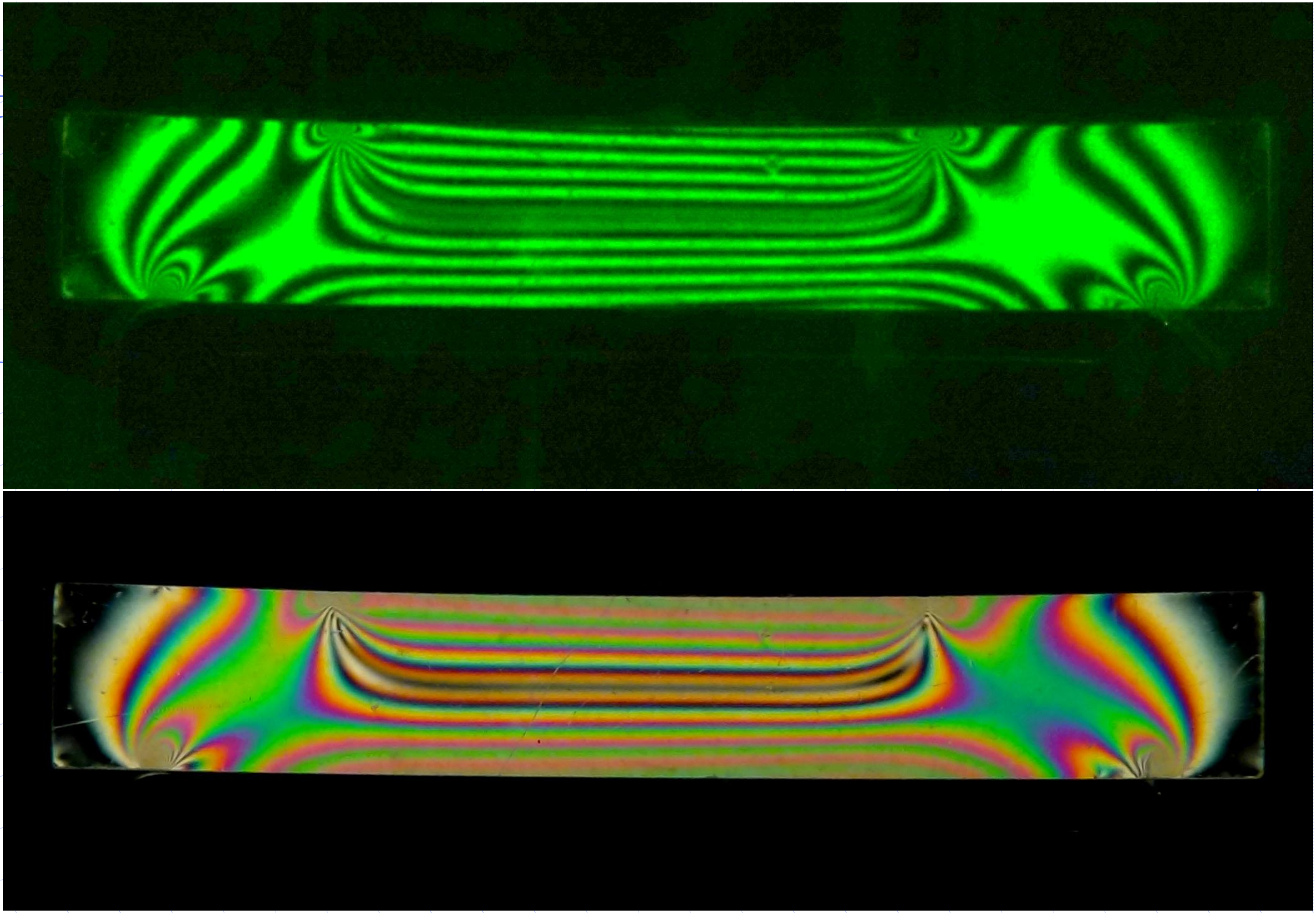
Major Full Field Optical Techniques	Major Development Period
Coherent Speckle Techniques:	
•Two-Beam Laser Speckle Interferometry & ESPI (Electronic Speckle Pattern Interferometry)	1970's - 1980's
•One Beam Speckle Interferometry (Speckle Photography)	
•Shearography	
Incoherent Speckle Techniques:	1980's
•White light Speckle Photography	
•Image Correlation Technique	
Digital Techniques:	1990's
•Digital Moiré	
•Digital Projection Grating	
•Digital Holography	
•Digital Image Correlation (DIC)	
•Digital Speckle Photography (DSP)	
Micro/Nano Techniques:	2000's
•Electron Beam Moiré	
•AFM Speckle Image Correlation Technique	
•Electron Speckle Photography (with SEM, TEM, etc.)	
3D Digital Methods	2010's
• Digital Volume Correlation (DVC)	
• Digital Volumetric Speckle Photography(DVSP)	

Photoelasticity



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Publications in photoelasticity

1. Durelli, A.J., Chiang, F.P., et al., 1968. "Maximum stress at the angular corners of long strips bonded on one side and shrunk," Experimental Mechanics, 8(6), pp. 278-281.
2. Durelli, A.J., Chiang, F.P., et al., 1969. "Stresses and strains in reinforced concrete," J. Of the Structural Division, Proc. Of the Am. Soc. of Civil Engineers, 95 (ST5), pp. 871-887.
3. Durelli, A.J., Chiang, F.P., et al., 1970. "Strain and stresses in matrices with inserts," *Mechanics of Composite Materials*, F. W. Wendt, H. Liebowitz and N. Perrone eds., Pergamon Press, pp. 265-336.
4. and Khetan, R.P., Chiang, F.P., 1974. "A new method to increase the sensitivity of photoelasticity," Experimental Mechanics, 14(1), pp. 29-32.
5. Lu, H. and Chiang, F.P., 1993. "Photoelastic determination of stress intensity factor of an interfacial crack in a biomaterial," J. Applied Mechanics 60, pp. 93-100.

Moiré Patterns

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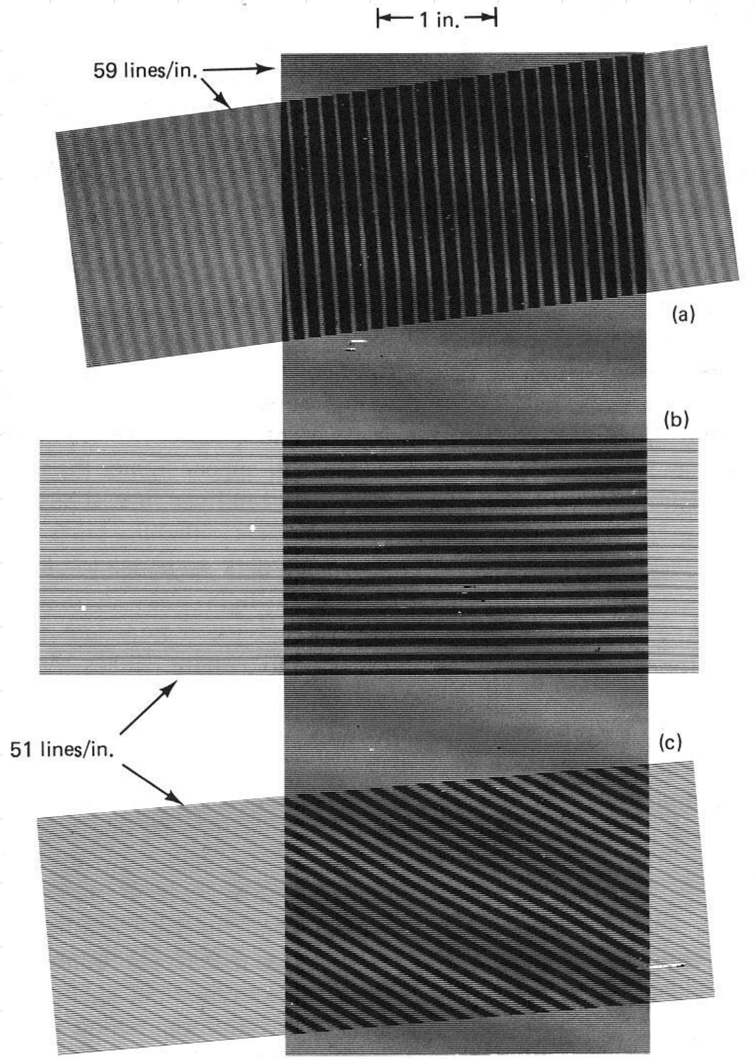
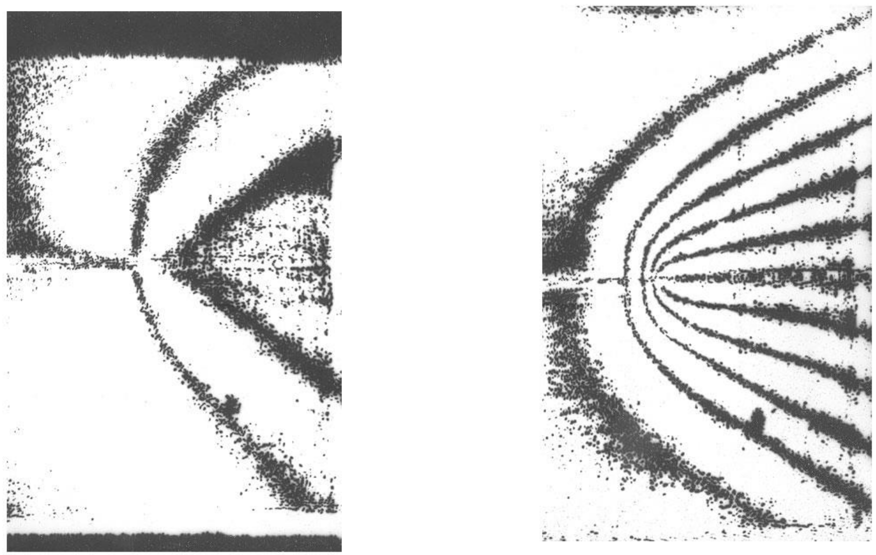


In-plane Moiré

Crack Tip Deformation

u - field = NP   v - field = MP

N,M= fringe order
P=grating pitch



0.0508 mm/fringe

1. Chiang, F.P., 1969. "Determination of signs in the moiré method," Journal of Engineering Mechanics Division, Proc. of the Am. Soc. Civil Engineers, 95(EM6), pp. 1379-1391.
2. Chiang, F.P., 1972. "On a moiré method applied to the determination of two-dimensional dynamic strain distribution," J. Applied Mechanics, Trans. of the ASME, 39(3), Series E., pp. 829-830.
3. Lin, C.J., and Chiang, F.P., 1982. "Time average in-plane moiré method for the analysis of general periodic loading," Experimental Mechanics, 22(2), pp. 64-68.
4. Kin, C.C., and Chiang, F.P., 1983. "Some optical techniques of displacement and strain measurements on metal surfaces," J. of Metals, pp. 49-54.

Shadow Moiré

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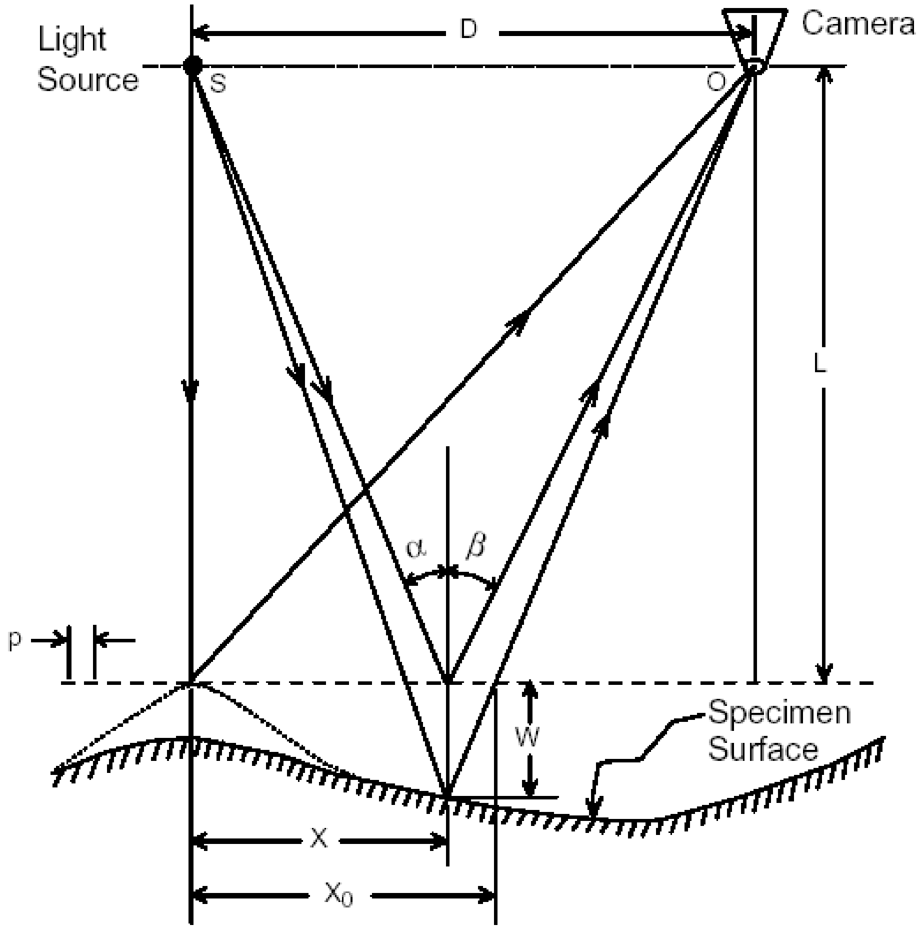
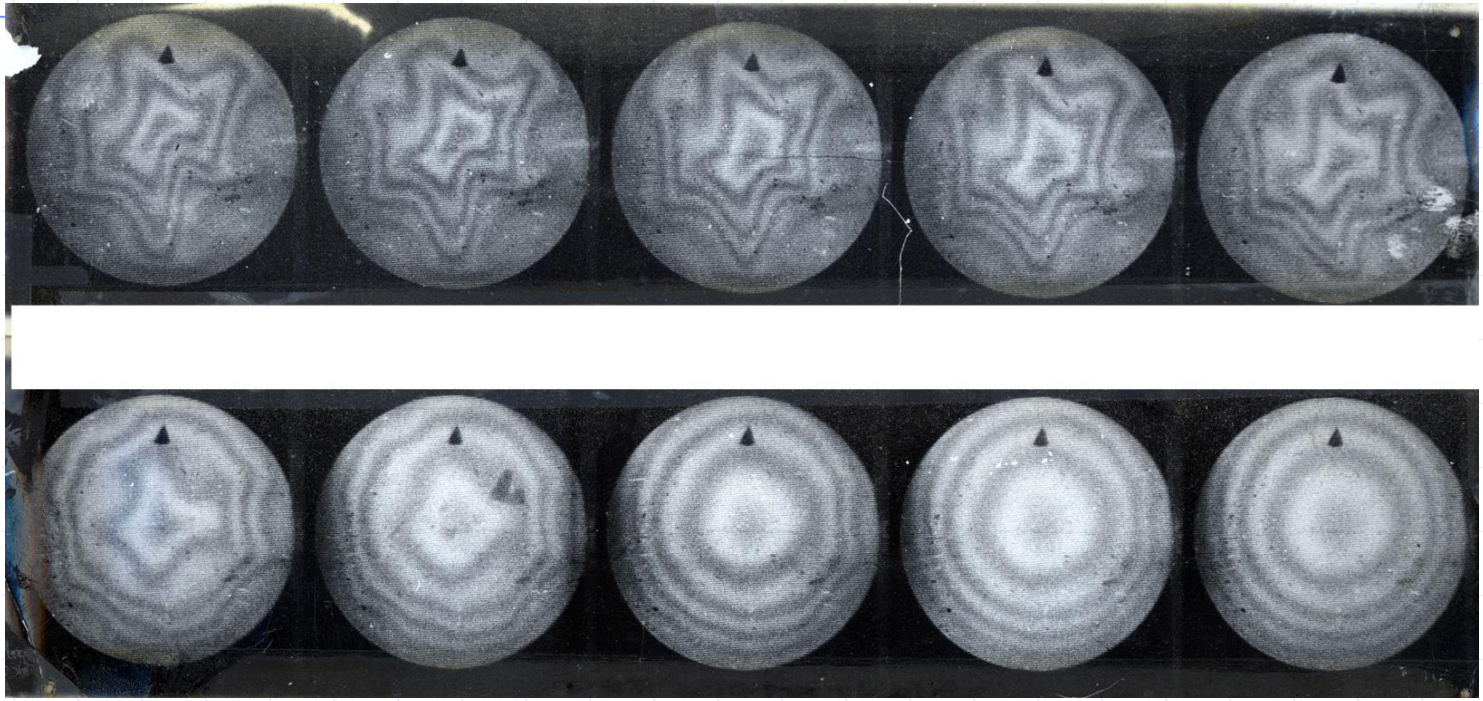


Pirodda, 1969
Meadows et al., 1970
Takasaki, 1970

$$W = \frac{NP}{\tan\alpha \tan\beta}$$

1. Chiang, F.P., 1795. "A shadow moiré method with two discrete sensitivities," Experimental Mechanics, 15(10), pp. 282-285.
2. Wei, S., Wu, S., Kao, I., and Chiang, F.P., 1998. "Measurement of Wafer Surface Using Shadow Moiré Technique with Talbot Effect", ASME J. of Electronic Packaging, 120 (2), pp. 166-170.



Dynamic Buckling of a Spherical Cap and Shock Pressure

Army Materials & Mechanics Research Center reports 1970s

An interesting application of the shadow moiré method

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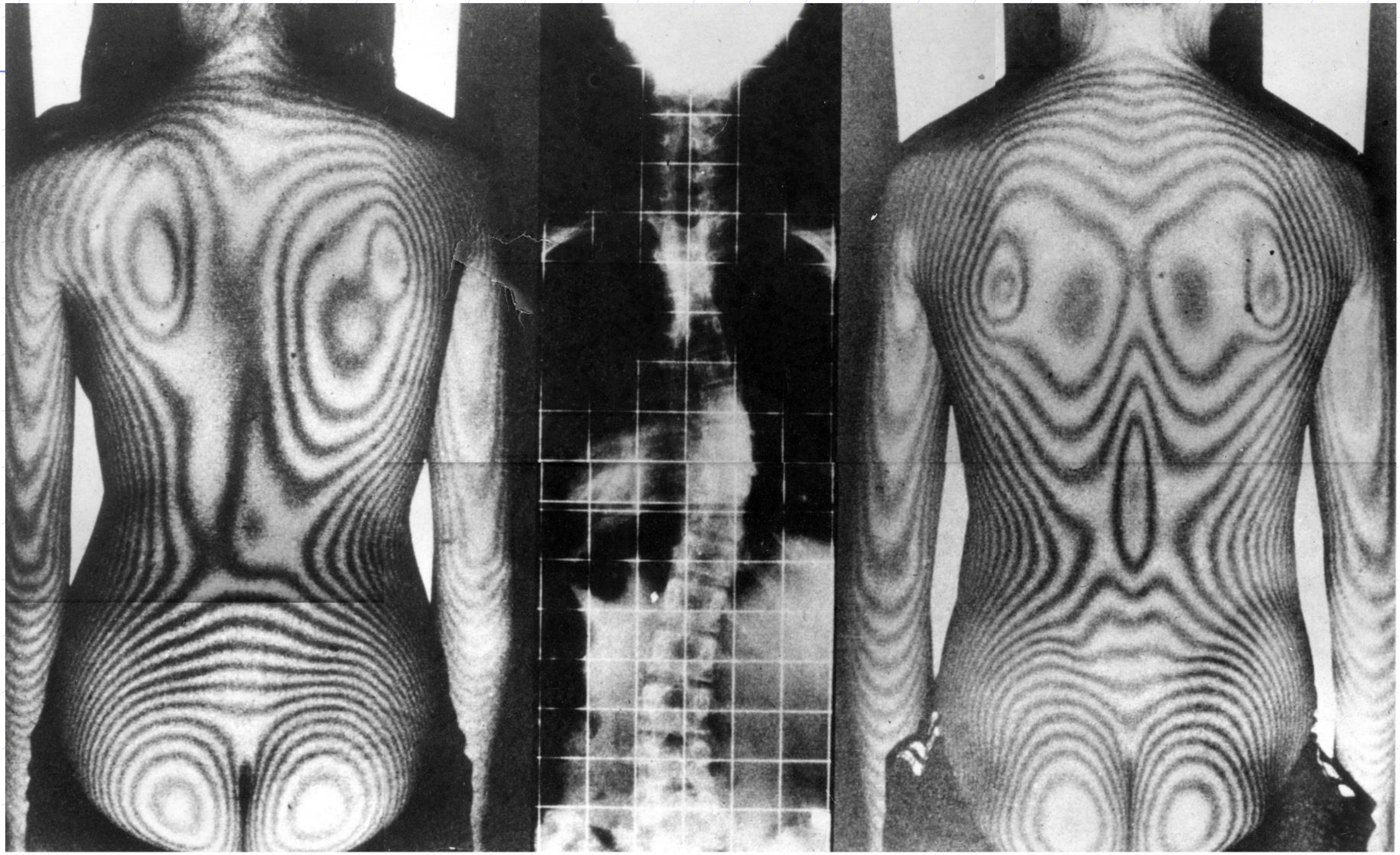


The Moire Topogram of a scoliotic patient

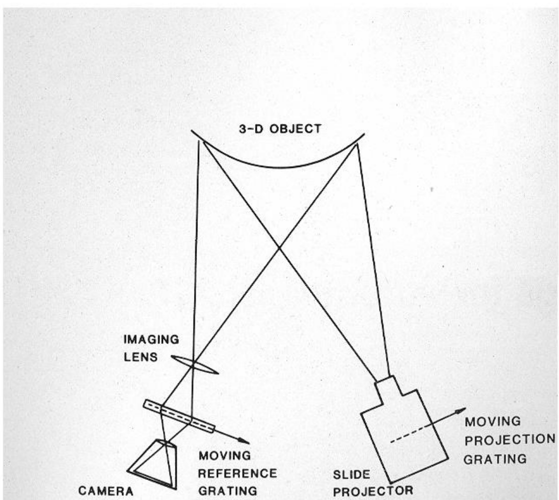
X ray image

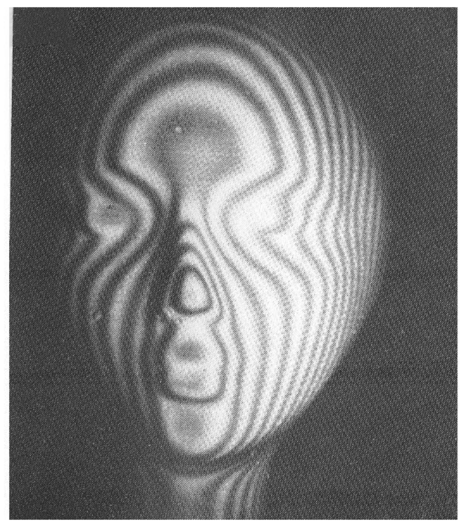
Normal

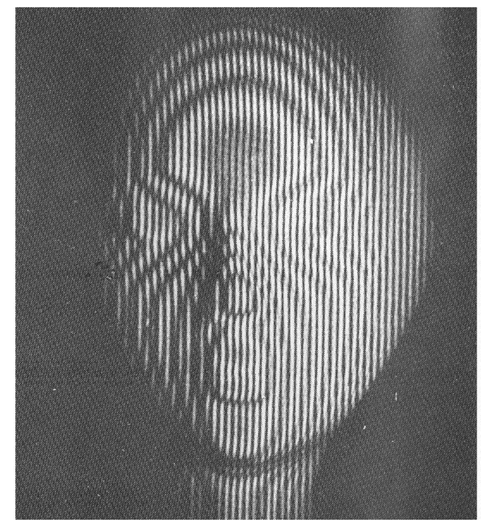
Takasaki 1970

Projection Moiré

Projection moire with moving gratings for automated 3-D topography




Moving-grating fringes


Stationary-grating fringes

1. Halioua, M., Chiang, F.P., et al., 1983. "Projection moiré with moving gratings for automated 3D topography," Appl. Opt., 22(6), pp. 850-855.

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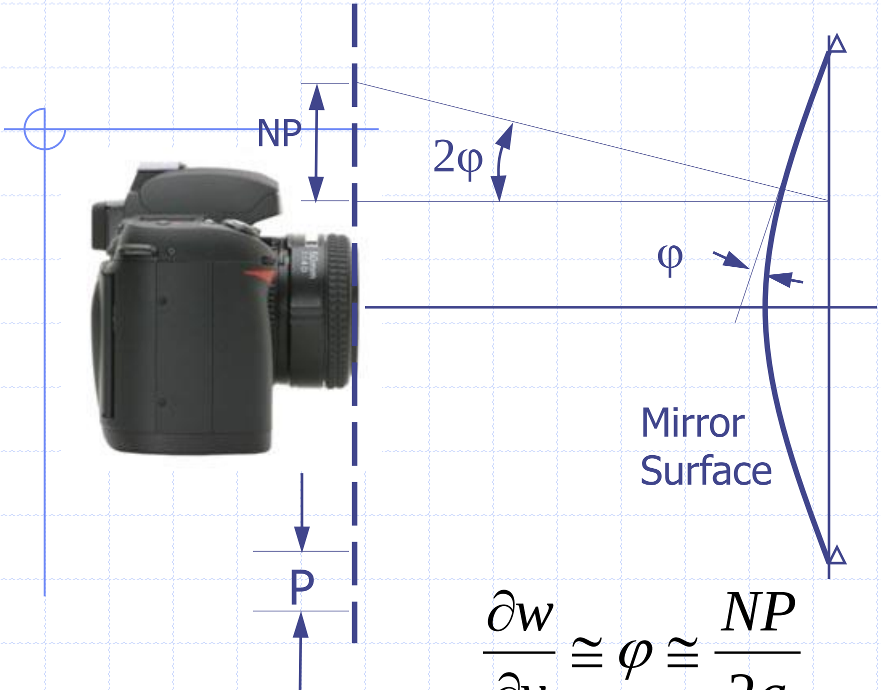
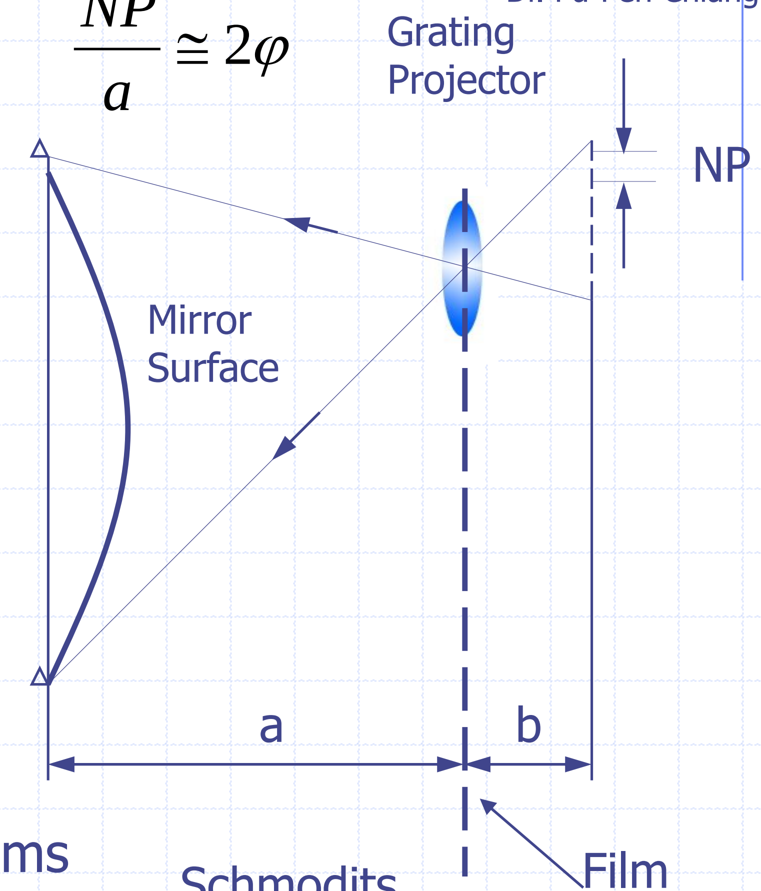
Reflection Moiré



$$\frac{\partial w}{\partial y} \cong \varphi \cong \frac{NP}{2a}$$

Ligtenberg

$$\frac{NP}{a} \cong 2\varphi$$



Schmodits

Reflection Moiré Systems

1. Lin, C.J., Chiang, F.P., 1979. "A time average reflection moiré method for vibration analysis of plates," Applied Optics, 18(9), pp. 1424-1427.
2. Chiang, F.P., Faber, C., et al., 1971. "Two dimensional stress measurement in permalloy thin films by moiré method," J. Applied Physics, 42(4), pp. 1422-1423.
3. Chiang, F.P., 1972. "A whole field method for the measurement of two-dimensional state of stress in thin films," Experimental Mechanics, 12(8), pp. 277-379.

Reflection Moiré

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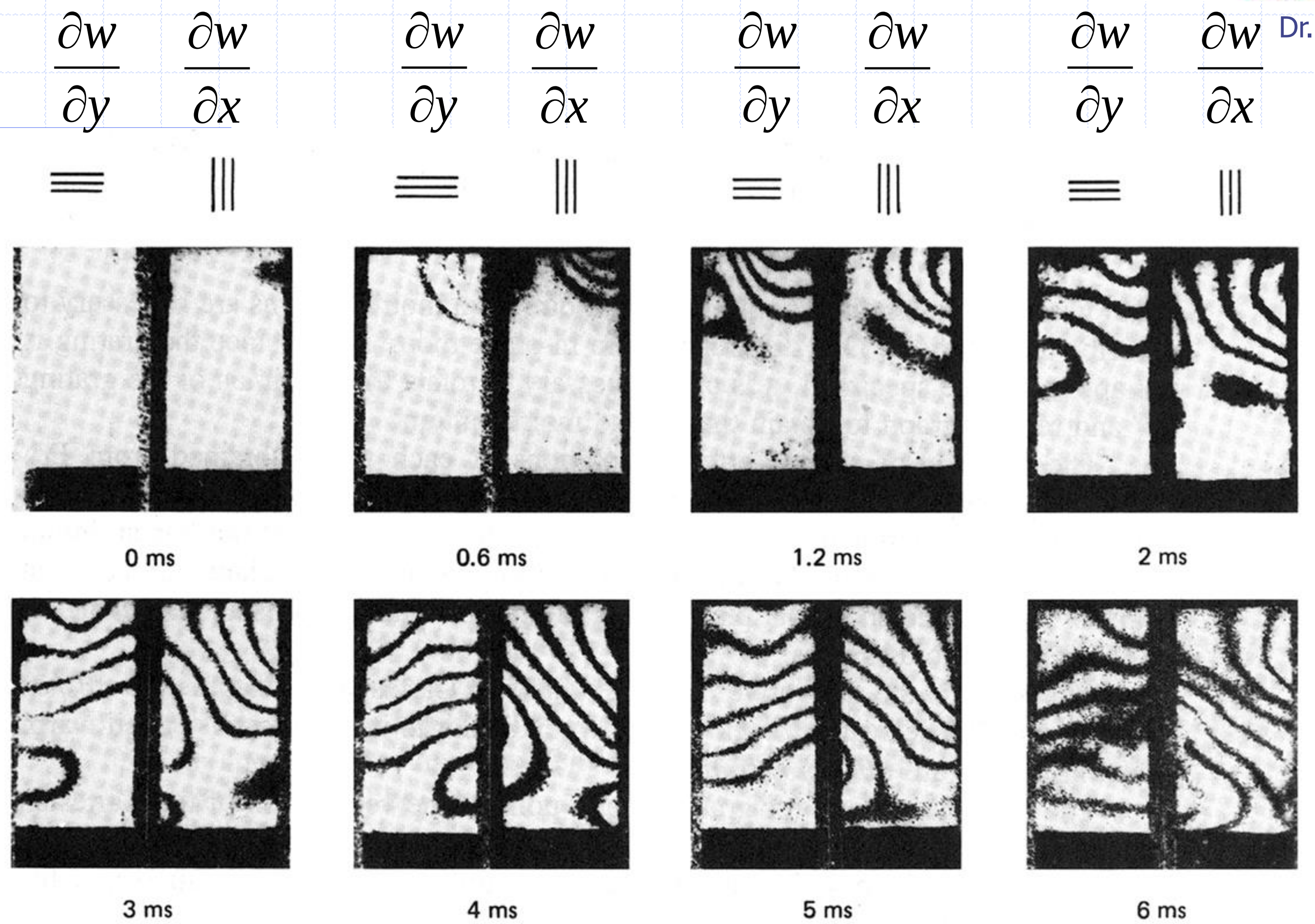

Dynamic Bending of a Plate

1. **Chiang, F.P., and Jaisingh, G., 1973. "Dynamic moiré methods for the bending of plates," Experimental Mechanics, 1(4), pp. 168-171.**
2. **Chiang, F.P., 1969. "Techniques of optical spatial filtering applied to the processing of moiré fringe patterns," Experimental mechanics, 6(11), pp. 5223-5226.**

Refraction Moiré & Moiré Deflectometry

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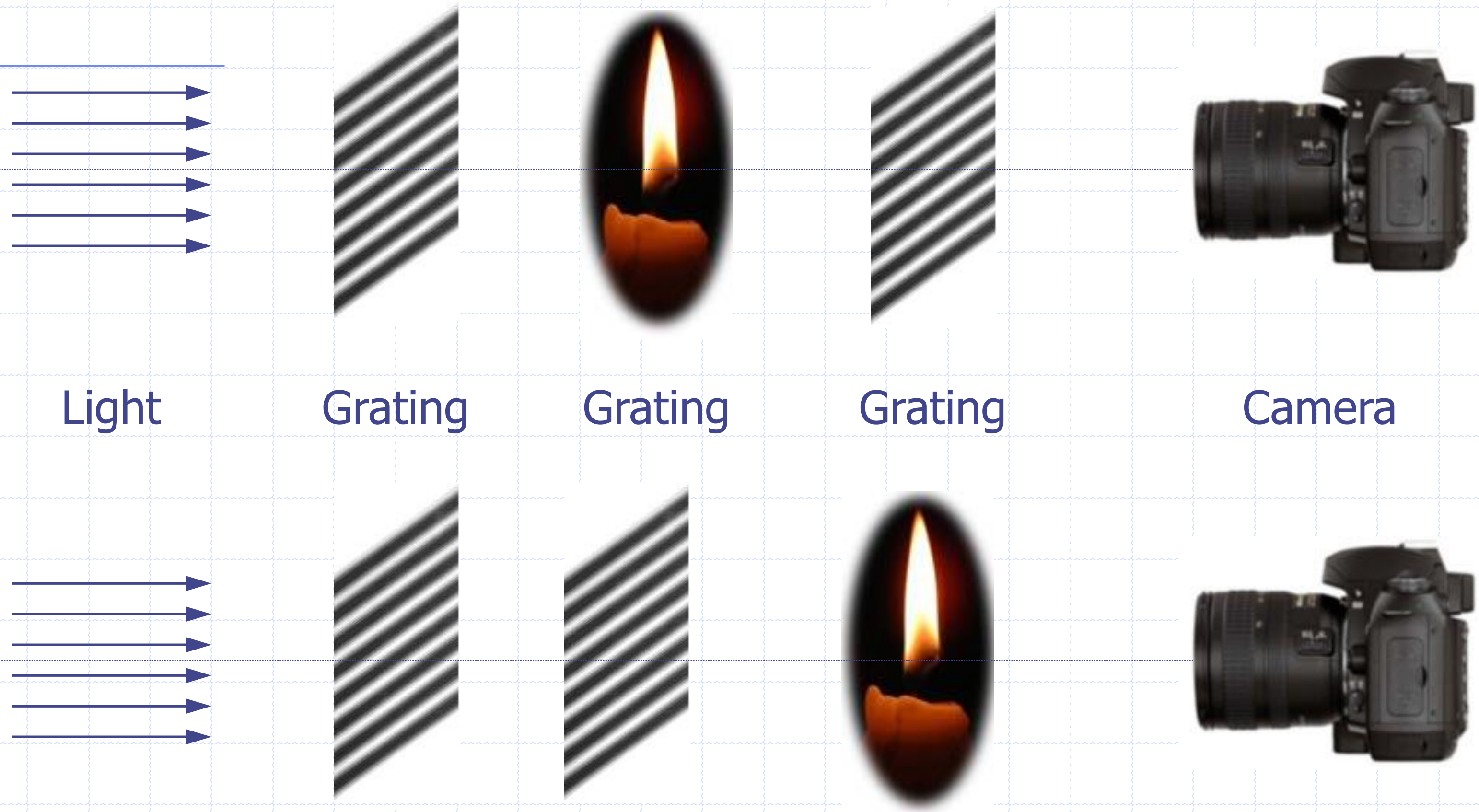

CGS (Coherent Gradient Sensor)

by Harresh Tippar

Moiré Interferometry

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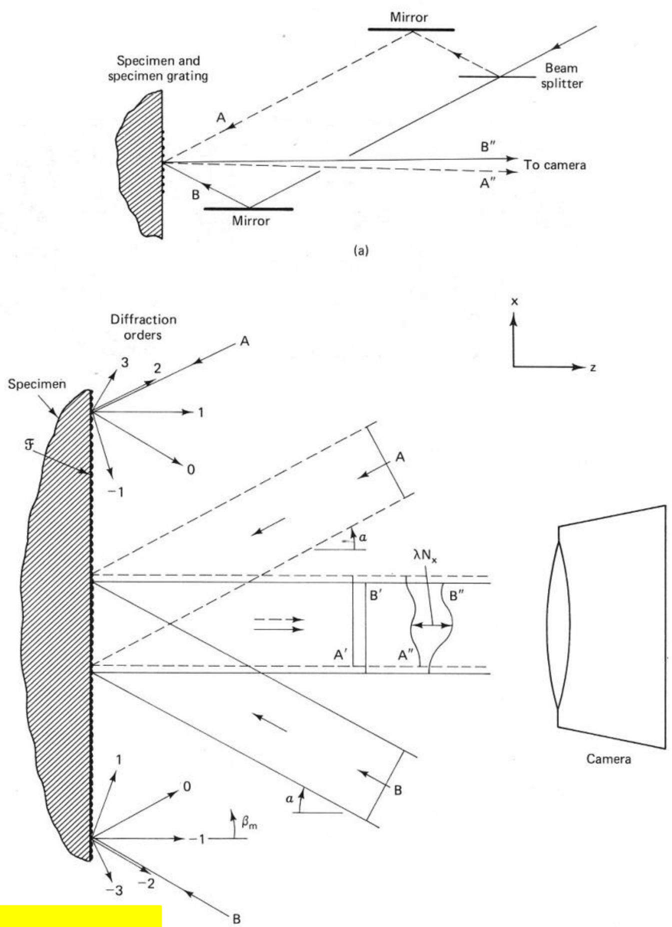

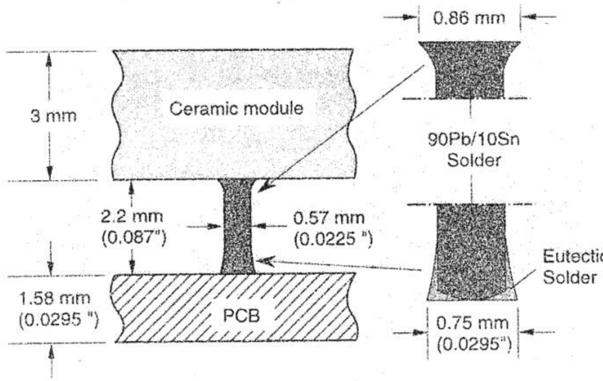

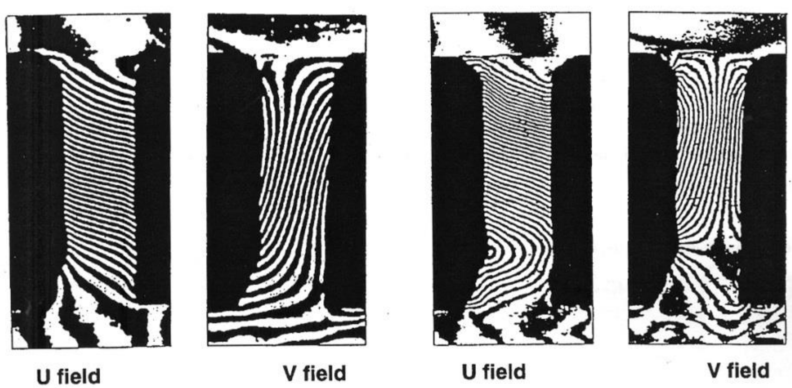

Han. B, 1997

1. Wang, Y.Y., and Chiang, F.P., 1997. "Experimental Study of Three-Dimensional Residual Stresses in Rails by Moiré Interferometry and Dissecting Method," Optics & Lasers in Engineering, 27, pp. 89-100.
2. Kin, C.C., and Chiang, F.P., 1984. "A three-beam interferometric technique for the determination of strain on curved surface," Optical Engineering, 23(6), pp. 766-768.

Holographic Interferometry

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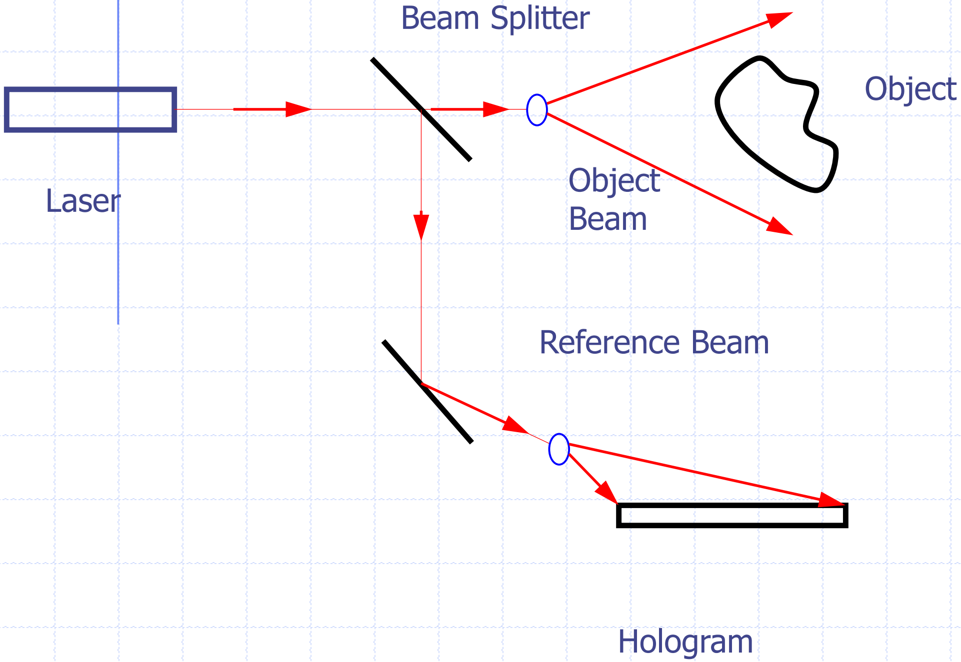
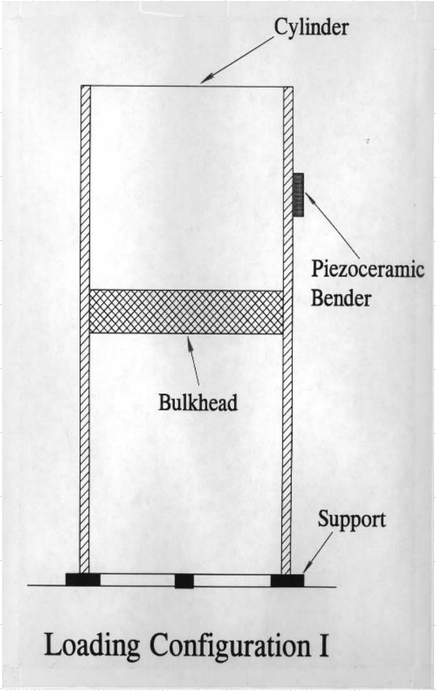
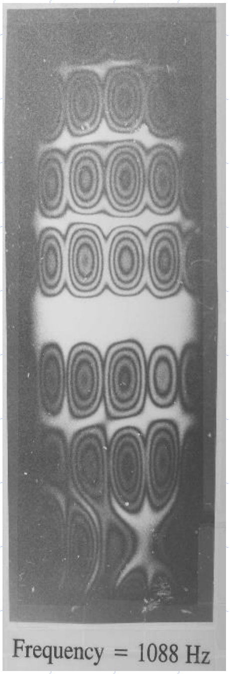
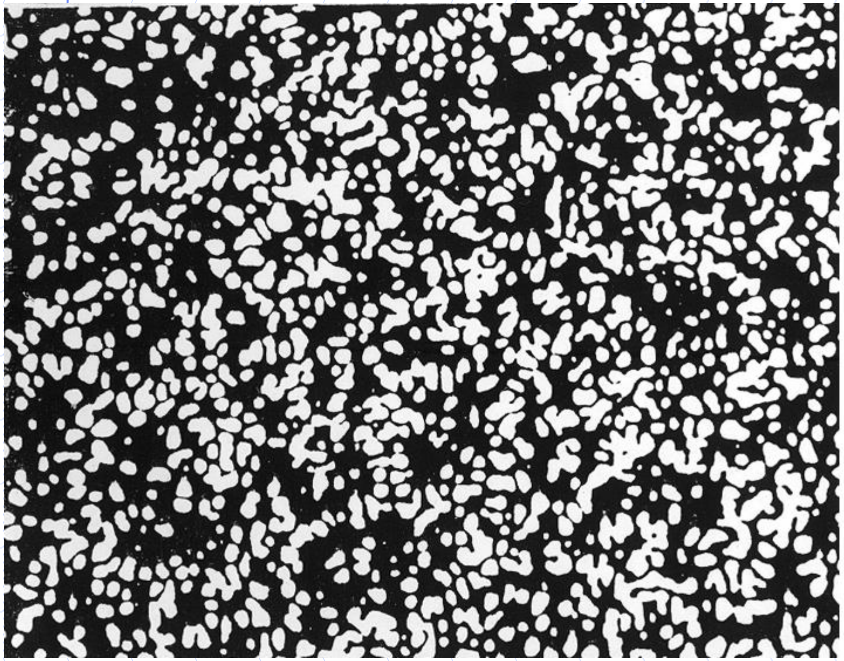


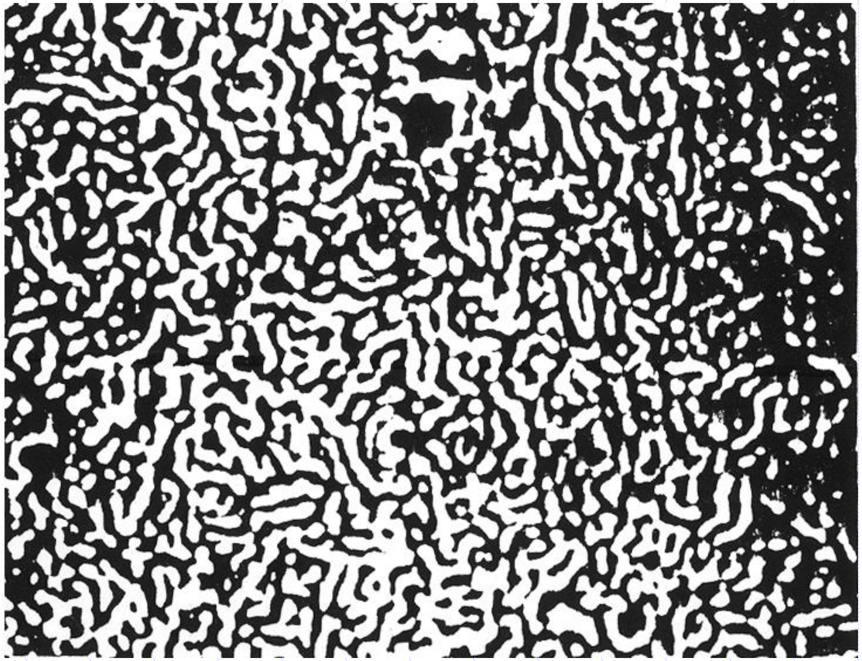




General Dynamics Company Electric Boat Division

One Beam Laser Speckles





Two-Beam Laser Speckle Interferometry

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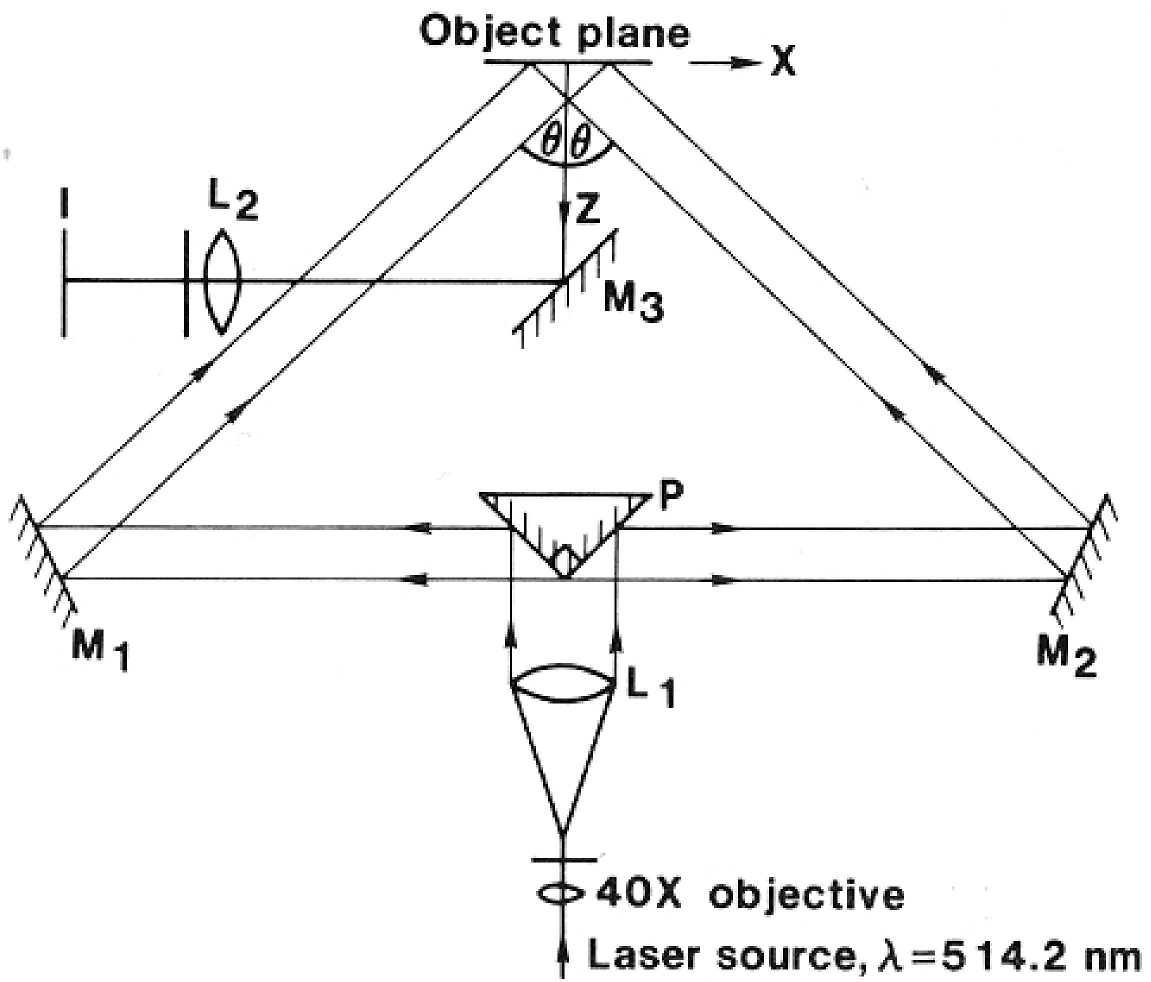

Butters *et al*, 1977

ESPI
(Electronic Speckle Pattern Interferometry)

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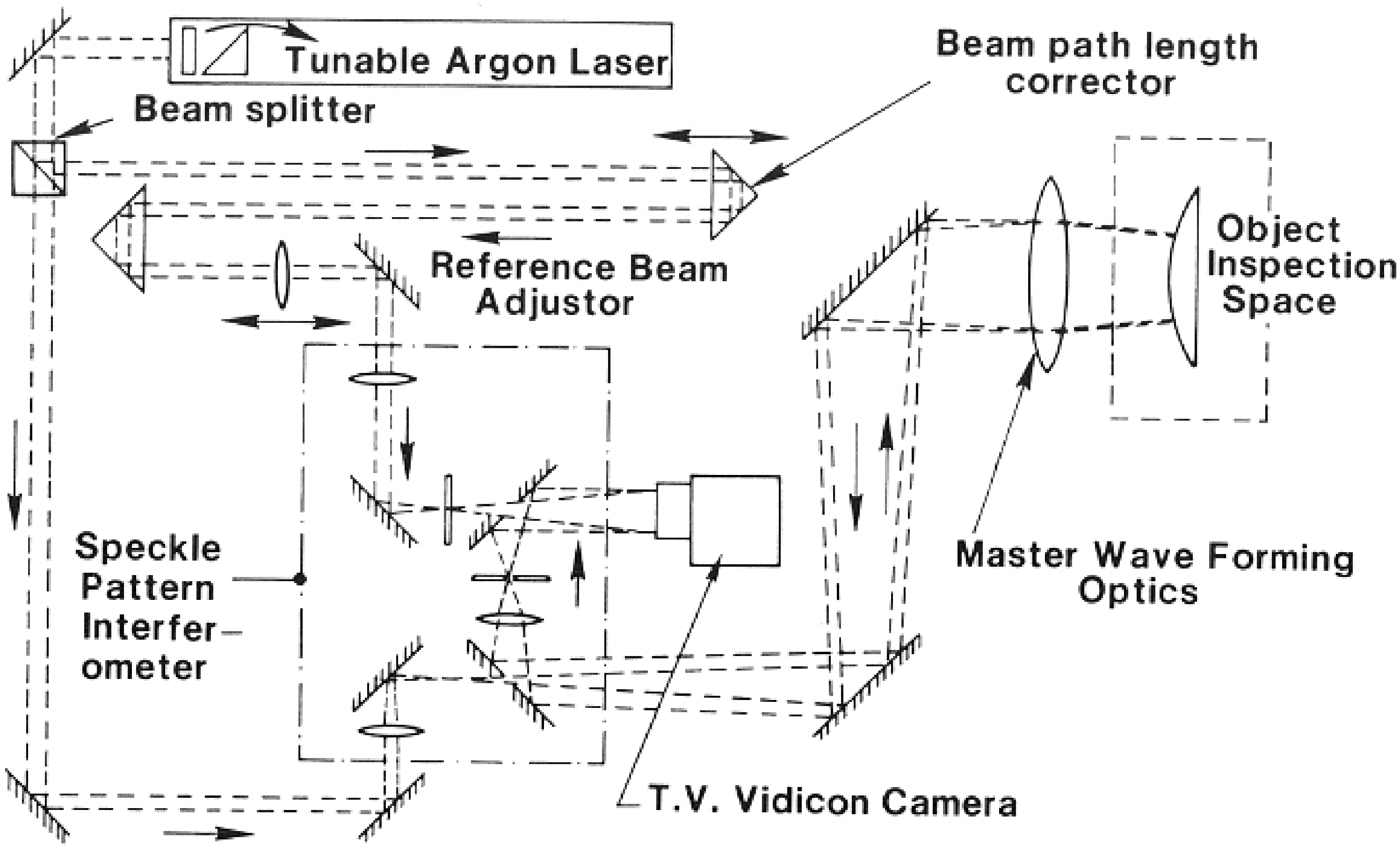

Butters *et al*, 1977

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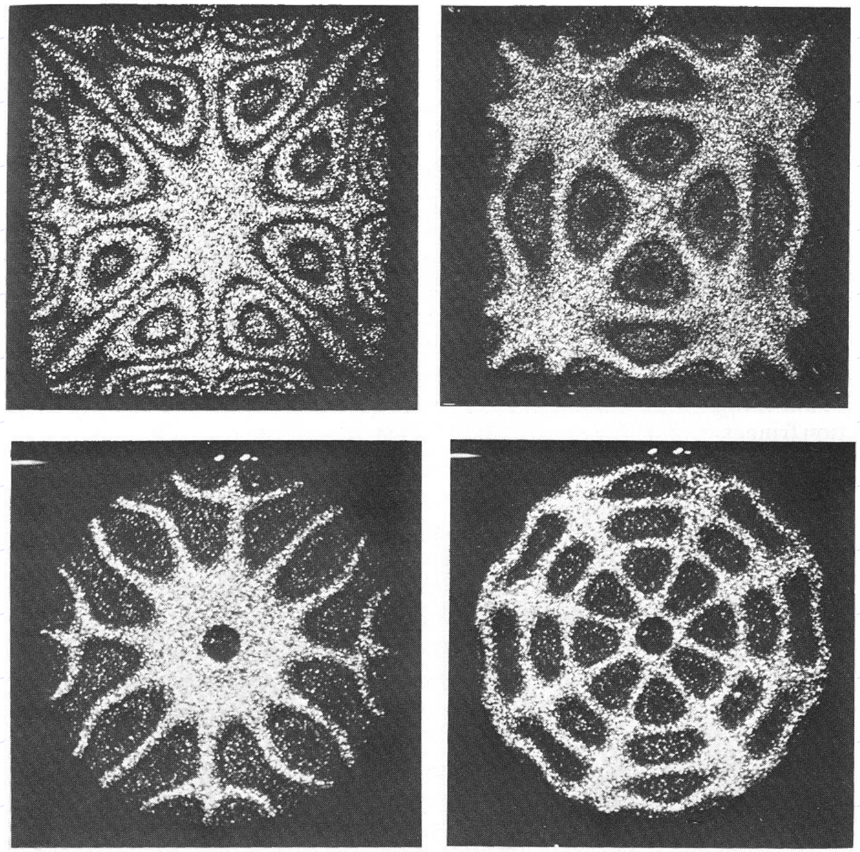

Butters *et al*, 1977

Advanced work by C.C.M,C.Y.Chang, et. al

One-Beam Laser Speckle Interferometry (Speckle Photography)

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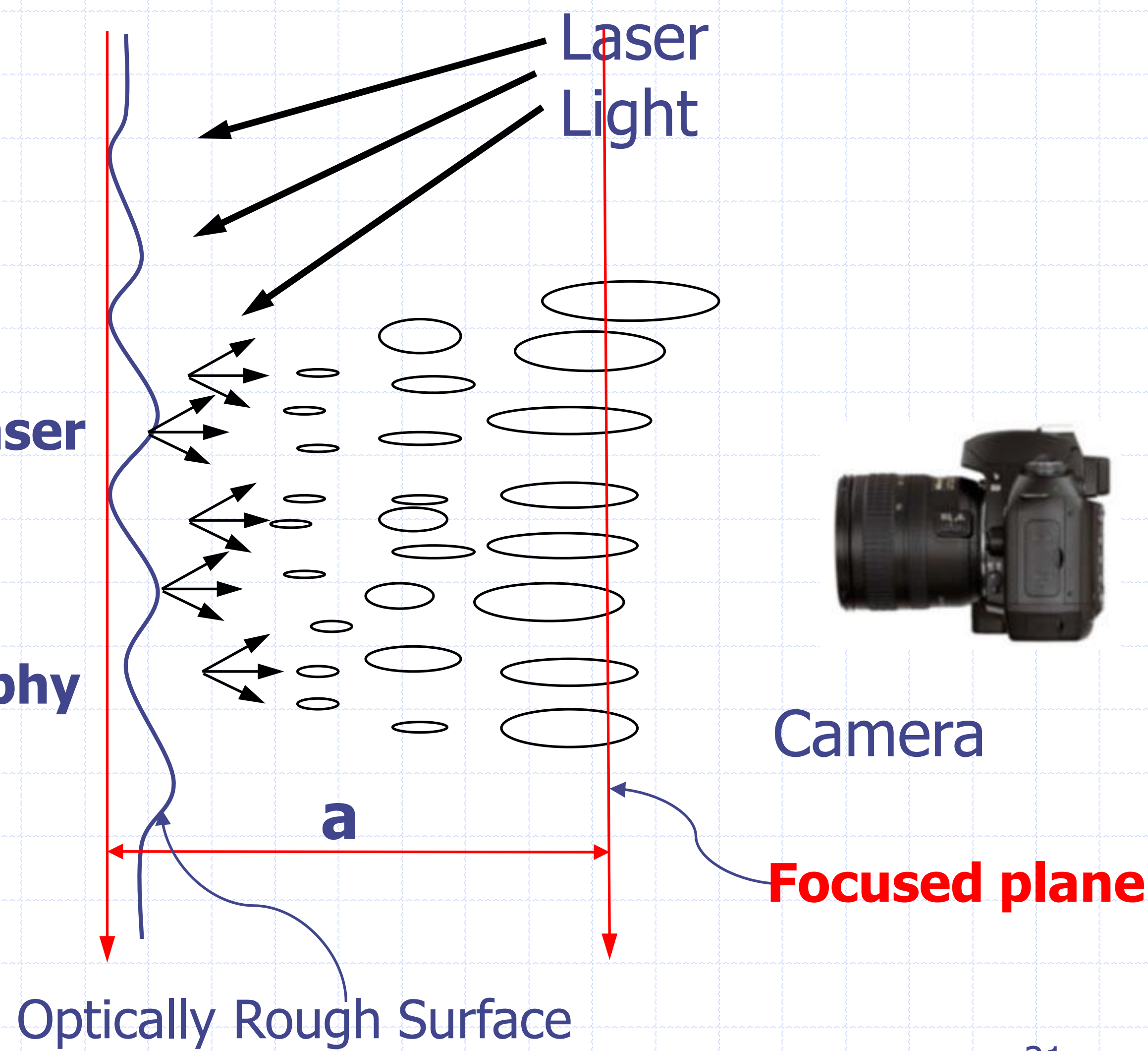
a= focused distance

When a = 0, in-plane laser speckle photography;

When a ≠ 0, defocused laser speckle photography



Processing of Specklegram

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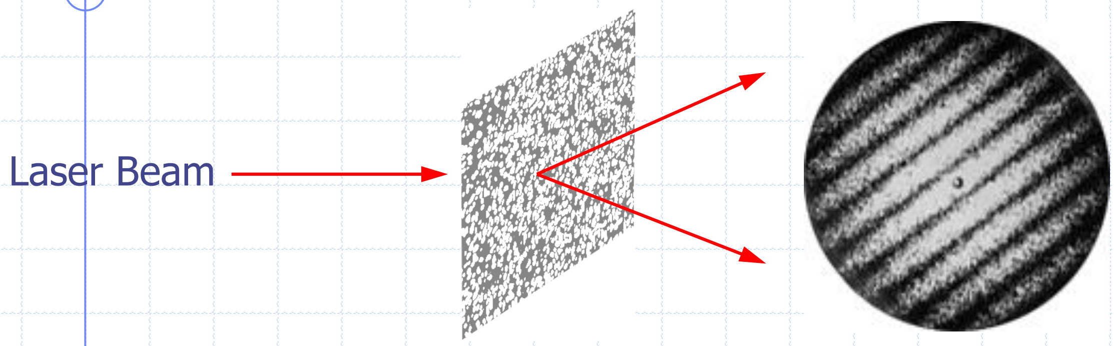
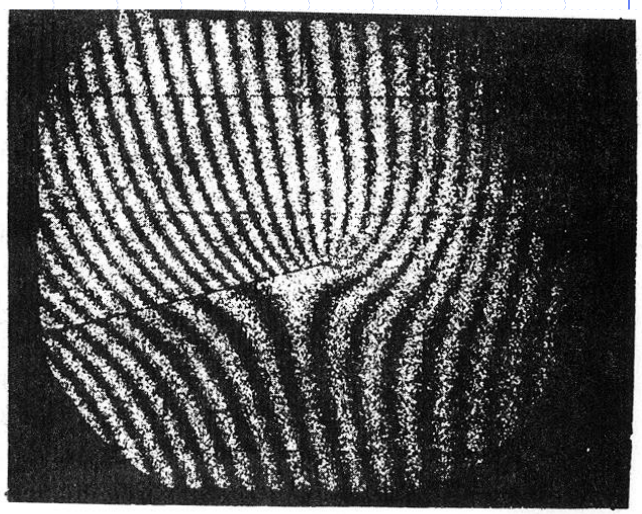
Pointwise Approach

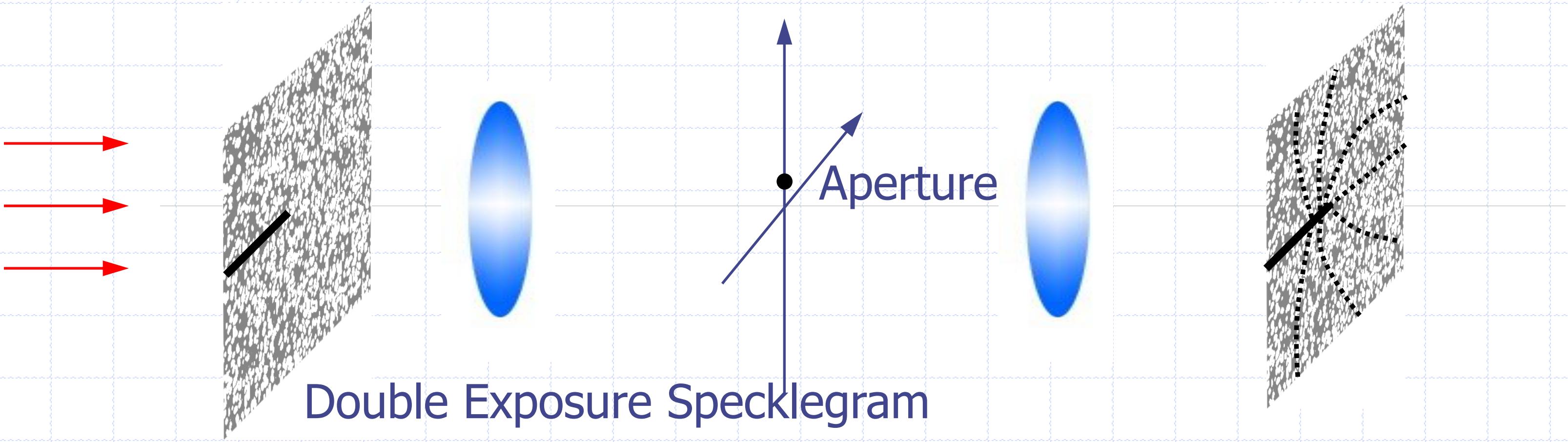


Double Exposure Specklegram



V-field Displacement Fringe Surrounding a Crack by One-beam Laser Speckle Photography

Full Field Approach



Double Exposure Specklegram

Contributions to in-plane laser speckle photography

1. Khetan, R.P., Chiang, F.P., 1976. "Strain analysis by one-beam laser speckle interferometry I: single aperture method," Applied Optics, 15(9), pp. 2205-2215.
2. Chiang, F.P., 1976. "A new three-dimensional strain analysis technique by scattered light speckle interferometry," The Engineering Uses of Coherent Optics, E.R. Robertson ed., Cambridge University Press, pp. 249-262.
3. Li, D.W., Chiang, F.P., 1978. "Mapping in-plane stress waves in solids by laser speckles," Mechanics Research Communications, 5(3), pp. 133-137.
4. Chiang, F.P., 1978. "Effect of magnification change in laser speckle interferometry," J. of Optical Soc. of America, 68(12), pp. 1742-1748.
5. Khetan, R.P., Chiang, F.P., 1979. "Strain analysis by one-beam laser speckle interferometry II," Applied Optics, 18(13), pp. 2178-2186.
6. Pedretti, M., Chiang, F.P., 1979. "On the lower limit of one beam laser speckle interferometry," Optics and Laser Technology, 11(3), pp. 143-147.
7. Adachi, Chiang, F.P., et al., 1980. "Thermal strain measurement by one-beam laser speckle method," Applied Optics, 19(16), pp. 2701-2704.
8. Lin, C.J., Chiang, F.P., 1980. "Stress analysis of in-plane vibration of 2D structure by a laser speckle method," Applied Optics, 19(16), pp. 2705-2708.
9. Lin, C.J., Chiang, F.P., 1981. "Laser speckle method for the analysis of steady-state in-plane vibrations of plates," J. of Acoustic Soc. of Am., 69(2), pp. 456-459
10. Adachi, J., Chiang, F.P., et al., 1982. "The subjective laser speckle method and its application of solid mechanics problems," Opt. Eng., 21(3), pp. 379-380.
11. Chen, J.B., Chiang, F.P., 1984. "Statistical analysis of whole field filtering of specklegram and its upper limit of measurement," J. of Optical. Soc. of Am., 1(8), 845-89.
12. Li, D.W., Chiang, F.P., 1985. "Statistical analysis of one-beam subjective laser speckle interferometry for displacement and strain analysis," J. Opt. Soc. Am., 2(5), pp. 657-666.
13. Chen, J.B., Chiang, F.P., 1985. "An investigation of speckle field in a diffusing cylinder," J. Opt. Soc. Am., 2(6), pp. 803-807.
14. Li, D.W., Chiang, F.P., 1985. "Diffraction halo functions of coherent and incoherent random speckle patterns," Applied Optics, 24(4), 2166-2170.
15. Li, D.W., Chiang, F.P., 1986. "Laws of laser speckle movement," Optical Engineering, 25(5), 667-670, May, 1986.
16. Li, D.W., Chiang, F.P., 1986. "De-correlation function in speckle photography," J. Opt. Soc. Am., 3(7), 1023-1031.
17. Gupta, P.K., Chiang, F.P., 1989. "Laser speckle interferometry applied to studying transient vibrations of a cantilever beam," J. Of Sound and Vibration, 133(2), 251-259.
18. Gupta, P.K., Chiang, F.P., 1990. "Resolution of resultant displacement into components in double exposure speckle photography," Applied Optics, 29(11), 1642-1645.

Some fundamental studies of laser speckle and speckle photography

1. Chen, J.B., Chiang, F.P., 1984. "Statistical analysis of whole field filtering of specklegram and its upper limit of measurement," J. of Optical. Soc. of Am., 1(8), 845-89.
2. Li, D.W., Chiang, F.P., 1985. "Statistical analysis of one-beam subjective laser speckle interferometry for displacement and strain analysis," J. Opt. Soc. Am., 2(5), pp. 657-666.
3. Chen, J.B., Chiang, F.P., 1985. "An investigation of speckle field in a diffusing cylinder," J. Opt. Soc. Am., 2(6), pp. 803-807.
4. Li, D.W., Chiang, F.P., 1985. "Diffraction halo functions of coherent and incoherent random speckle patterns," Applied Optics, 24(4), 2166-2170.
5. Li, D.W., Chiang, F.P., 1986. "Laws of laser speckle movement," Optical Engineering, 25(5), 667-670, May, 1986.
6. Li, D.W., Chiang, F.P., 1986. "De-correlation function in speckle photography," J. Opt. Soc. Am., 3(7), 1023-1031.
7. Li, Q. B., and F. P. Chiang. "Three-dimensional dimension of laser speckle". Applied *optics* 31.29 (1992): 6287-6291.

An interesting application of in-plane laser speckle photography

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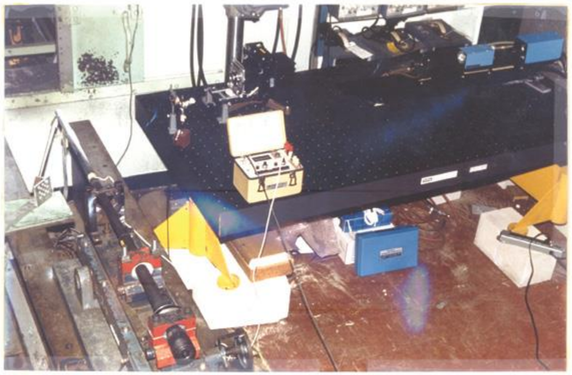
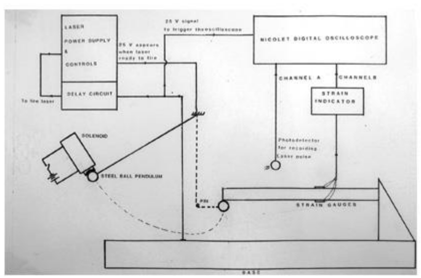
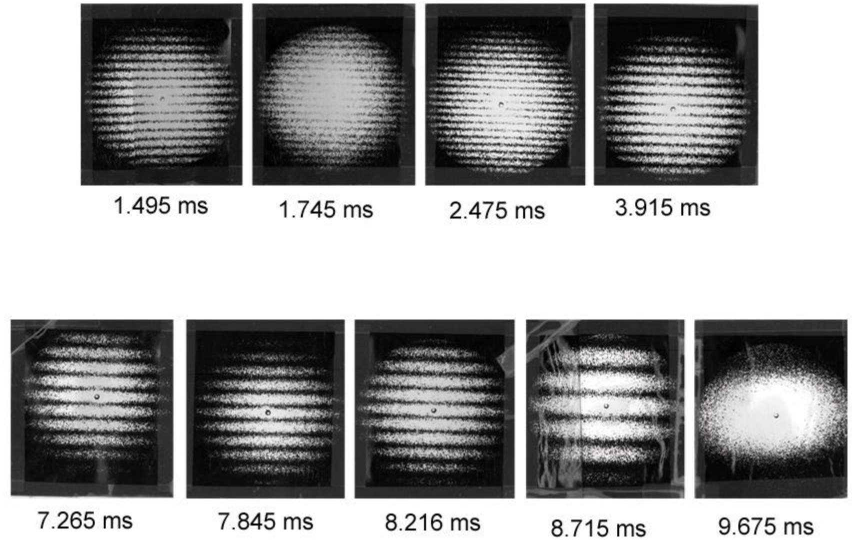
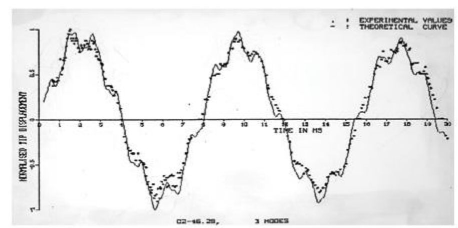




Dynamic Oscillation of the Tip of a Cantilever Beam under Impact



Young's Fringes at different times



Tip Displacement (Impact Loading)

1. **Chiang, F.P., and Gupta, P.K., 1989. "Laser speckle interferometry applied to studying transient vibrations of a cantilever beam," J. Of Sound and Vibration, 133(2), 251-259.**

One-Beam Laser Speckle Interferometry (Speckle Photography)

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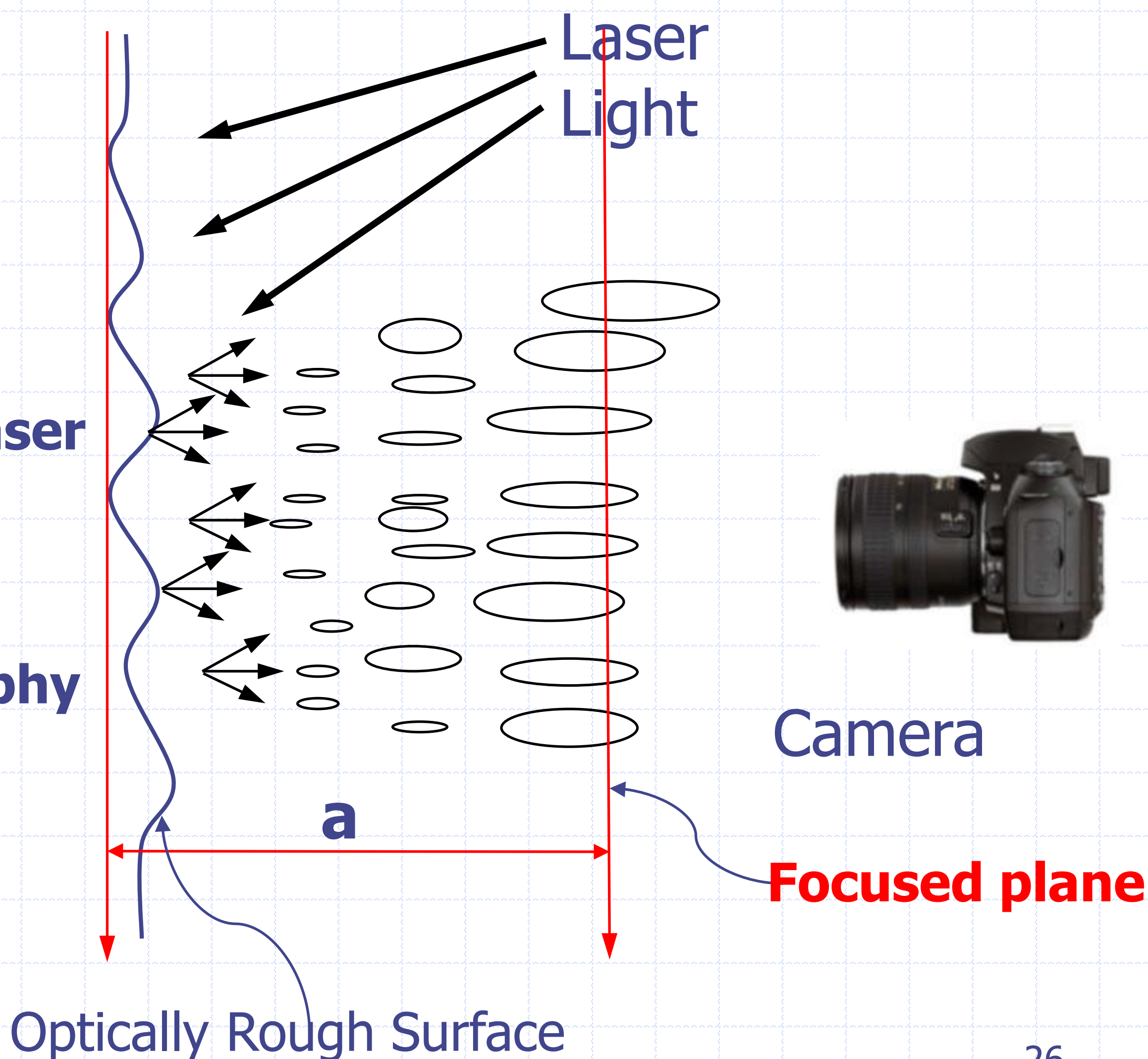
a= focused distance

When a = 0, in-plane laser speckle photography;

When a ≠ 0, defocused laser speckle photography



Contributions to defocused laser speckle photography

1. Chiang, F.P., 1976. "Laser speckle interferometry for plate bending problems," Applied Optics, 15(9), pp. 2219-2204.
2. Juang, H., Chiang, F.P., 1976. "Vibration analysis of plates and shells by laser speckle interferometry," Optica Acta, 23(12), pp. 997-1009.
3. Chiang, F.P., 1977. "Dynamic laser speckle interferometry applied to transient flexure problems," Applied Optics, 15, pp. 2199-2200.
4. Lin, C.J., Chiang, F.P., 1980. "A Ligtenberg method for plate bending studies using laser speckles," Mechanics Research Communications, 7(4), pp. 241-246.
5. Chin, K.C., Chiang, F.P., and Chang, W.B., 1981. "Time average laser specklegram of plate vibration using multi-aperture recording," Appl. Opt., 20(7), pp. 1123-1124.
6. Jin, F., Chiang, F.P., 1997. "A New Technique Using Digital Speckle Correlation for Nondestructive Inspection of Corrosion", Material Evaluation, 55(7), pp. 813-816.
7. Keene, L., and Chiang, F.P., 2009. "Real-time Anti-node Visualization of Vibrating Distributed Systems in Noisy Environments Using Defocused Laser Speckle Contrast Analysis," Journal of Sound and Vibration, 320, pp. 472-481.

An interesting application of defocused laser speckle photography

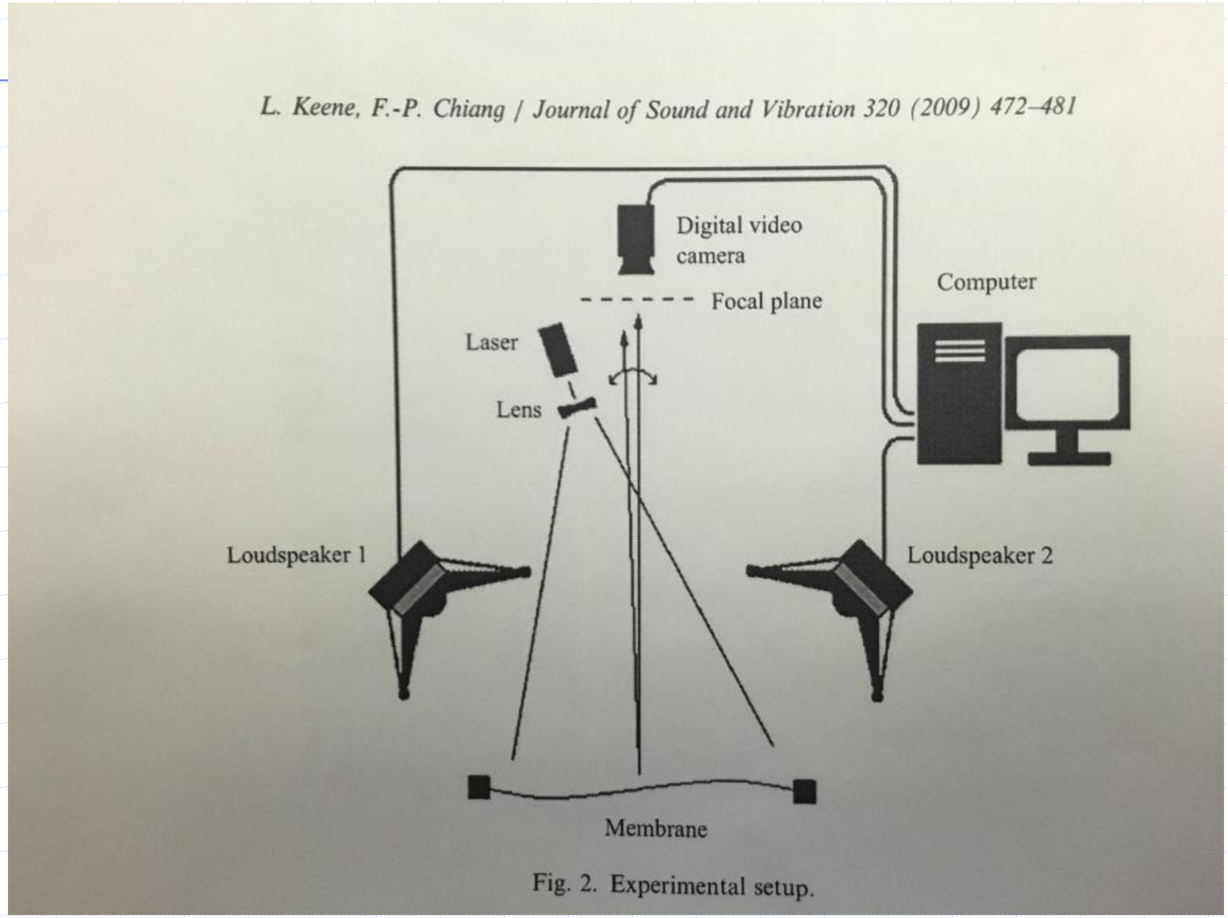


Fig. 2. Experimental setup.

Keene, L., and Chiang, F.P., 2009. "Real-time Anti-node Visualization of Vibrating Distributed Systems in Noisy Environments Using Defocused Laser Speckle Contrast Analysis," Journal of Sound and Vibration, 320, pp. 472-481.

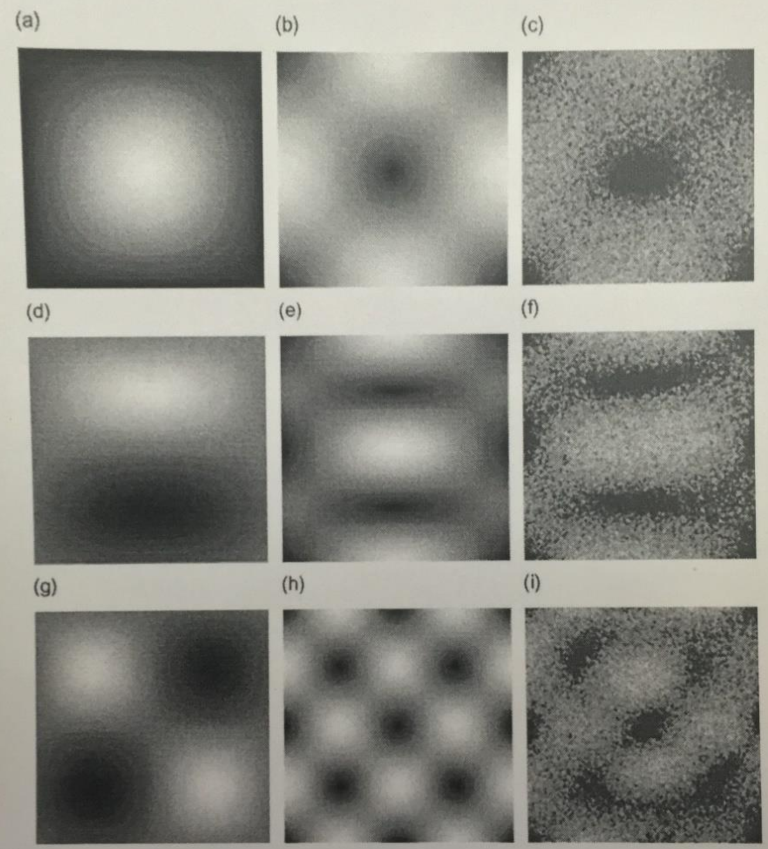


Fig. 3. (a) Mode 1,1 (deflection), (b) mode 1,1 (gradient). (c) mode 1,1 (imaged), (d) mode 2,1 (deflection), (e) mode 2,1 (gradient), (f) mode 2,1 (imaged), (g) mode 2,2 (deflection), (h) mode 2,2 (gradient) and (i) mode 2,2 (imaged).

Objective laser speckle method of strain analysis

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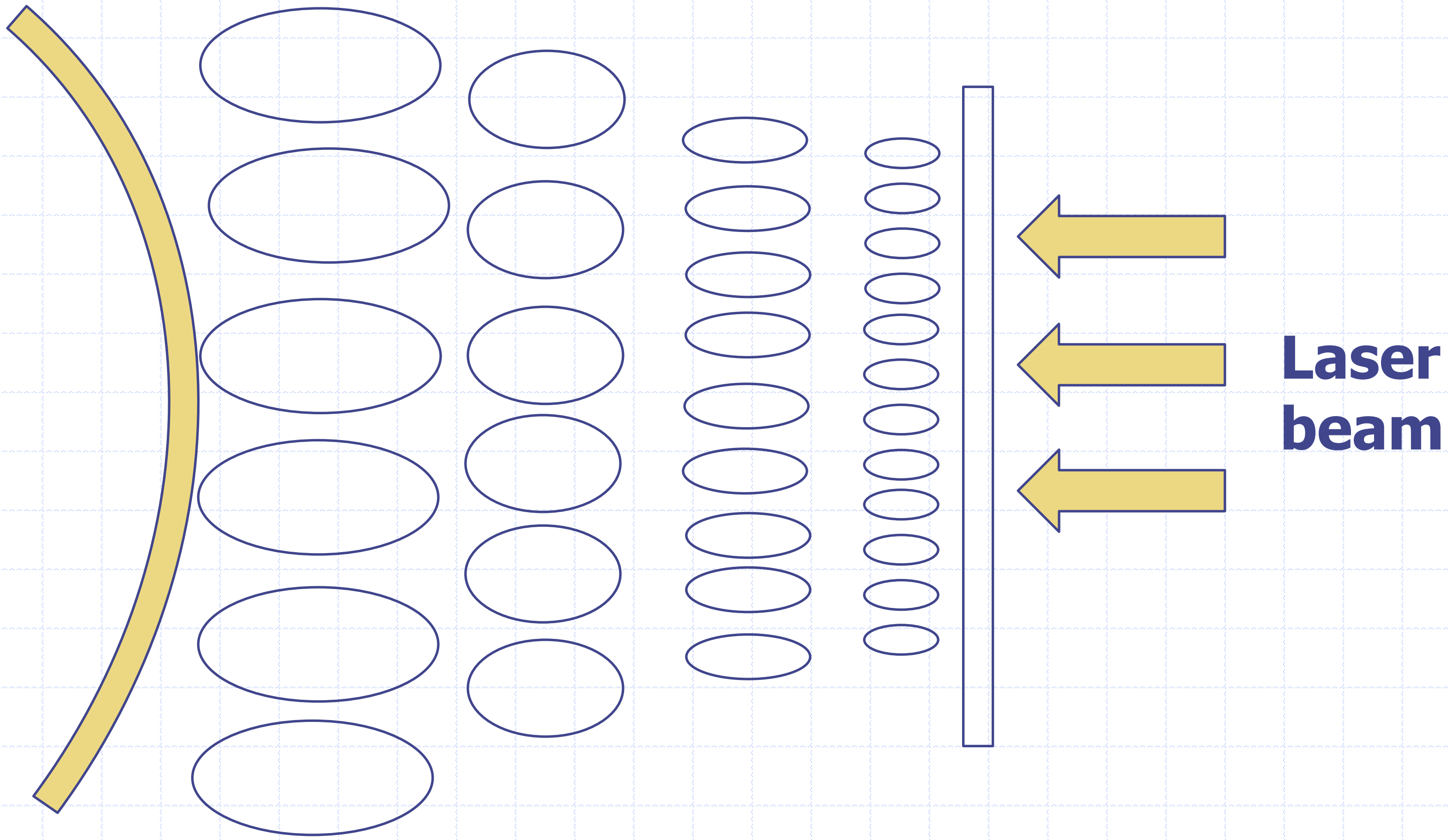

1. Kin, C.C., Chiang, F.P., 1982. "Strain Determination on curved surfaces using far-field objective laser speckles," Opt. Eng., 21(3), pp. 444-446.
2. Kin, C.C., Chiang, F.P., 1983. "Objective laser speckle method for 3D displacement measurement on curved surfaces," Opt. Engrg., 22(1), pp. 153-155.

Incoherent Speckle Method (White Light Speckle Method)

Stony Brook University
Dr. Fu-Pen Chiang

Surface with attached or natural speckles

Camera

1. Asundi, A., Chiang, F.P., 1979. "White light speckle method of experimental strain analysis," Applied Optics., 18(4), pp. 409-11.
2. Asundi, A., Chiang, F.P., 1980. "Interior displacement and strain measurement using white light speckles," Applied Optics, 19(4), pp. 2152-2256.
3. Bailangadi, M.N., Chiang, F.P., 1980. "White light projection speckle method for generating deflection contours," Applied Optics, 19(15), pp. 2623-2626.
4. Bailangadi, M.N., Chiang, F.P., 1981. "General analysis of the projection speckle method," Applied Optics, 20(9), pp. A90-A91.
5. Asundi, A., Chiang, F.P., 1982. "Measurement of large deformation using the white light speckle method," Mechanics Research Communication, 9(5), pp. 325-330.
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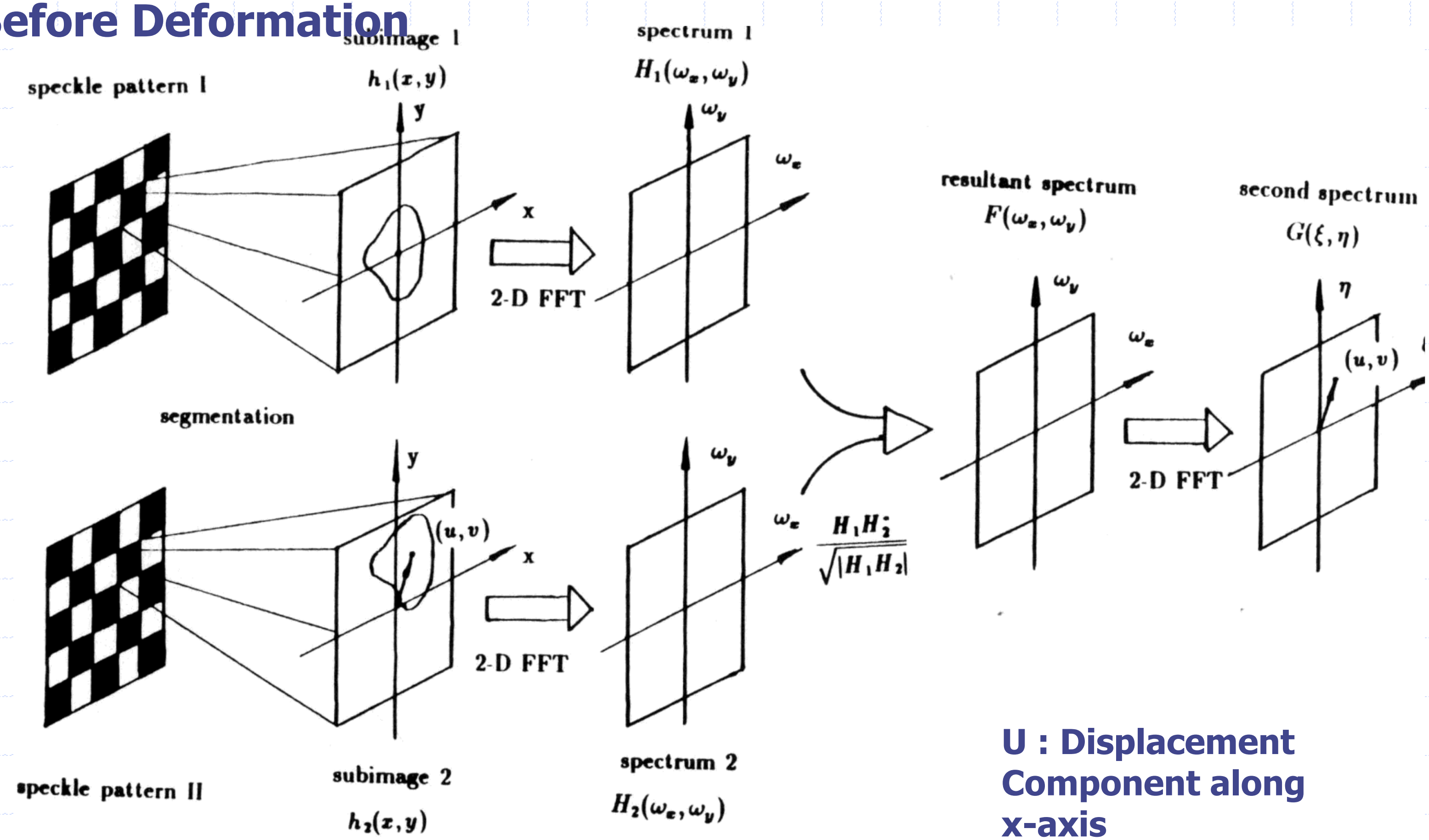
7. Wu, X.P., and Chiang, F.P., et al., 1985. "Chromatic speckle: its characteristics and applications," Proc. OSA 1985 Annual Meeting, Washington, D.C., Oct. 14-18, 1985, (Abstract).

Digital Speckle Photography :

Digital Recording and Digital Processing Using CASI (Computer Aided Speckle Interferometry)

Stony Brook University
Dr. Fu-Pen Chiang

Digital Specklegram Before Deformation



Digital Specklegram After Deformation

U : Displacement Component along x-axis
V : Displacement Component along y-axis

Contracting Heart

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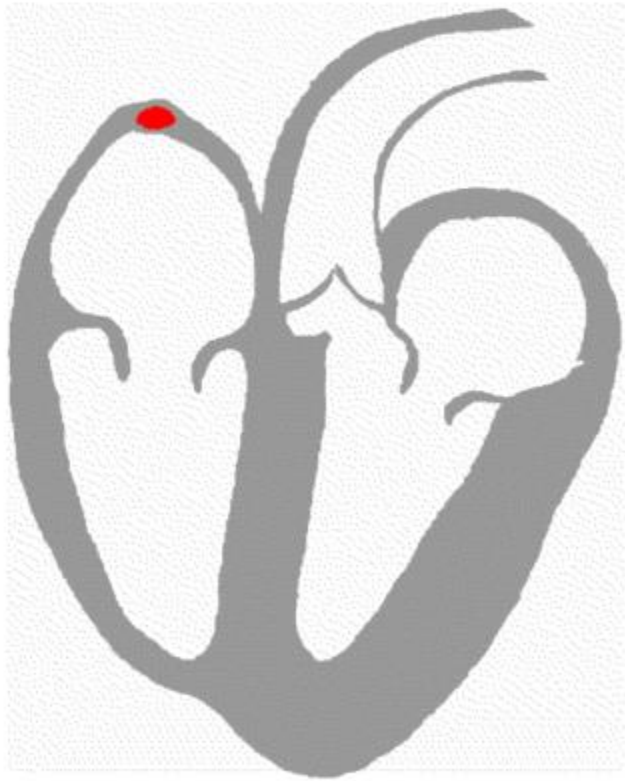
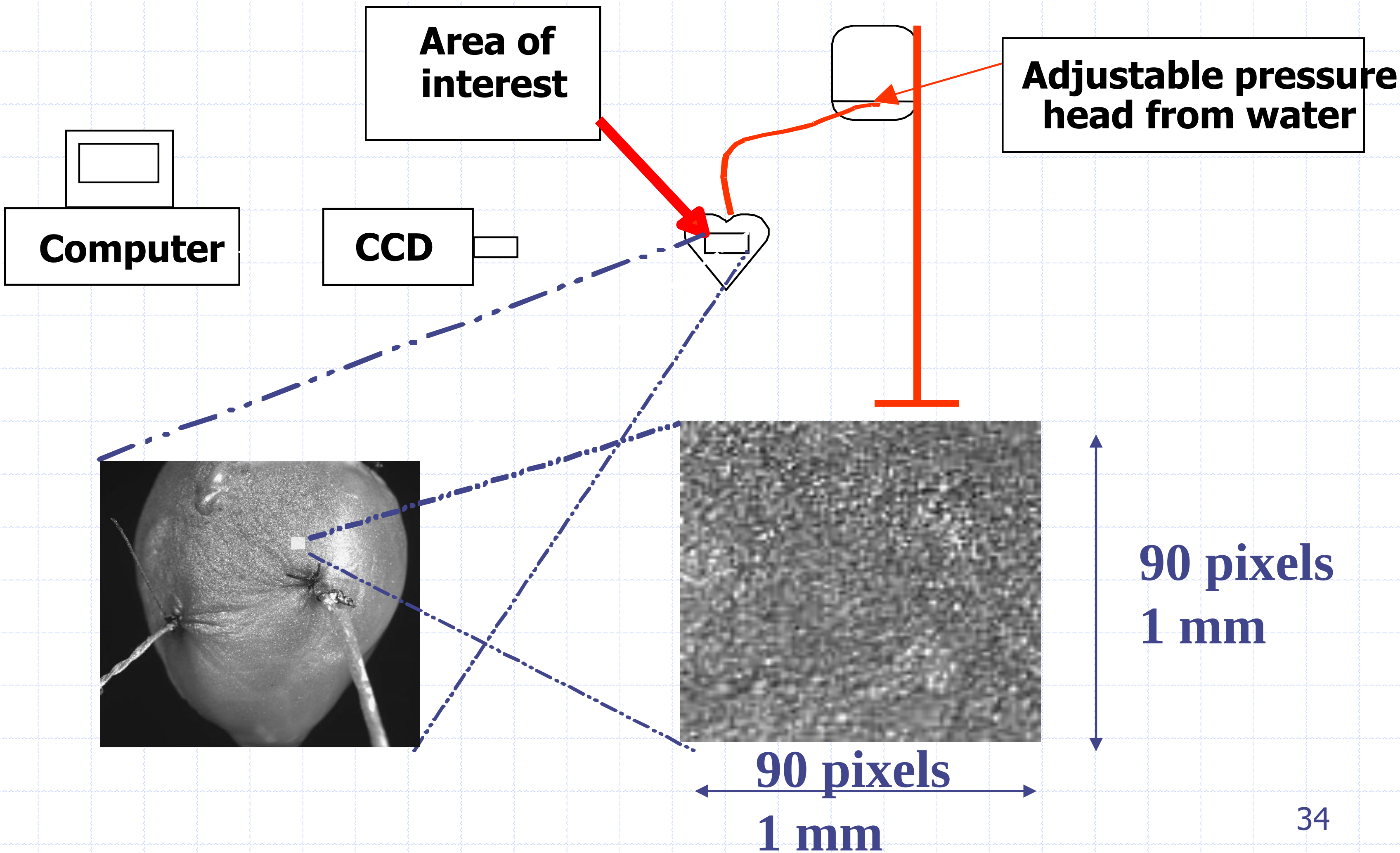


Validation of CASI as a Measuring Technique for Myocardial Deformation

Stony Brook University
Dr. Fu-Pen Chiang



Non-ischemic vs. Ischemic Work Loops Determined by CASI

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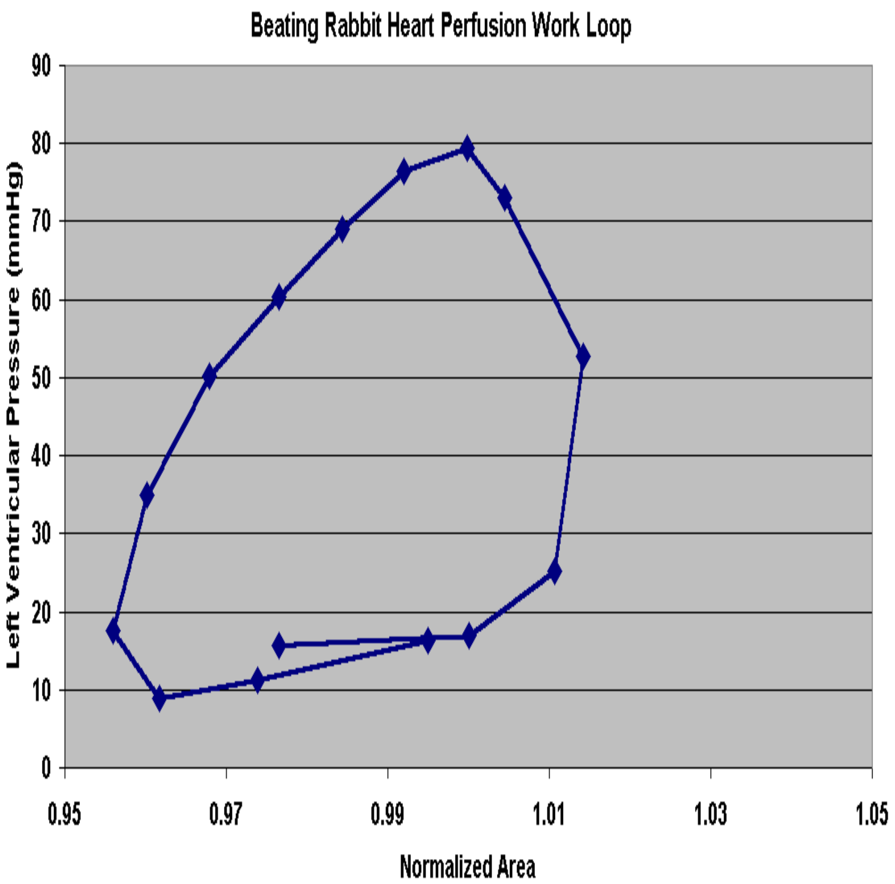

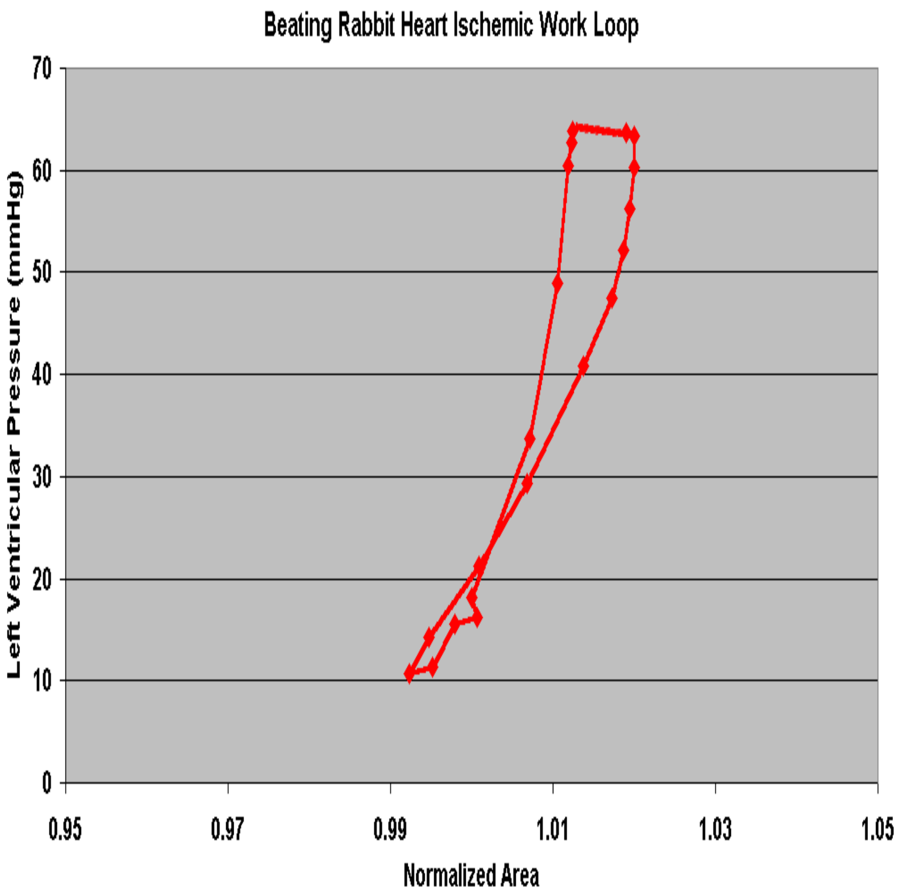

Contributions to Heart Mechanics:

1. Gaudette, G.R., Todaro, J., Krukenkamp, I.B., and Chiang, F.P. 1999. “A Novel Technique for Measuring Epicardial Deformation with High Spatial Resolution” Biophysical Journal 76(1), pp. A309.
2. Gaudette, G.R., Azeloglu, E.U., Oleszak, L., Saltman, A.E., Krukenkamp, I.B., and Chiang, F.P. 2002. “Determination of Regional Area Stroke Work with High Spatial Resolution in the Heart”, Cardiovascular Engineering, 2(4), pp. 129-137.
3. Chiang, F.P., Gaudette, G.R., Todaro, J., Keene, J., and Krukenkamp, I.B. 2002. “The Application of Speckle Metrology to the Heart”, Recent Advances in Experimental Mechanics, E.E. Gdoutos (Ed.) Kluwer Academic Publishers.
4. Gaudette, G.R., Lense, M., Todaro, J., Azeloglu, E.U., Oleszak, L., Saltman, A.E., Krukenkamp, I.B., and Chiang, F.P. 2004. “Effects of Eschemia on Epicardial Deformation in the Passive Rabbit Heart”, J. of Biomech Eng 126(1), pp. 70-75.
5. Chiang, F.P., Qin, Y.X., McLeod, K.J., and Guilak, F. 2005. “Correlation of Bony Ingrowth to the Distribution of Stress and Strain Parameters Surrounding a Porous-Coated Implant”, J. Orthopedics Research 14, pp. 862-870.
6. Chiang, F.P., Gaudette, G.R., Yun, Y., Azeloglu, E.U., Chen, W., Saltman, A.E., and Krukenkamp, I.B. 2006 “High Resolution Mechanical Function in the Intact Porcine Heart: Mechanical Effects of Pacemaker Location”, J. Biomechanics, 39, pp. 717-725.

Electron Speckle Photography (ESP) Technique

- laser and white light speckle technique have resolution limits, λ=wavelength of visible light, ~0.5 micro

- Speckle size = 1.2λF
λ: wavelength, F = f/number of lens aperture

- Using electron speckle photography extends the resolution into nanometer region.

Electron Speckle Photography (ESP)

Procedure

- Creating micro/nano particles on specimen surface which are used as gauging devices to map the full field deformation.

- Recording and digitizing speckle patterns using an electron microscope.

- Analyzing speckle images by CASI (Computer Aided Speckle Interferometry)

Stony Brook University

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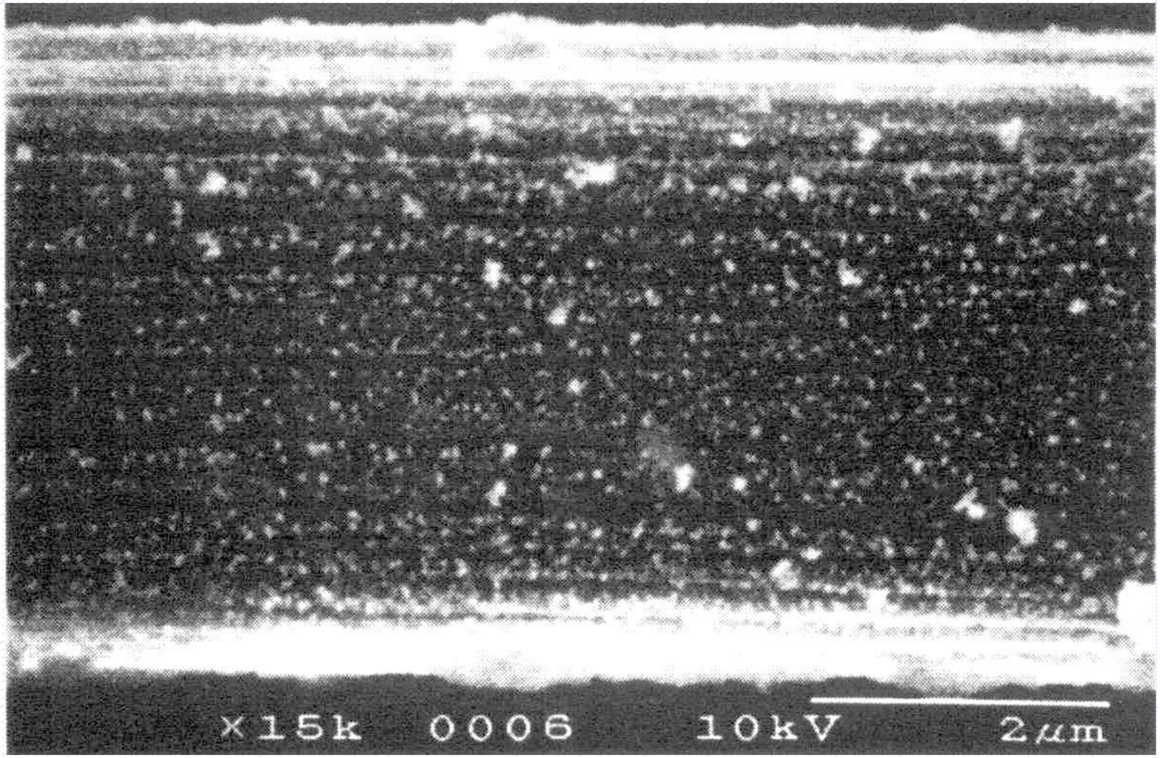
Submicron Speckle Pattern on a Strand of Graphite as recorded by SEM



Typical Electron Speckle Photography Pattern

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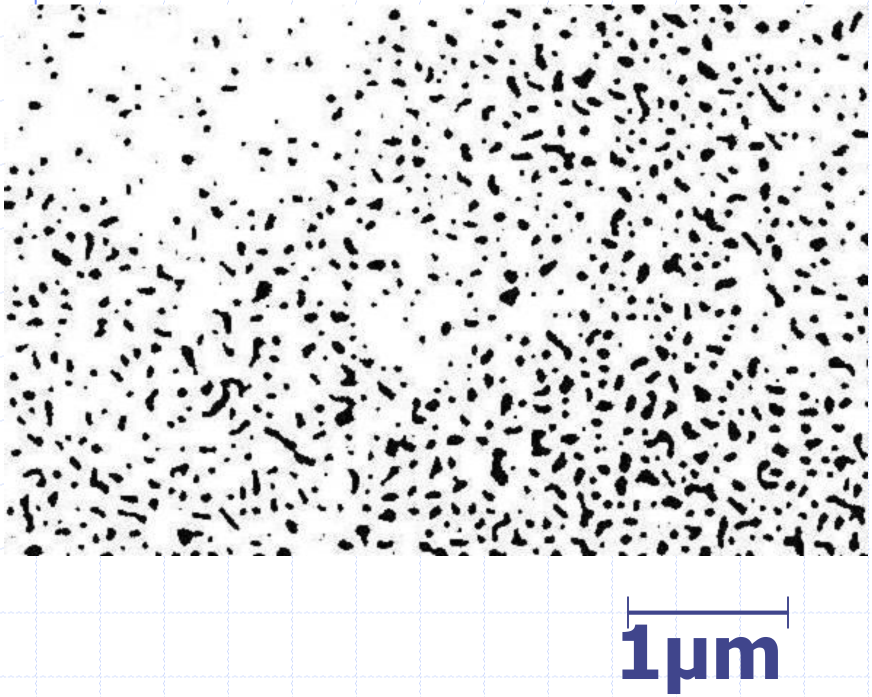

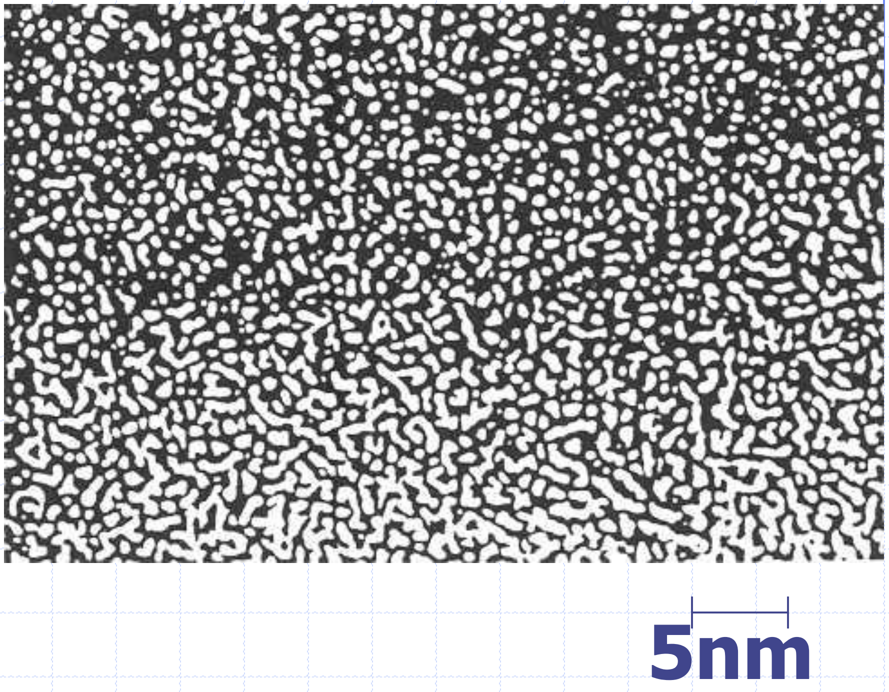

Observed by SEM **Observed by TEM**

Examples of ESP

crack tip residual strain distribution in steel

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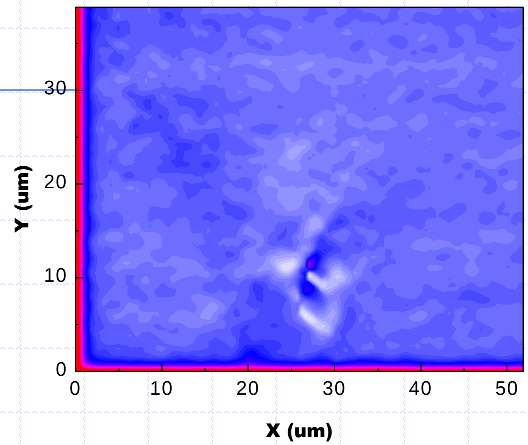
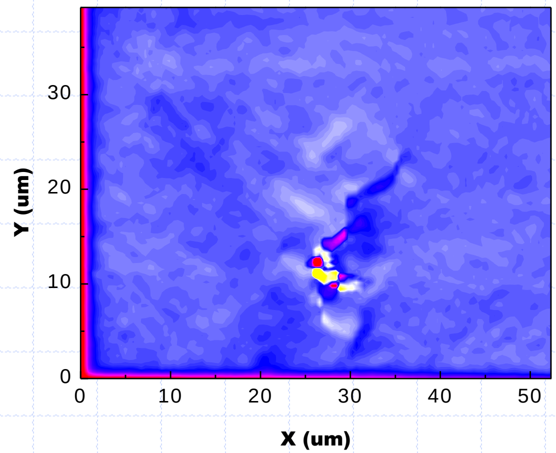
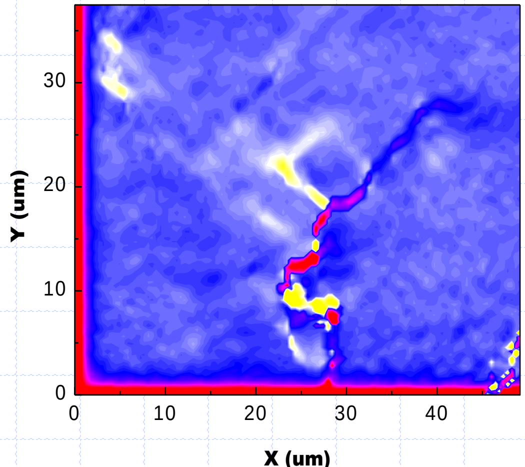
Dr. Fu-Pen Chiang



1,000 cycles



1,500 cycles



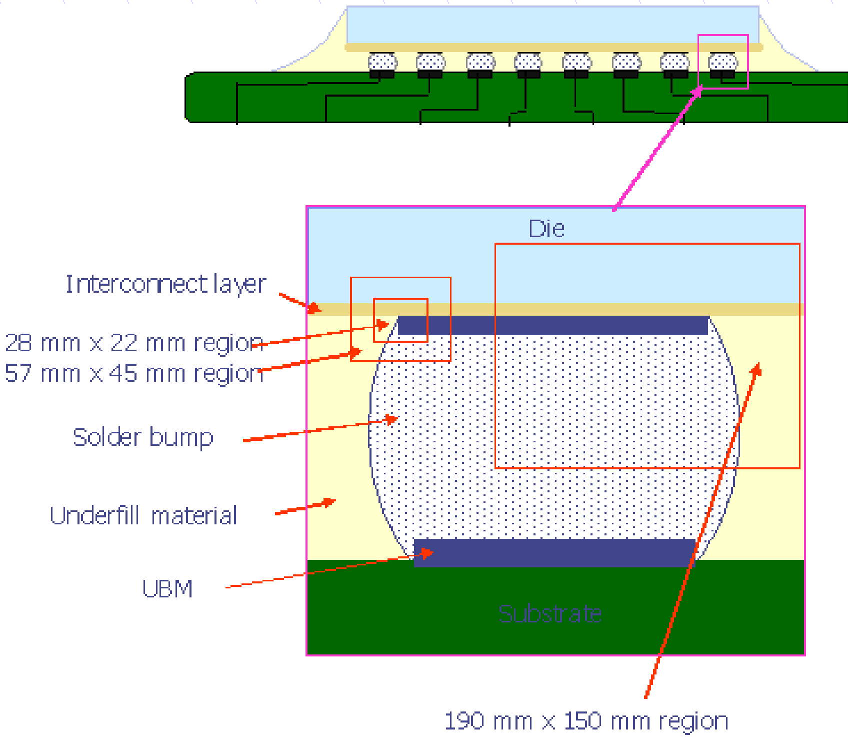
2,000 cycles

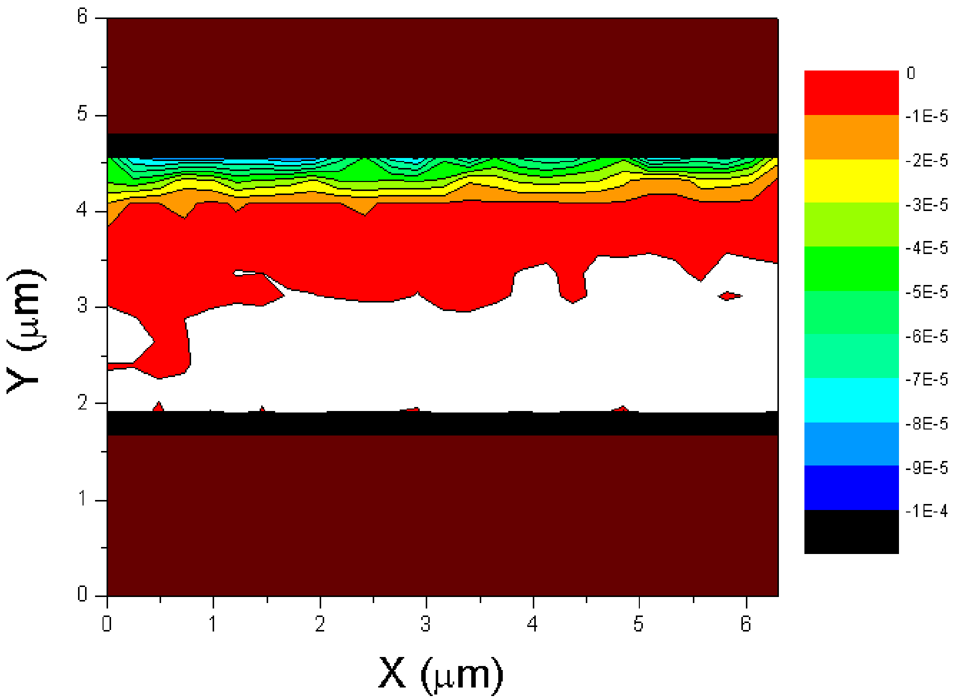
0.0750 -- 0.1000
0.0500 -- 0.0750
0.02500 -- 0.0500
0 -- 0.02500
-0.02500 -- 0
-0.0500 – -0.02500
-0.0750 – -0.0500
-0.1000 – -0.0750
-0.1250 – -0.1000
-0.1500 – -0.1250

Electron Speckle Photography

Application to Thermal Strain Determination in Electronic Packaging

Stony Brook University
Dr. Fu-Pen Chiang

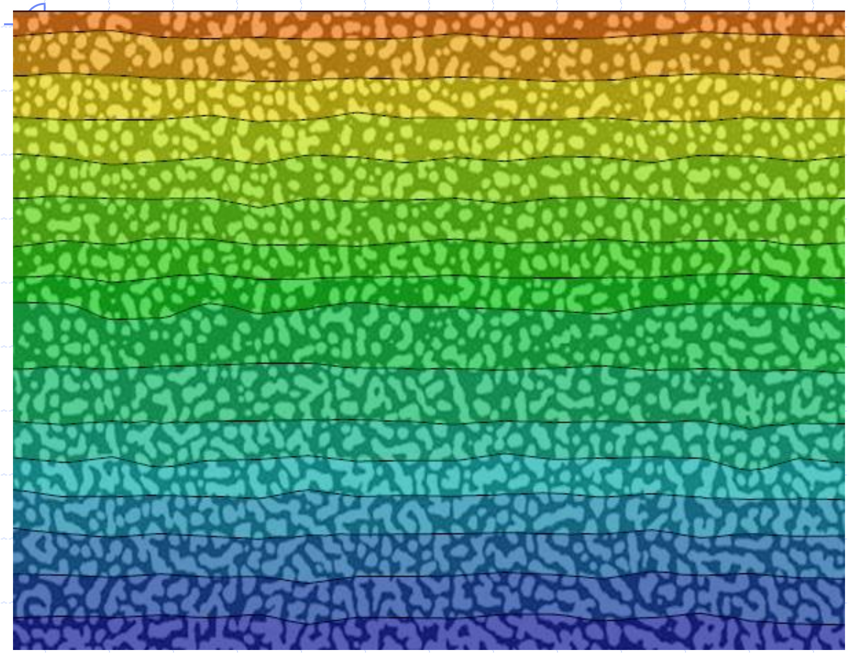




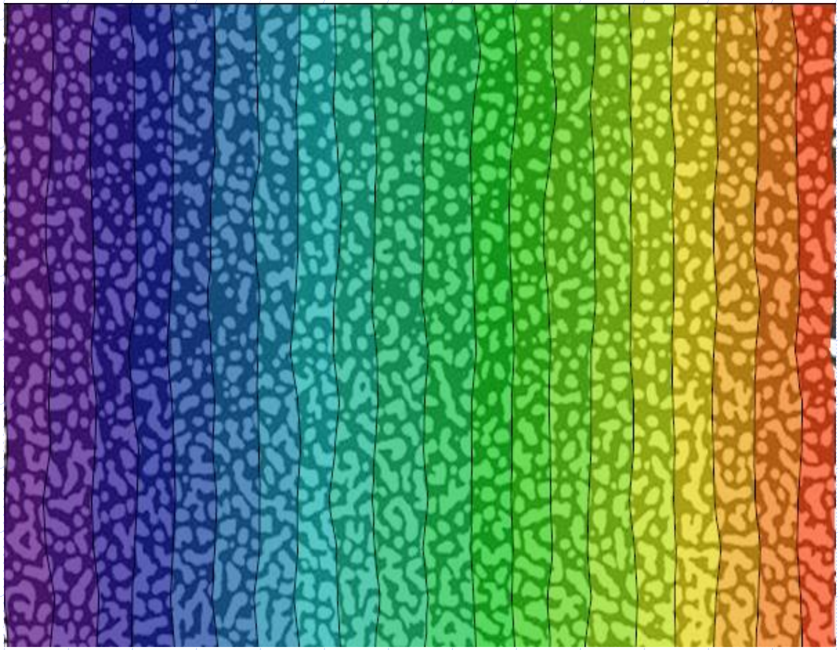
Testing Regions of Cu-Si3N4

V field at ΔT = 188ºC

Project from Motorola Inc.



v field



u field

v and u displacement fields after a virtue stretch of the image both in vertical and horizontal directions
The displacement contour interval is 0.04 nm.

Publications on facture mechanics

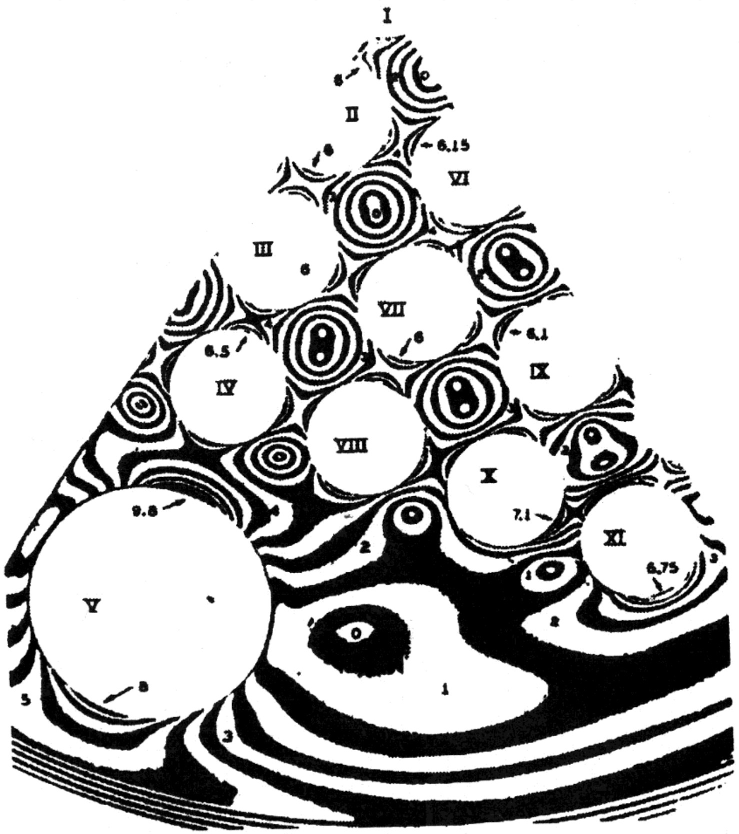
Dr. Fu-Pen Chiang

1. Chiang, F.P., and Williams, R. 1984. "Transient strain fields of ductile fracture of a centrally cracked aluminum sheet," *Modeling Problems in Crack Tip Mechanics*, G. Sih et al eds., Martinus Nijhoff Publishers, Boston, pp. 345-35.
2. Chiang, F.P., Williams Jr., R.C. 1985. "Simultaneous generation of 3D displacement contours of fracturing specimen using moiré," *Eng. Fracture Mech*. 22(5), pp. 731-735.
3. Chiang, F.P., Wu, X.P. 1986. "Three-dimensional crack tip deformation of plastically deformed 3-point bend specimens," Proc. 19th National Symposium on Fracture Mechanics, San Antonio, TX, June 30-July 2, 1986.
4. Chiang, F.P., and Hareesh, T.V. 1988. "Integrated experimental-finite element approach for studying elasto-plastic crack-tip fields," *Eng. Fracture Mechanics*, 31(3), pp. 451-461.
5. Chiang, F.P., and Hareesh, T.V. 1988. "Three-dimensional crack tip deformation, an experimental study and comparison to HRR field," *Int. J. of Fracture* 36, pp. 243-257.
6. Chiang, F.P., Liu, B.C. 1990. "Crack tip parameters and elastic-plastic Deformation of metals," *Int. J. of Fracture* 42, pp. 371-388.
7. Chiang, F.P., and Lu, H. 1990. "Surface & Interior Stress Intensity Factor Measurement by a Random Speckle Method," *Int. J. Fracture* 43, pp. 185-194.
8. Chiang, F.P., and Liu, B.C. 1990. "Crack tip parameters and elastic-plastic fracture of metals," *Int. J. of Fracture* 42(4), pp. 371-388.
9. Chiang, F.P., and Li, S. 1990. "Optical analysis of ductile fracture of metals," Proc. Conf. on Applied Stress Analysis, Nottingham, U.K., Aug. 30-31, 1990.
10. Chiang, F.P., and Hareesh, T.V. 1991. "Analysis of Combined Moiré & Laser Speckle Grating Methods Used in 3-D Crack Tip Deformation Measurements," Applied Optics 30(19), pp. 2478-2756.
11. Chiang, F.P., and Dai, Y.Z. 1991. "Scattering from plastically roughened surface and its applications to strain assessment," Optical Engineering 30(9), pp. 1269-1276.
12. Chiang, F.P., Dai, Y.Z., and Kato, A. 1991. "Fatigue monitoring by laser speckle," *Int. J. of Fatigue* 13(3), pp. 227-232.
13. Chiang, F.P., Li, X.M. 1992. "Experimental study of creep crack growth in coarse-grained aluminum" *Engineering Fracture Mechanics* 434(5), pp. 837-846.
14. Chiang, F.P., Li, X.M., Wu, J., Dudley, M. 1992. "Experimental measurement of the crack tip strain field in a single crystal," *Engineering Fracture Mechanics* 43(2), pp. 171-184.
15. Chiang, F.P., Li, S., and Wang, Y.Y. 1992. "Experimental study of near-crack-tip deformation fields," ASTM STP 1131, Atlurri et al., Eds, 225-244, ASTM, Philadelphia, PA 1992.
16. Chiang, F.P., Wang, Y.Y., Barsoum, R.S., and Chou, S.C. 1993. "Study of deformation field of interface crack in an adhesive joint," *Engineering Fracture Mechanics* 44(2), pp. 175-184.
17. Chiang, F.P., and Lu, H. 1993. "Photoelastic determination of stress intensity factor of an interfacial crack in a biomaterial," *J. Applied Mechanics* 60, pp. 93-100.
18. Chiang, F.P., and Du, M.L. 1998. "The Effect of Static Tensile Strain on Fatigue Failure", *International Journal of Fatigue* 20(5), pp. 331-338.

Three Dimensional Stress/Strain Analysis Techniques

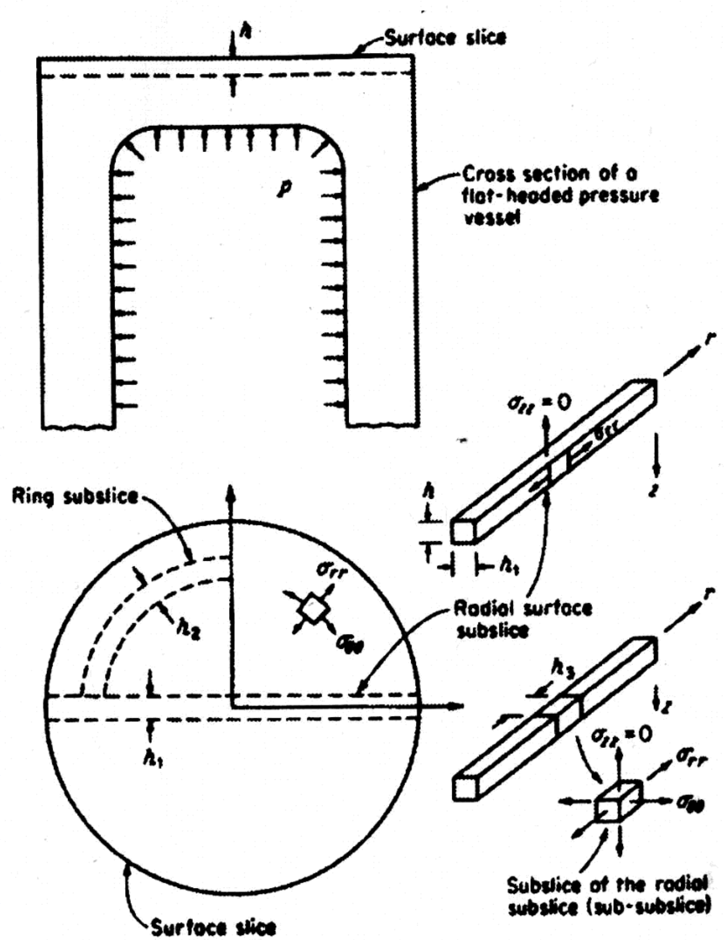
- **The Holy Grail of Experimental Mechanics Community: a powerful 3D stress/strain measurement technique that can probe the internal deformation field of opaque solids**

Frozen Stress Photoelasticity-The Most Widely Used 3D Stress Analysis Technique



Experimental Solid Mechanics A. Shukla & J. W. Dally P.346

Slicing and Cutting in Order to Obtain the Stress at a Point



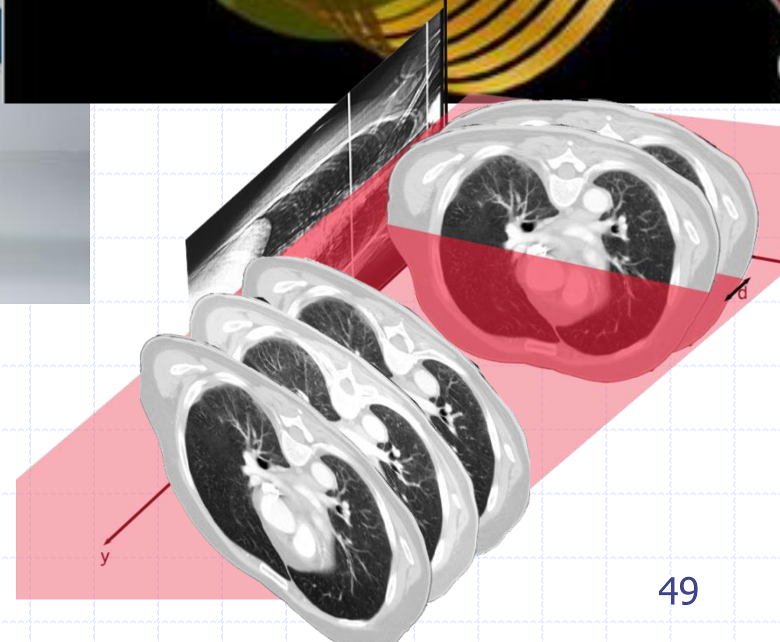
Experimental Solid Mechanics A. Shukla & J. W. Dally P.346

- **Digital Volumetric Speckle Photography (DVSP):**
- **a New 3D Strain Analysis Technique for Opaque Solids**

Stony Brook University
Dr. Fu-Pen Chiang

Theory of X-ray Computed Tomography

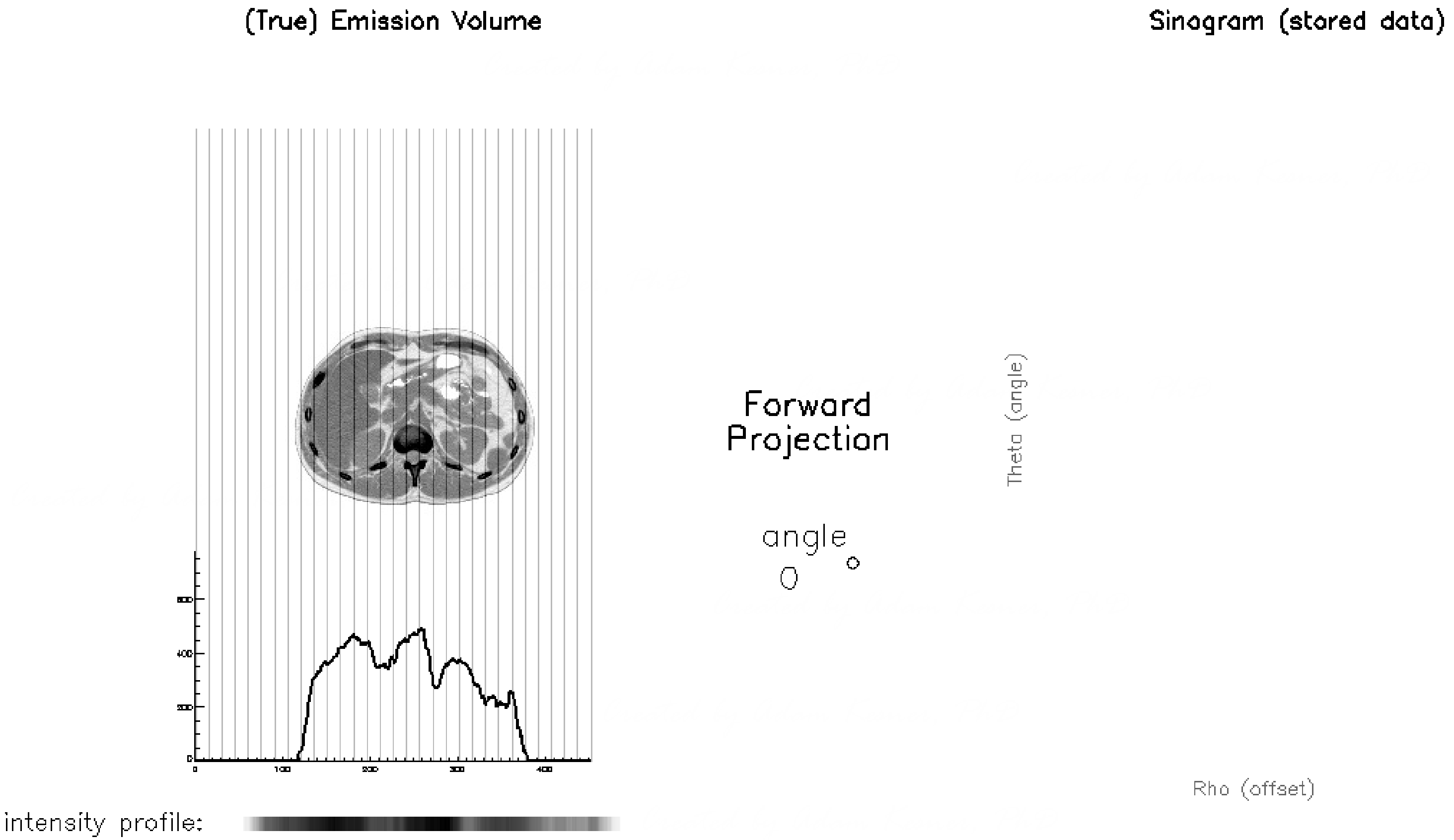
- Medical X-ray Computed Tomography



Theory of X-ray Computed Tomography

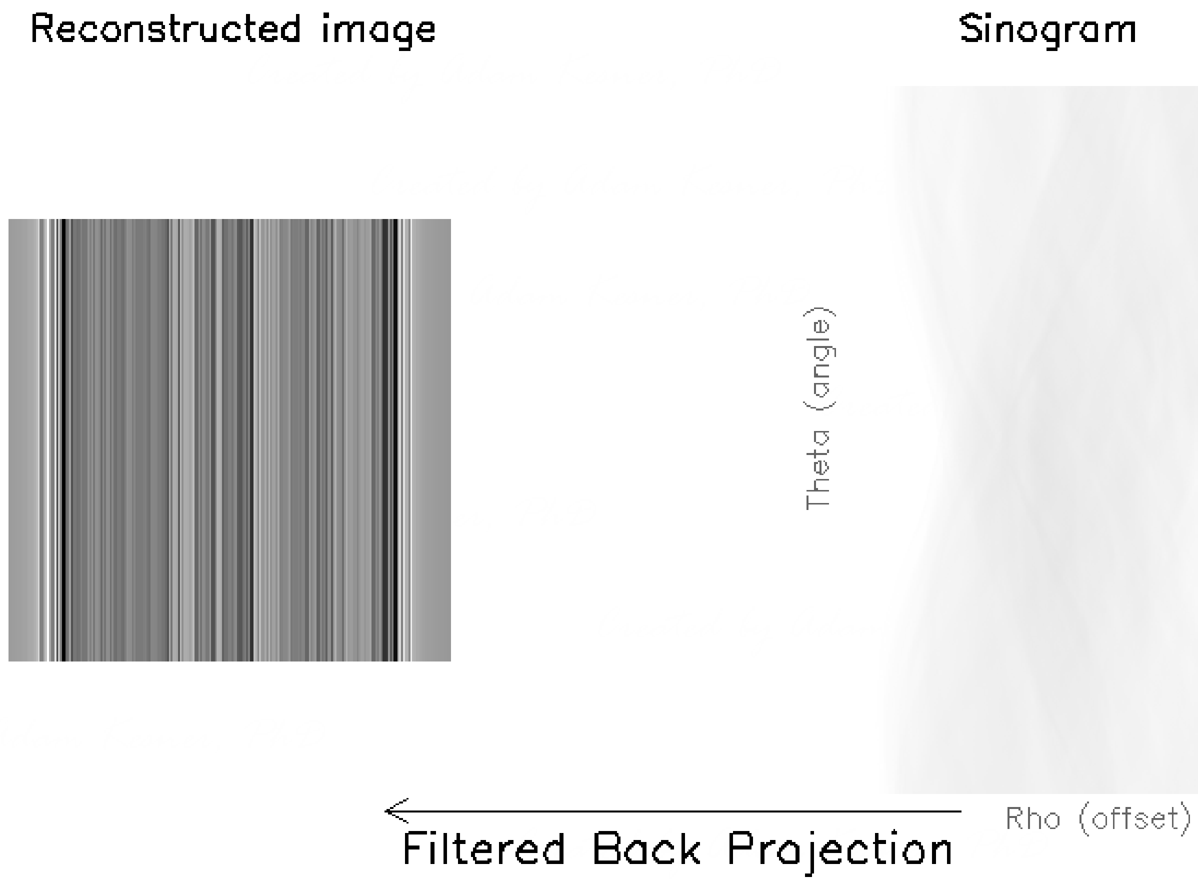
Stony Brook University
Dr. Fu-Pen Chiang

X-ray Computed Tomography -Image Reconstruction



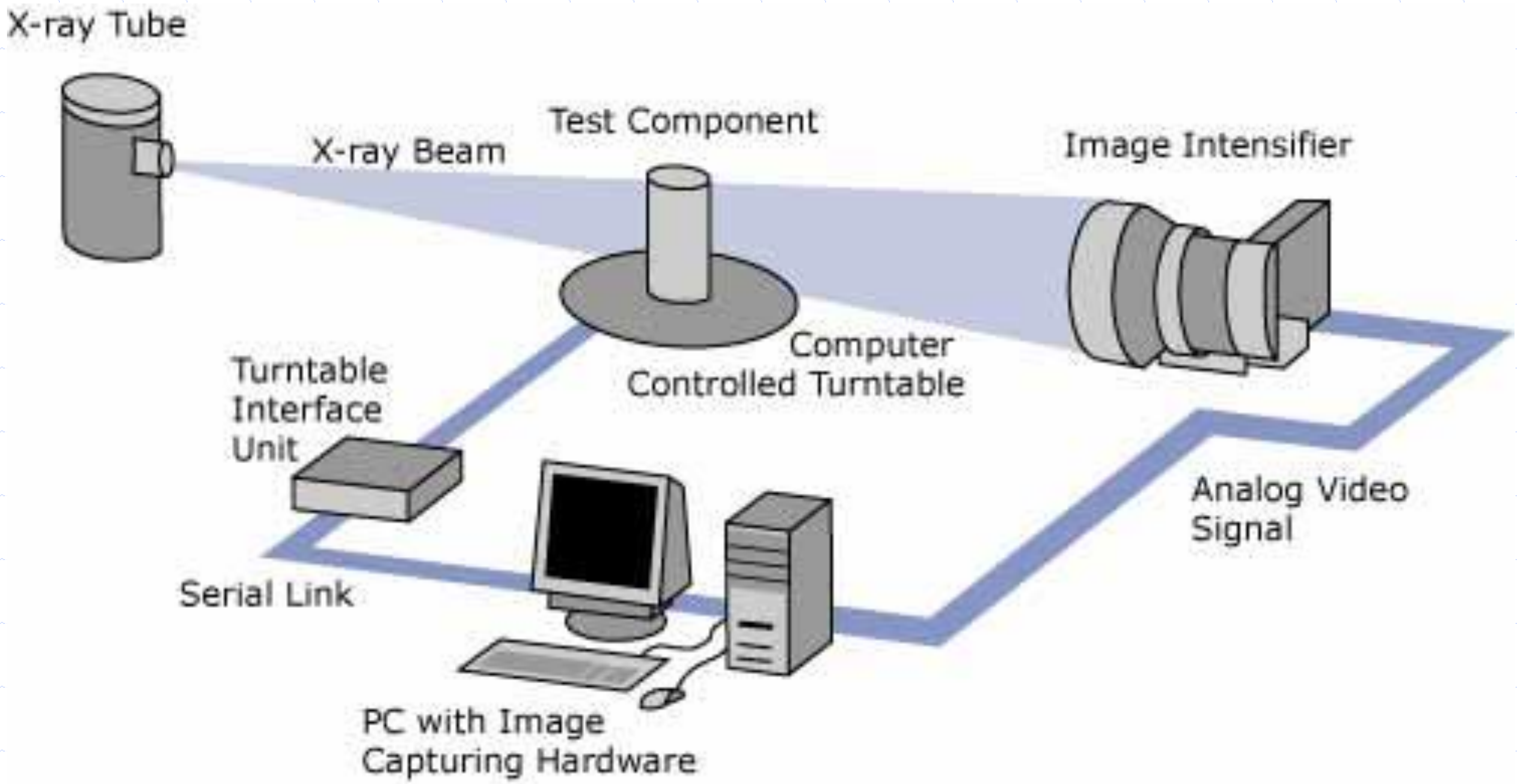
Theory of X-ray Computed Tomography

- X-ray Computed Tomography- Image Reconstruction



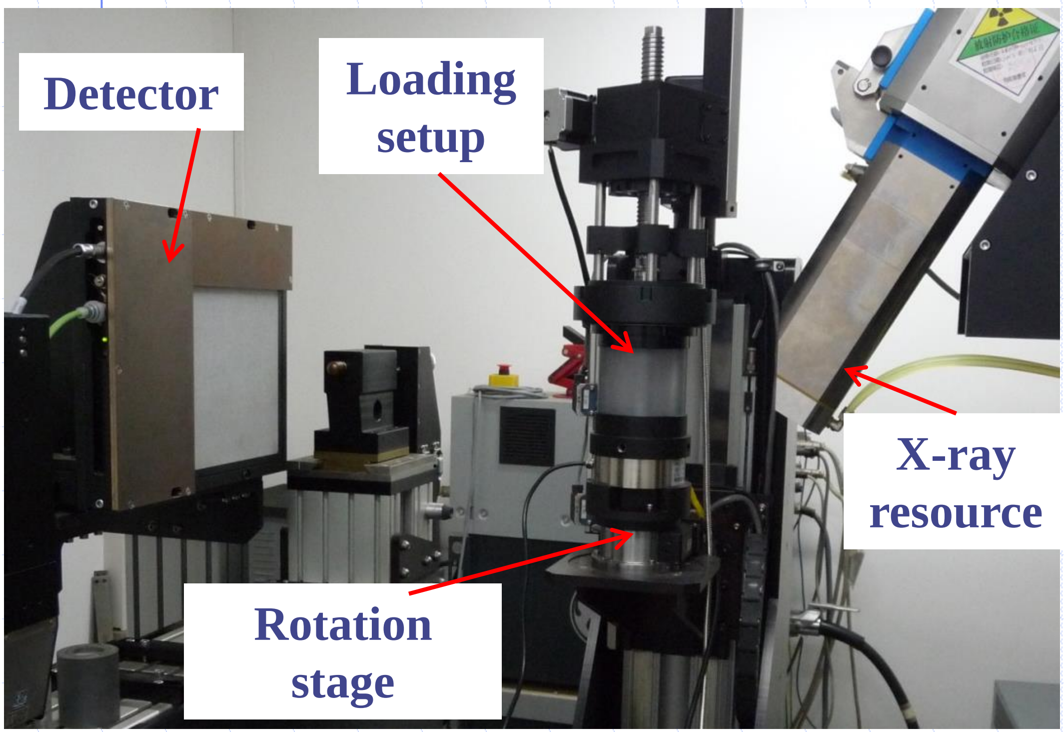
Principle of Industrial X-Ray Computed Tomography

Industrial X-ray CT



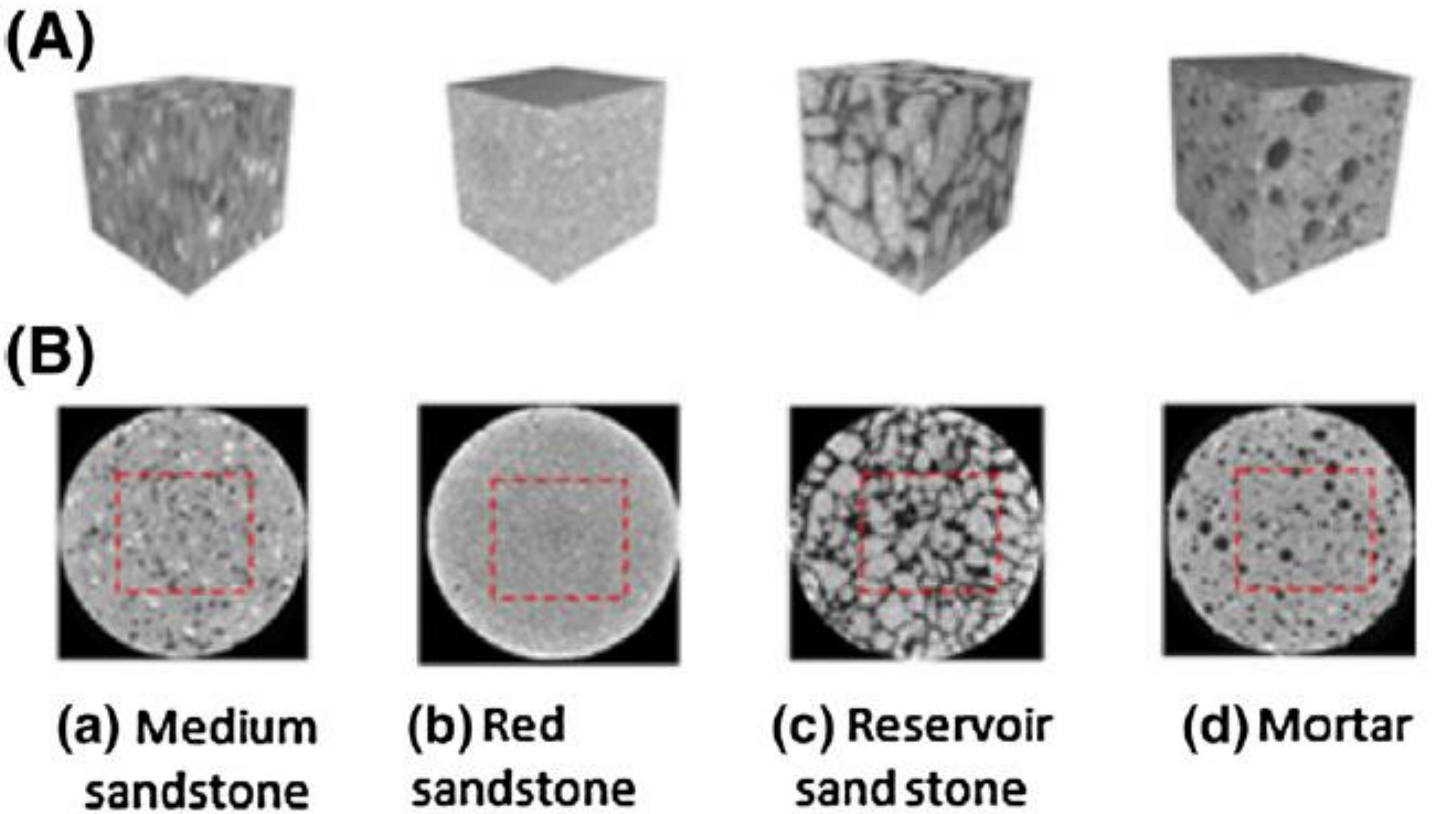
Hardware of Industrial X-Ray Computed Tomography

- CT System and Loading Setup



- ➢Microfocus x-ray resource from YXLON (FeinFocus FXE-225.48, size of focus:3 × 6 micron)
- ➢Motorized rotation stage from Newport
- ➢X-ray detector unit (1024×1024 pixels) from PerkinElme (XRD 0822AP 14)
- ➢Loading Cell is made of Polycarbonate

Typical Volumetric Speckles



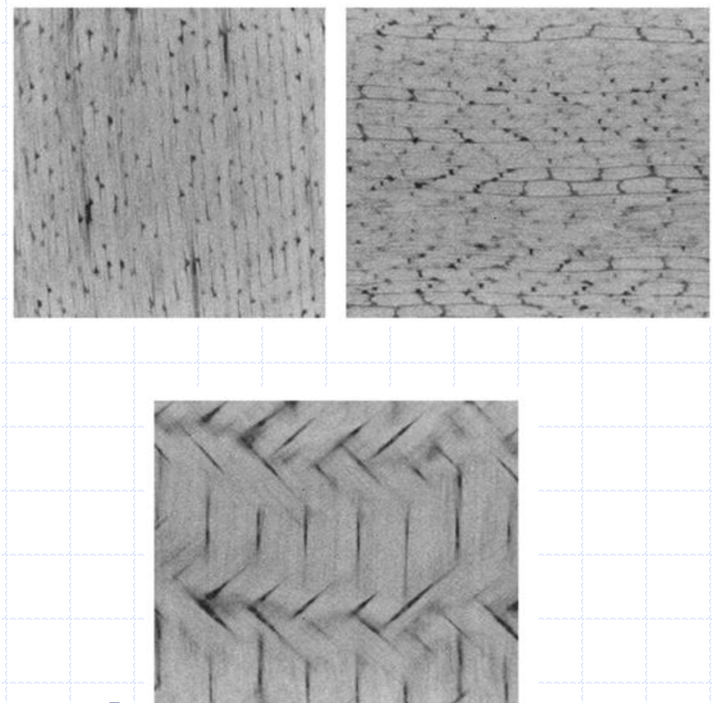
Volumetric Speckles in Rocks due to impurity and voids
(A) Cropped volume image (B) Cross-section of a cylinder

Any 3D Markings can be Considered as Speckles

- 3D Speckle structure in a fiber reinforced composite

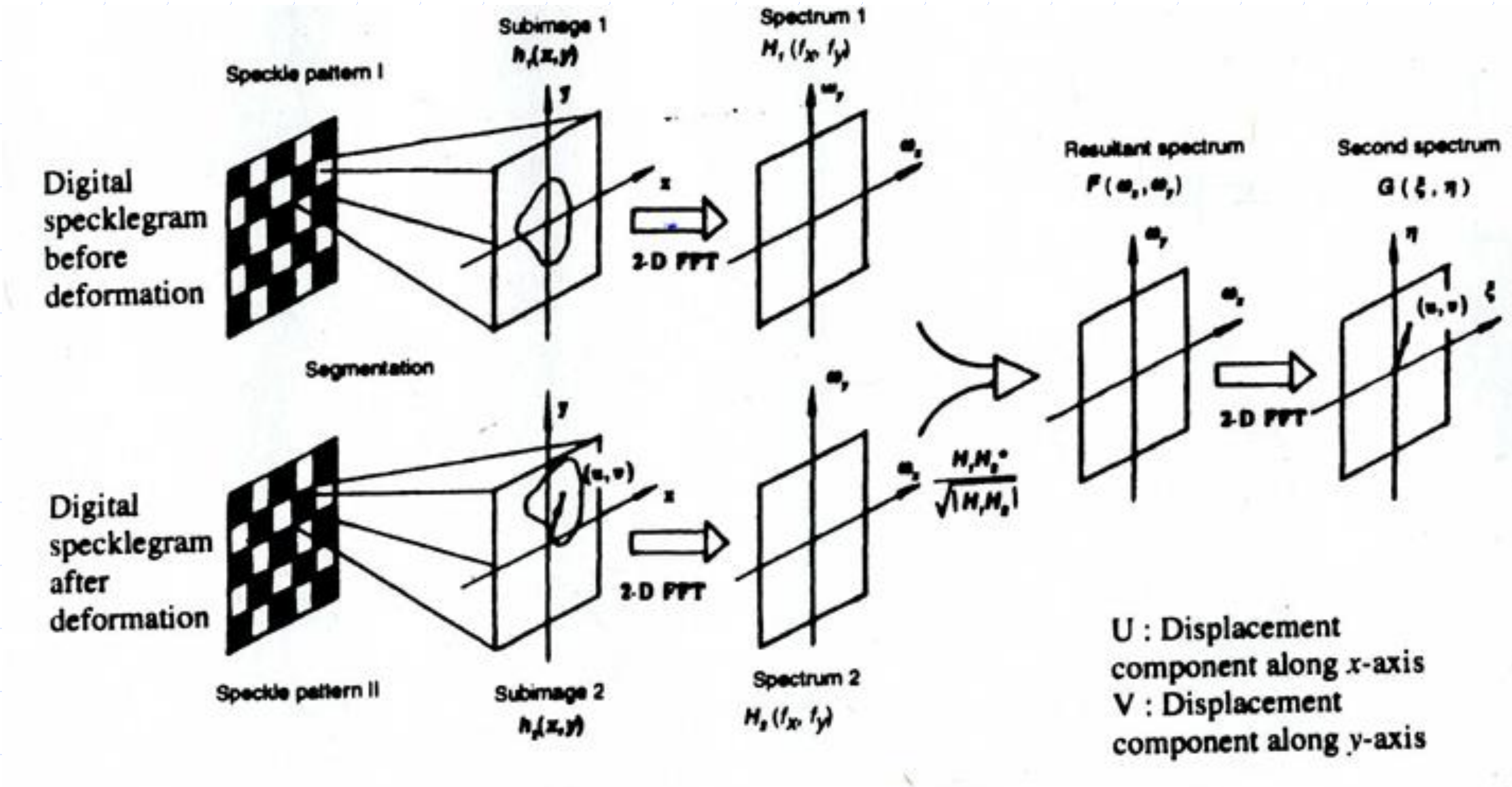
Specimen from a windmill blade by conventional photography

Cropped from reconstructed CT image



Three orthogonal cross sections

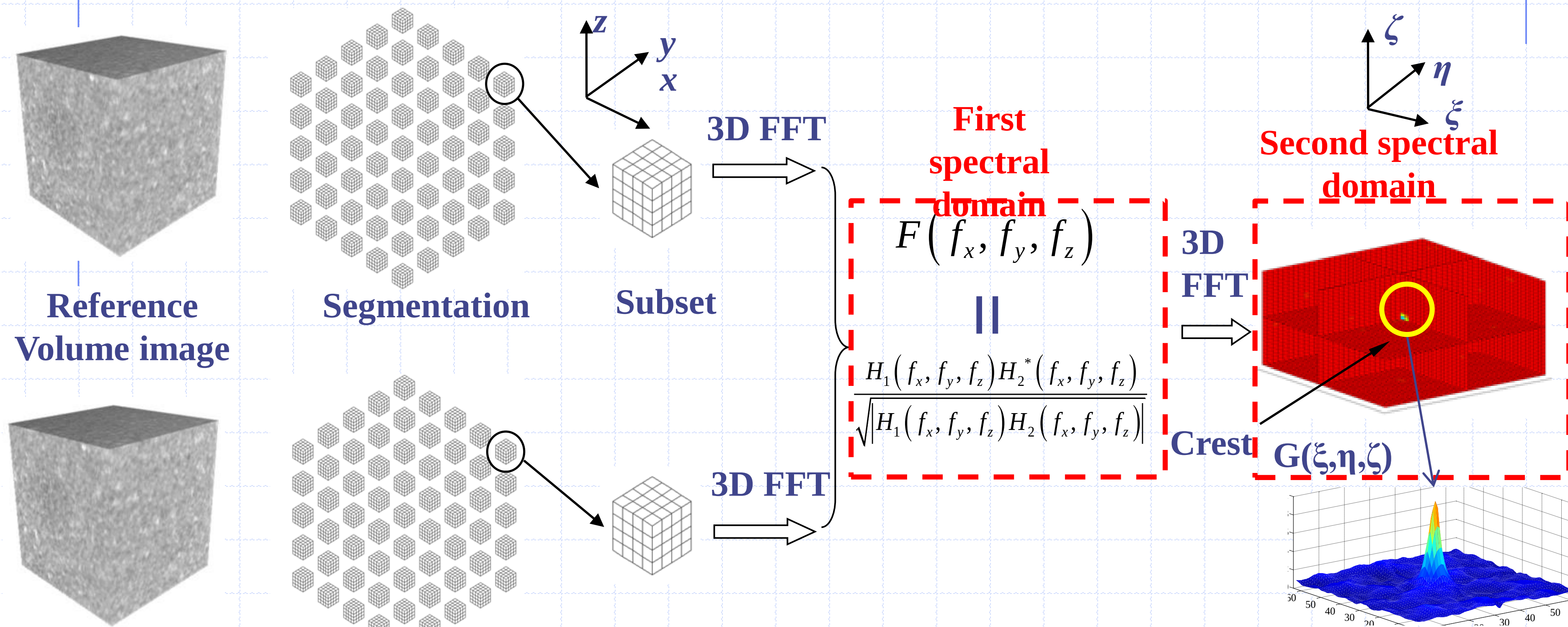
Principle of 2D Digital Speckle photography (DSP)



Schematics demonstrating the processing algorithm of CASI

Principle of 3D DSP or DVSP

- **Digital Volumetric Speckle Photography(DVSP)**



Deformed
Volume image

Segmentation

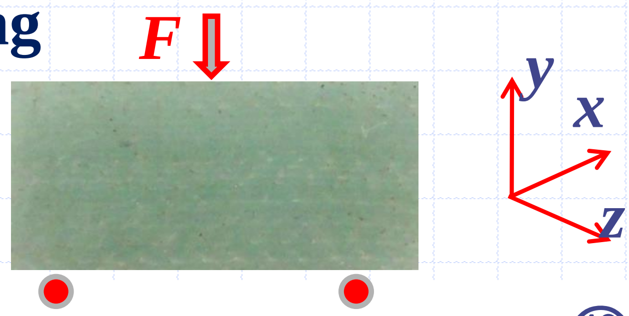
Subset

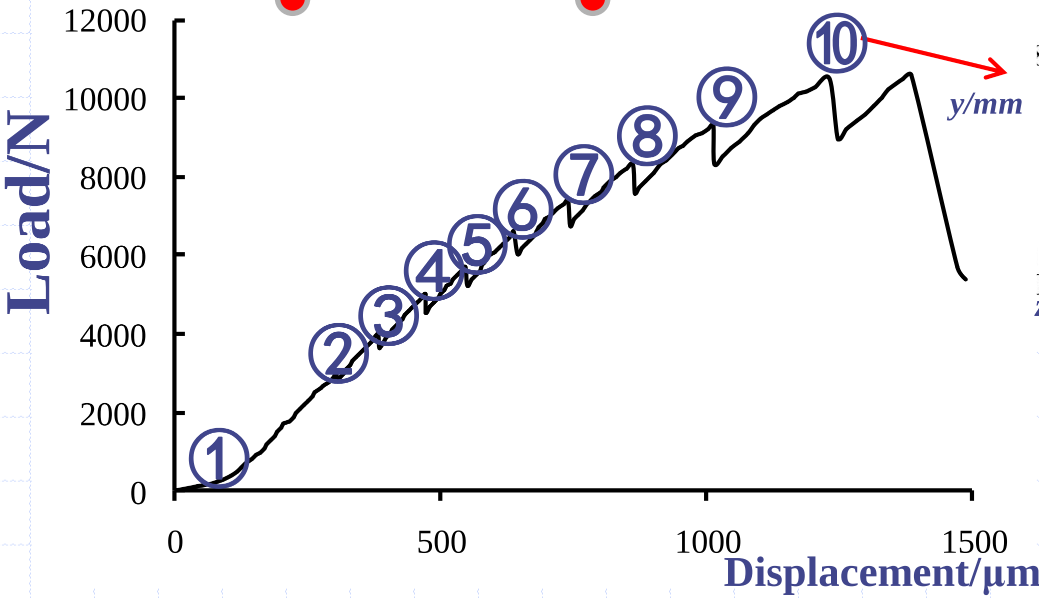
(*u,v,w*) indicates the displacement of subset

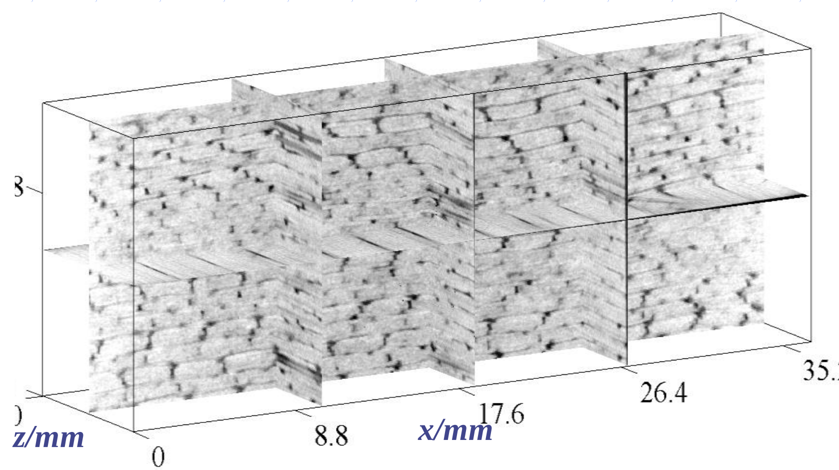
$$G(\xi,\eta,\zeta)=\Im\{F(f_x,f_y,f_z)\}=\bar{G}(\xi-u,\eta-v,\zeta-w)$$

Application of DVSP to Composites

- **Internal strain analysis of a composite beam under 3-point bending**







F=10.5kN

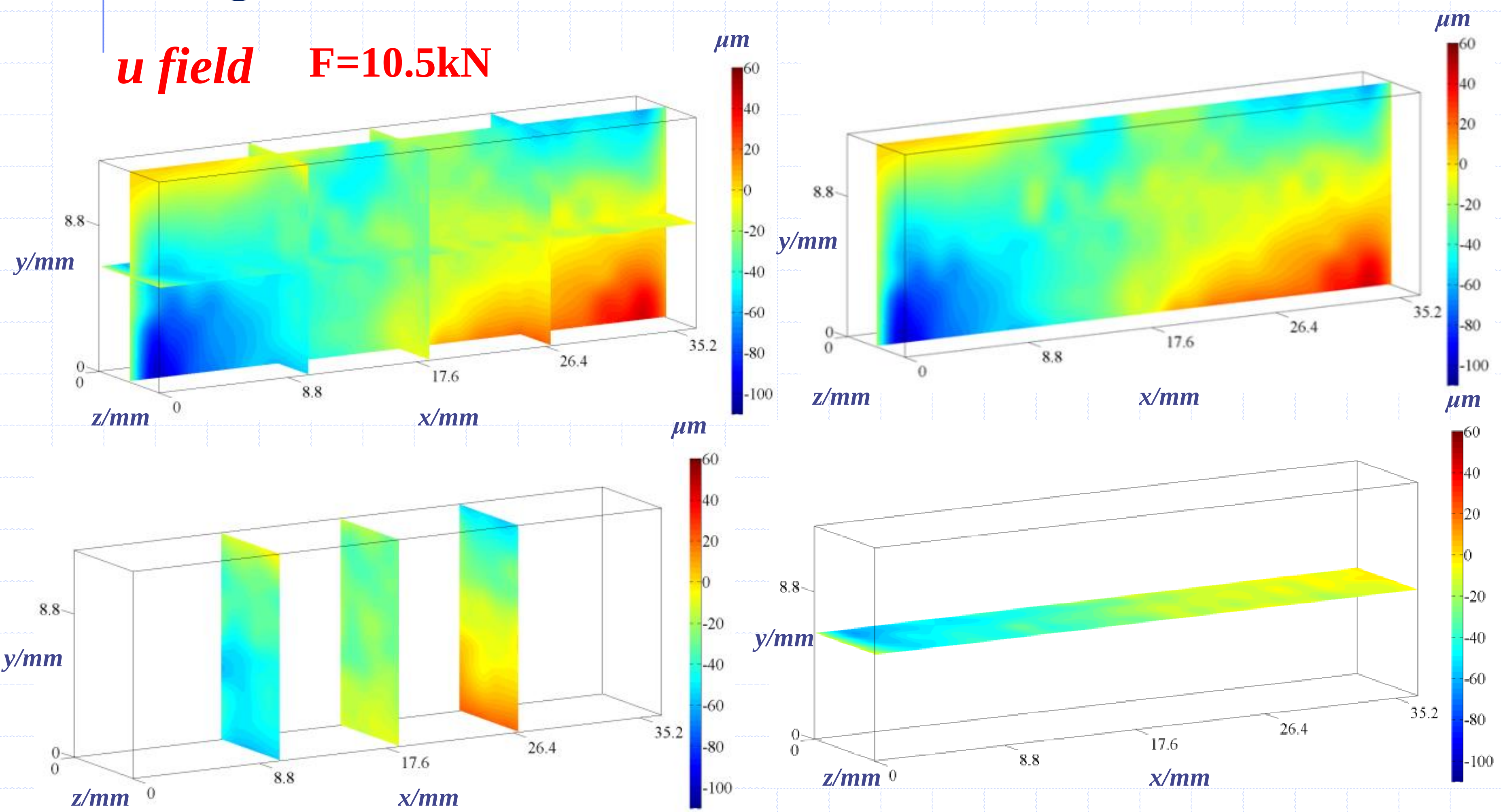
1. Lingtao Mao, Fu-pen Chiang, Interior Strain Analysis of a Woven Composite Beam Using X-ray Computed Tomography and Digital Volumetric Speckle Photography, Composite Structures, 2015,134:782-788

Stony Brook University

Dr. Fu-Pen Chiang

Application of DVSP to Composites

- Internal strain analysis of a composite beam under 3-point bending



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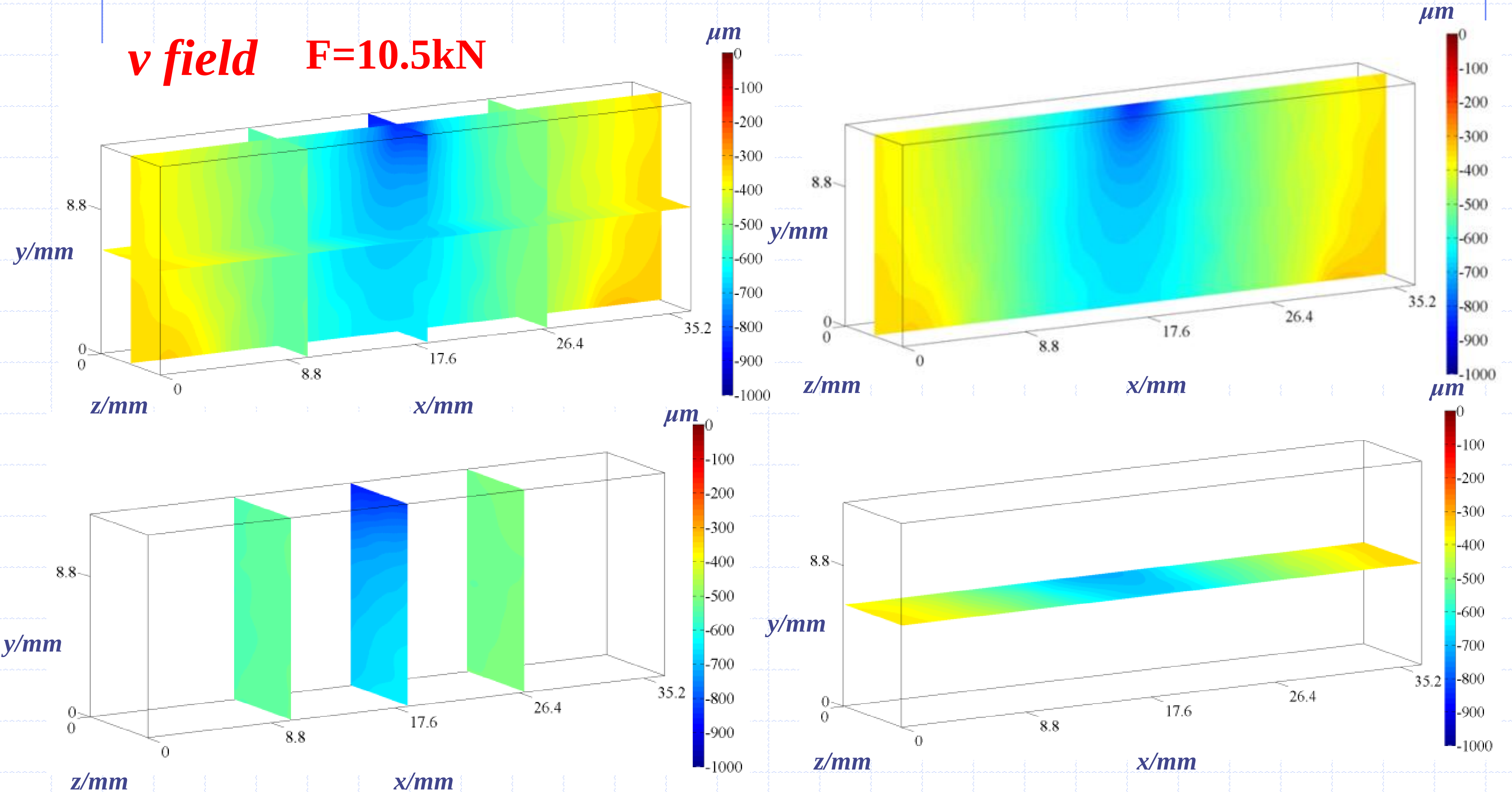
Dr. Fu-Pen Chiang

Application of DVSP to Composites

- **Internal strain analysis of a composite beam under 3-point bending**



Application of DVSP to Composites

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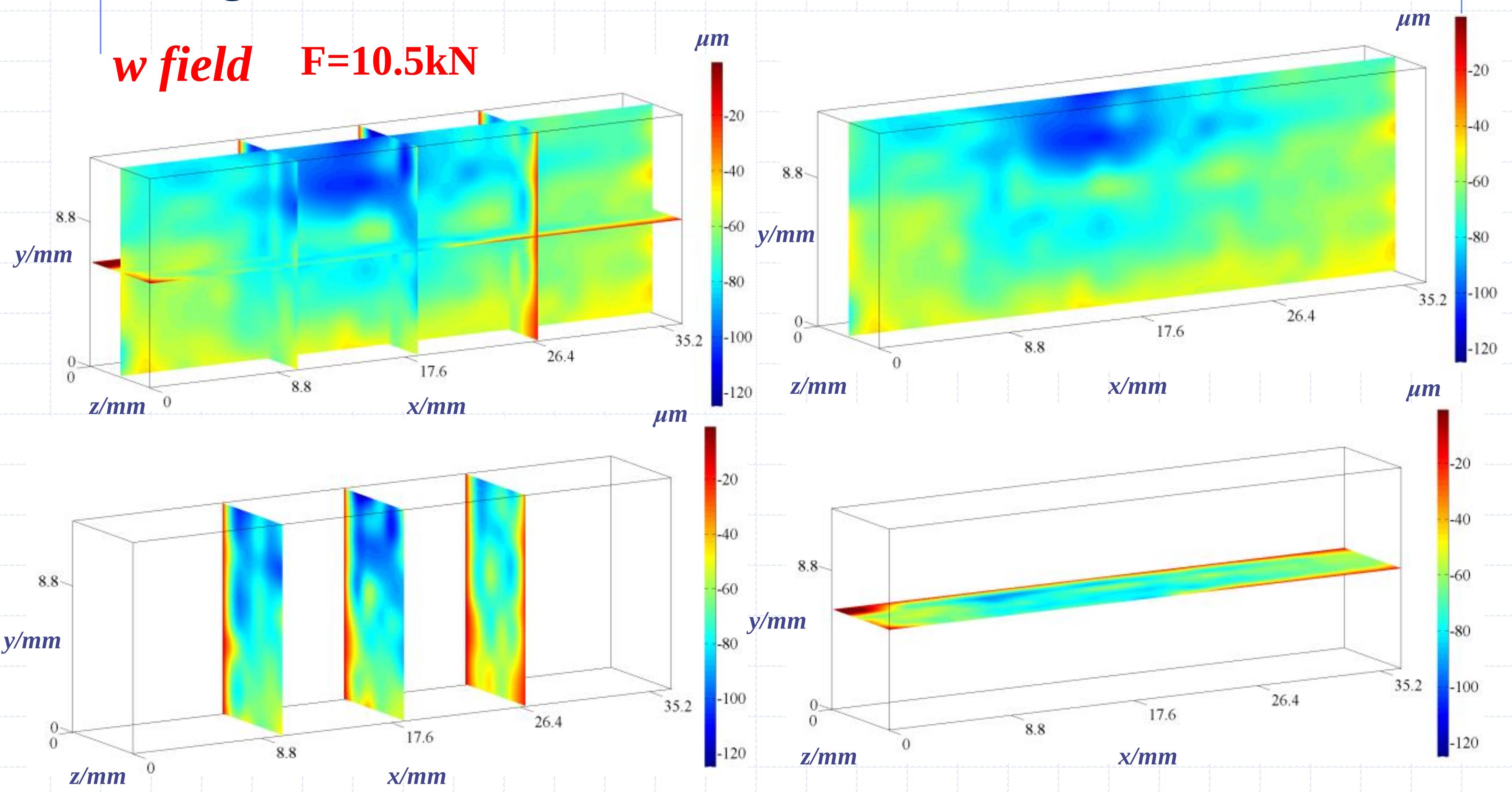
- **Internal strain analysis of a composite beam under 3-point bending**

w field F=10.5kN

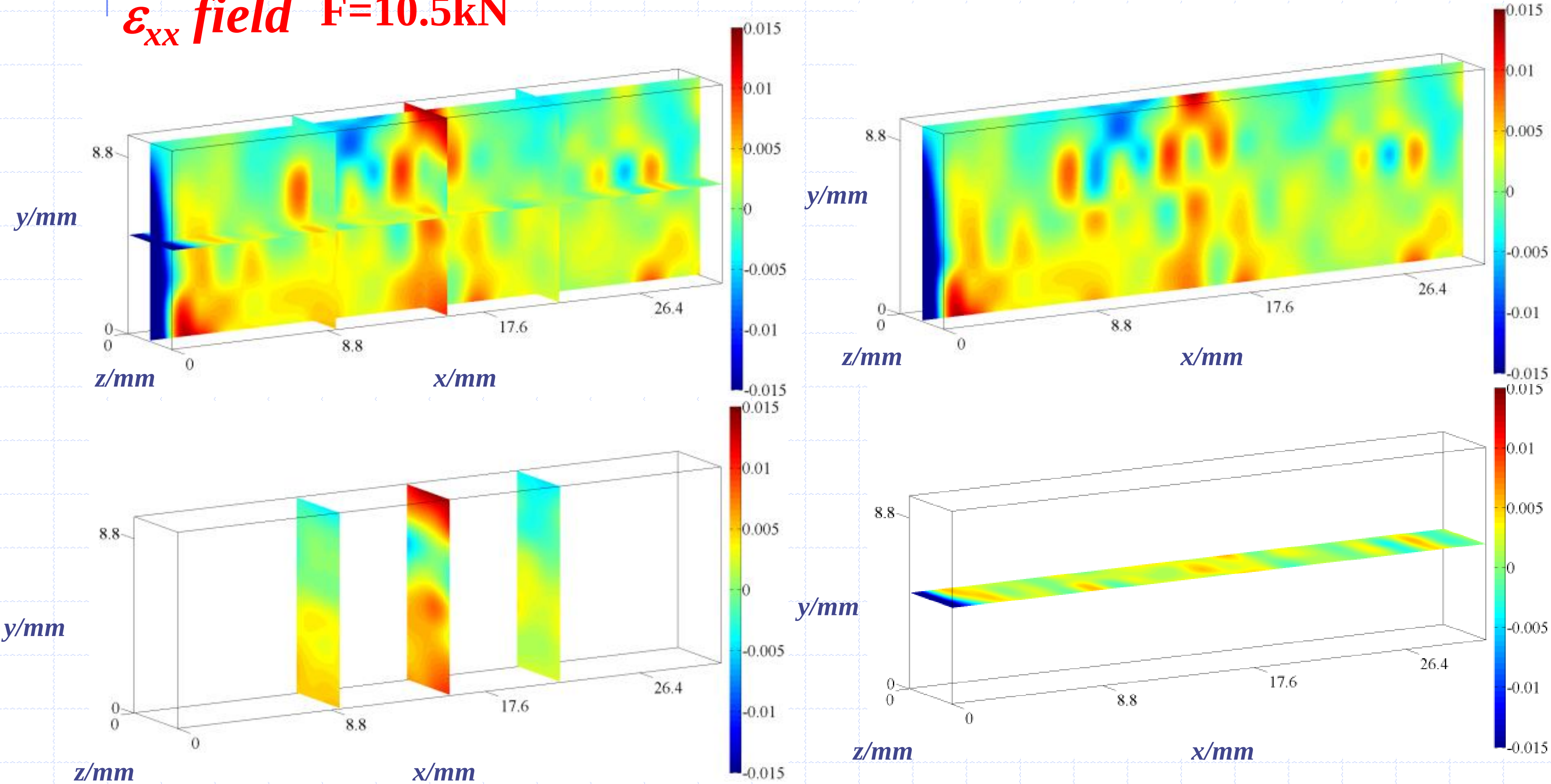


Application of DVSP to Composites

Dr. Fu-Pen Chiang

- Internal strain analysis of a composite beam under 3-point bending

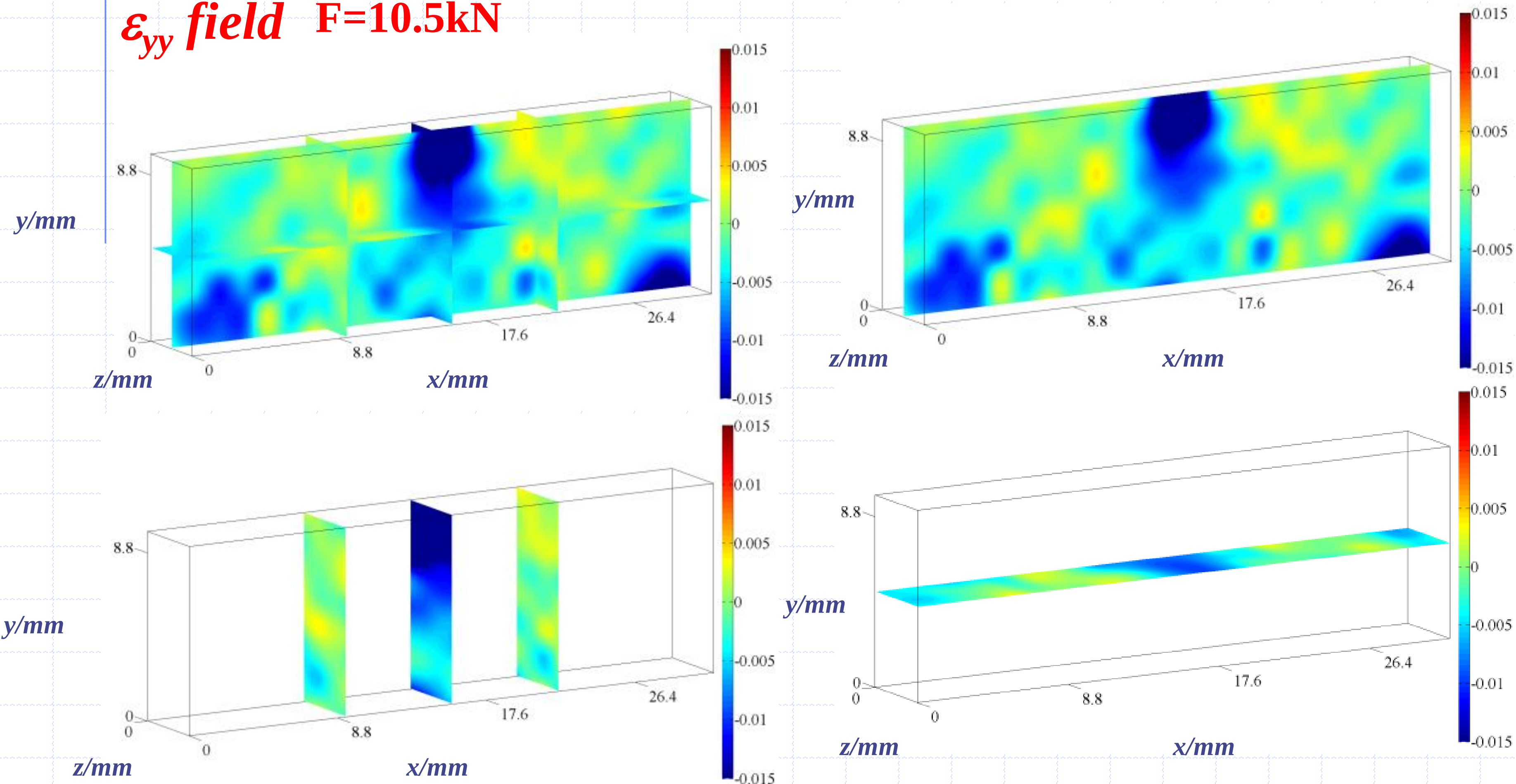
ε_{xx} *field* F=10.5kN



Application of DVSP to Composites

- **Internal strain analysis of a composite beam under 3-point bending**

ε_{yy} *field* **F=10.5kN**



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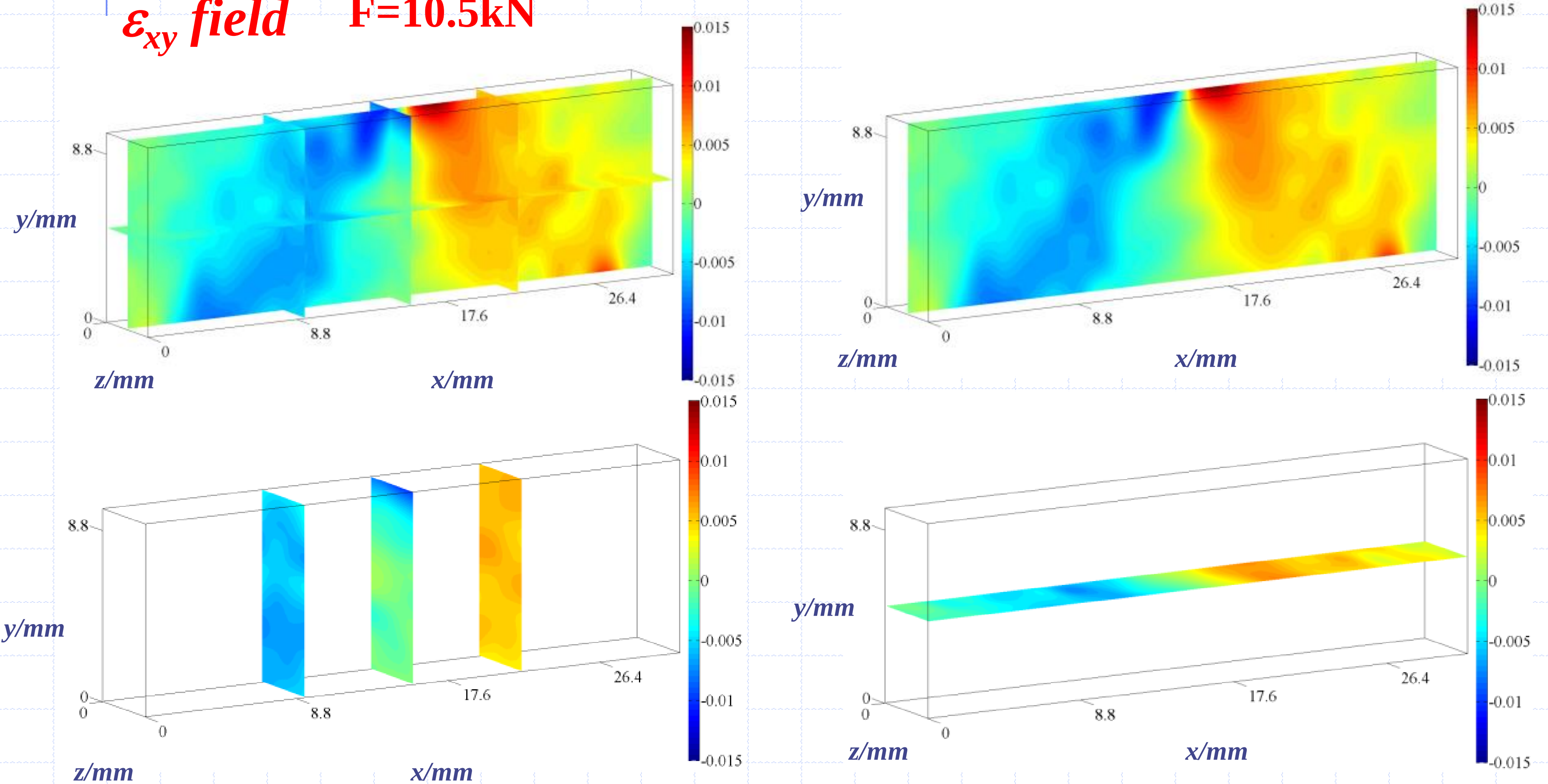
Application of DVSP to Composites

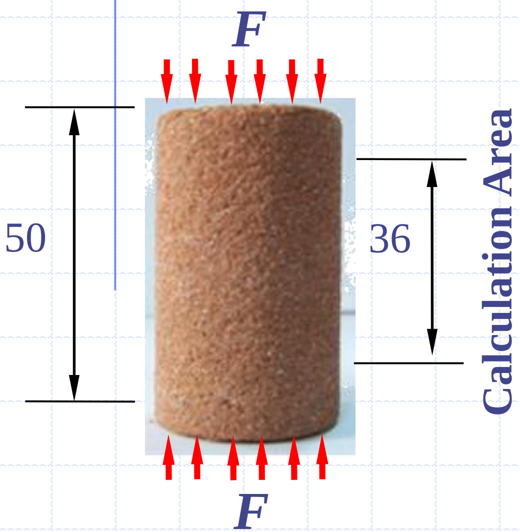
- **Internal strain analysis of a composite beam under 3-point bending**

ε_{xy} ***field*** **F=10.5kN**

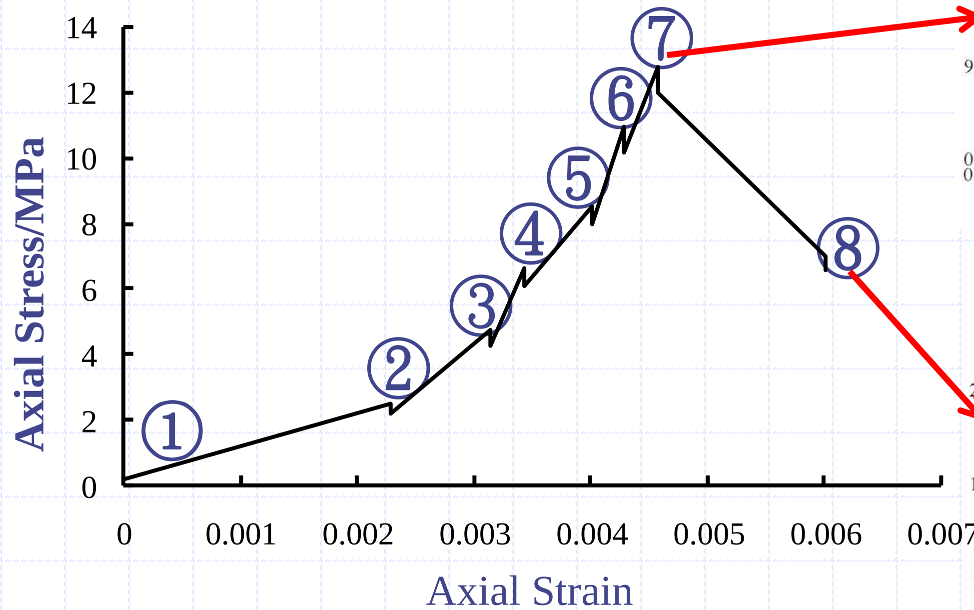


Applications of DVSP

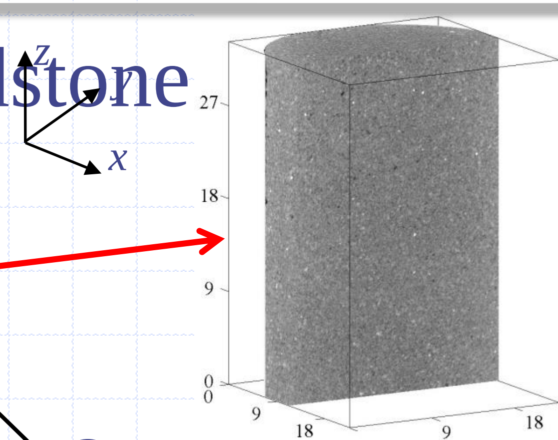
Internal Strain Analysis of Red Sandstone

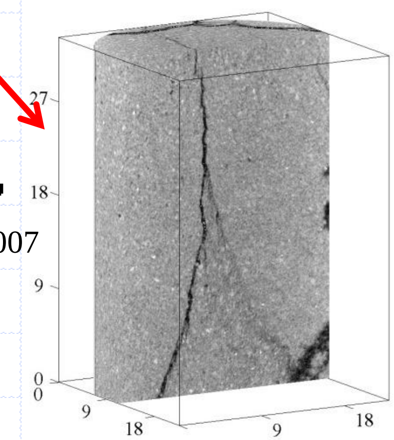


POF Filter



Stress-strain curve





Section image along x=12.5mm

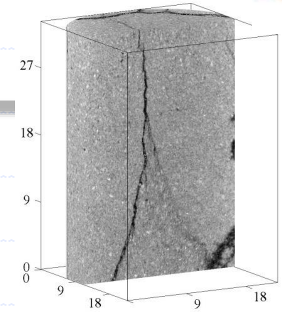
1. Lingtao Mao, Jianping Zuo, Zexun Yuan, Fu-Pen Chiang, Full-field mapping of internal strain distribution in red sandstone specimen under compression using digital volumetric speckle photography and X-ray computed tomography, Journal of Rock Mechanics and Geotechnical Engineering,2015, 7 (2015): 136-146

Stony Brook University

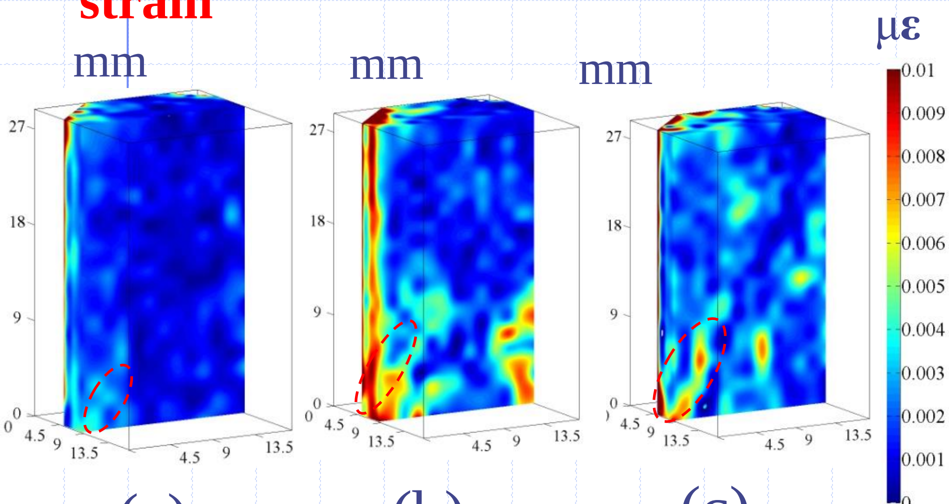
Dr. Fu-Pen Chiang

Applications of DVSP

- Internal Strain Analysis of Red Sandstone

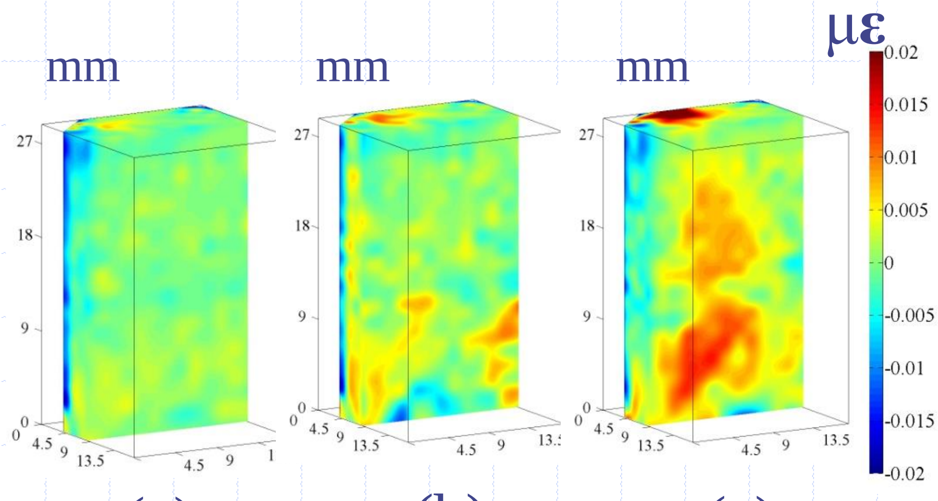


Von Mises equivalent strain



(a) (b) (c)

Volumetric strain



(a) (b) (c)

(**a**) 7.97MPa (Step5); (b) 10.19MPa(Step6); (c) 11.98MPa (Step7)

The onset of strain localization started at the lower left corner and propagated upward as indicted by the dotted lines in Fig.(d), (e), (f) . At the same time, the volumetric strain also increased.

Application of DVSP

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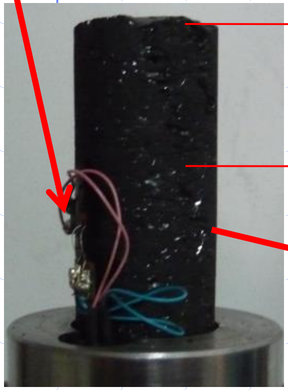
Internal Deformation Analysis of Coal Caused by CO_2 Sorption

Strain gage



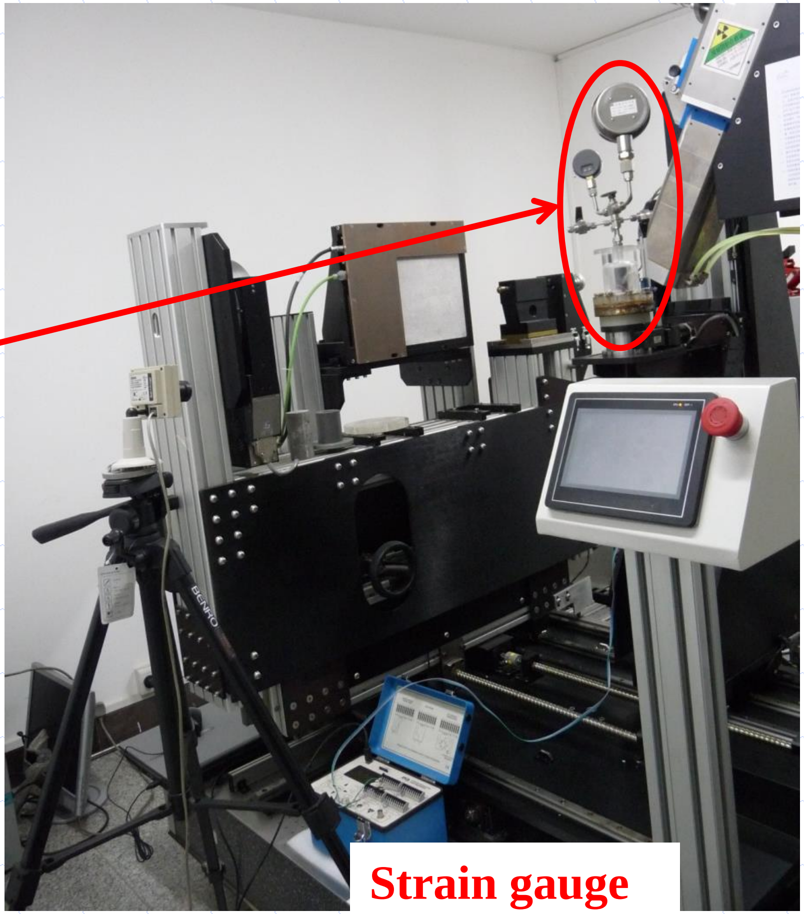
25mm

Scanning Area

Coal sample

Size: Φ25 ×50mm

Sealed container cell



Experimental system

Lingtao Mao, Nai Hao, Liqian An ,Fu-pen Chiang, Hongbin Liu, 3D mapping of carbon dioxide-induced strain in coal using digital volumetric speckle photography technique and X-ray computer tomography[J], International Journal of Coal Geology 147–148 (2015) 115–125

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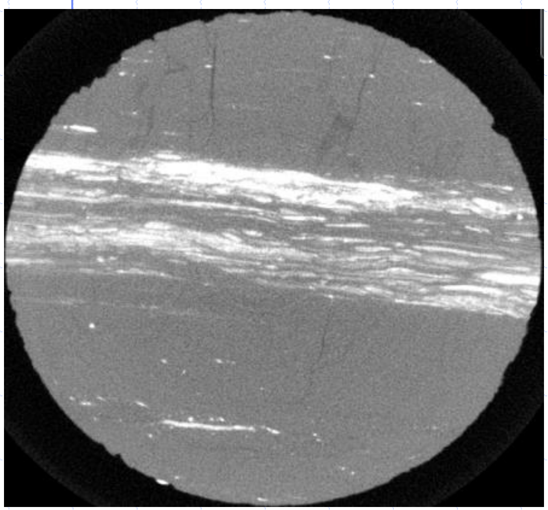
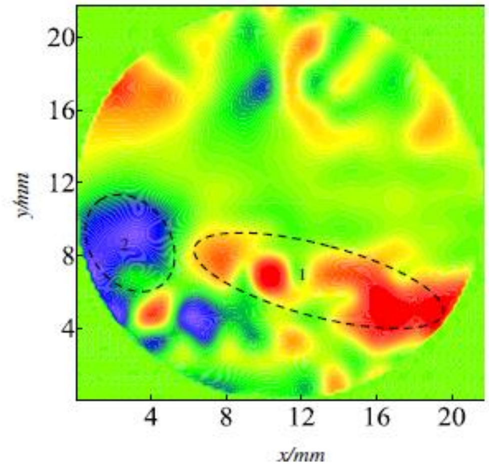
Volumetric strain distribution

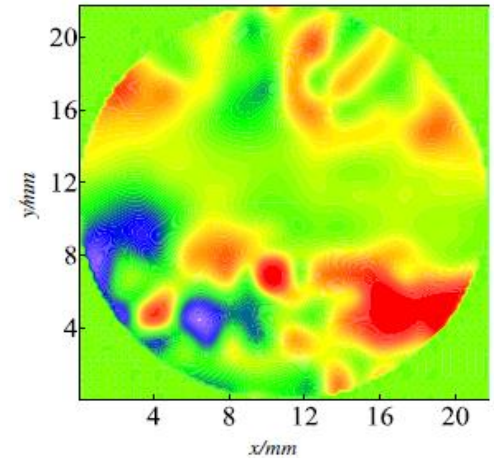


CT image

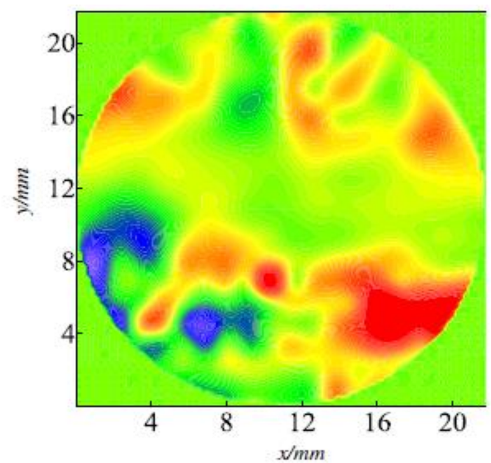
Calculation area: 800 ×800 ×750 voxels, subset size: 64 ×64 ×64 voxels, and the subset shifting is 32 voxels



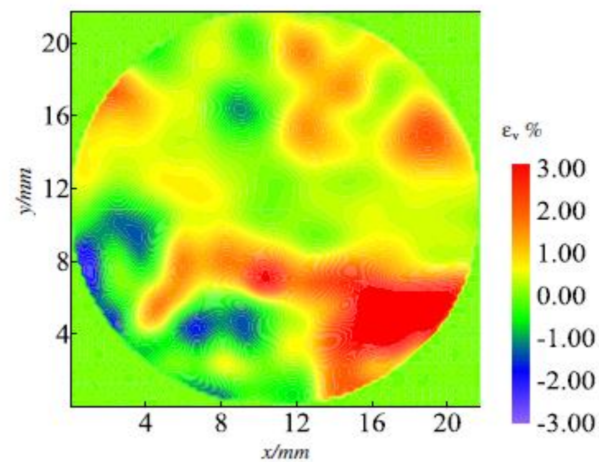
Absorption time:70min



Absorption time:170min



Absorption time:310min



Absorption time:1240min

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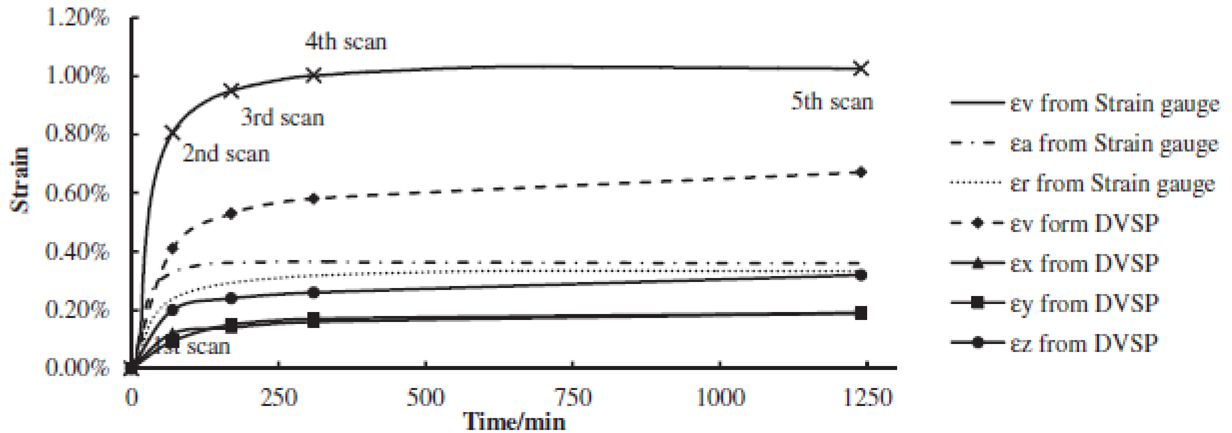
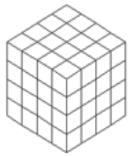
Internal Deformation Analysis of Coal Caused by CO_2 Sorption

Strain-time curve



The size of gauge:2mm ×3mm (64 ×100pixels)



The size of subset:64 ×64 ×64 voxels, 1 voxel = 32μm^3

In strain analysis, the number of calculation points is 16 ×16 ×19=4864

The strain from strain gauge is higher than those from DVSP. One reason could be that the strain gauge just indicates the strain value of point measured, while the data from DVSP are average value of calculation volume, which includes the expanded area as well as shrunk area.

Application of DVSP

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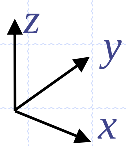
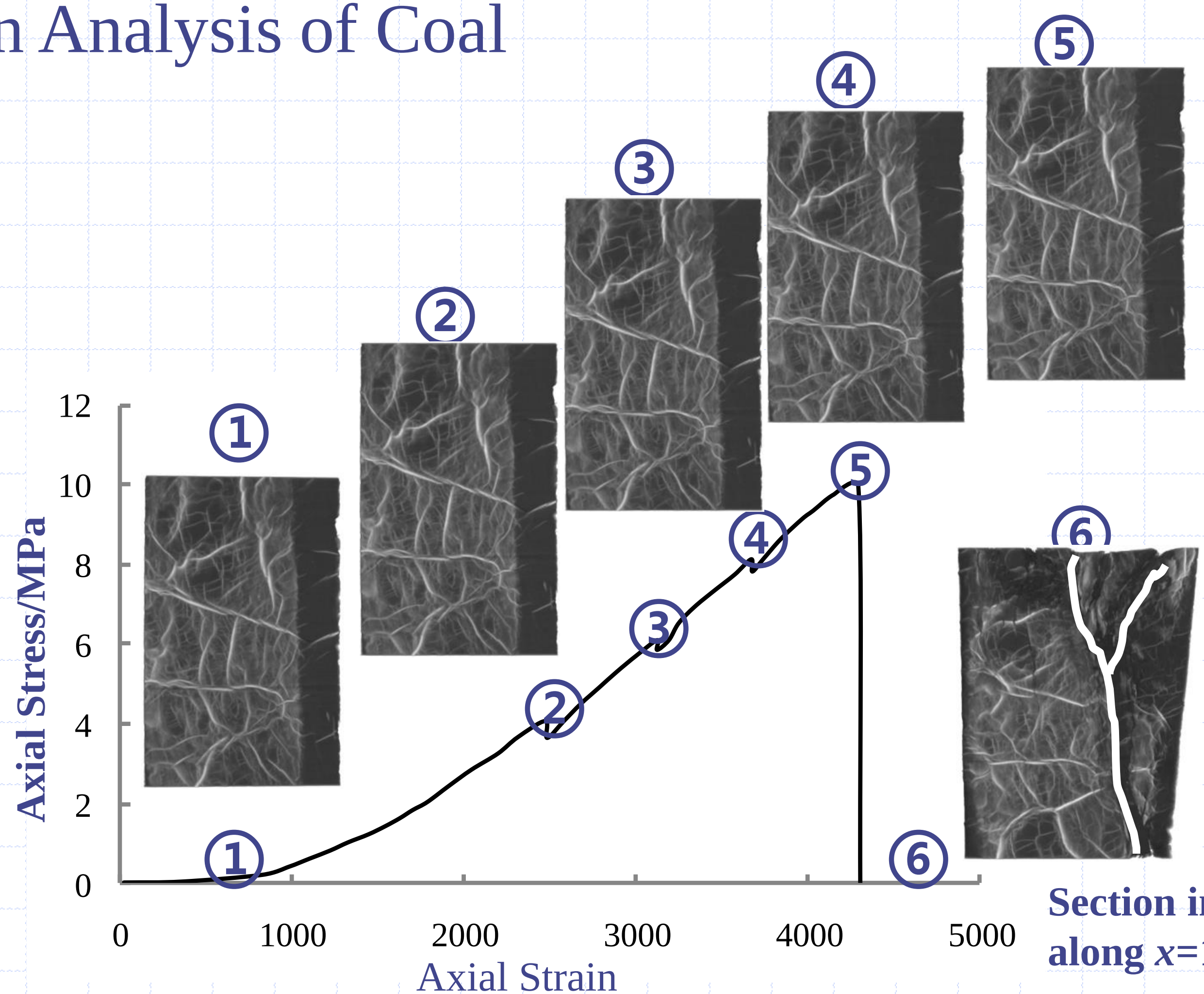
- Internal Strain Analysis of Coal

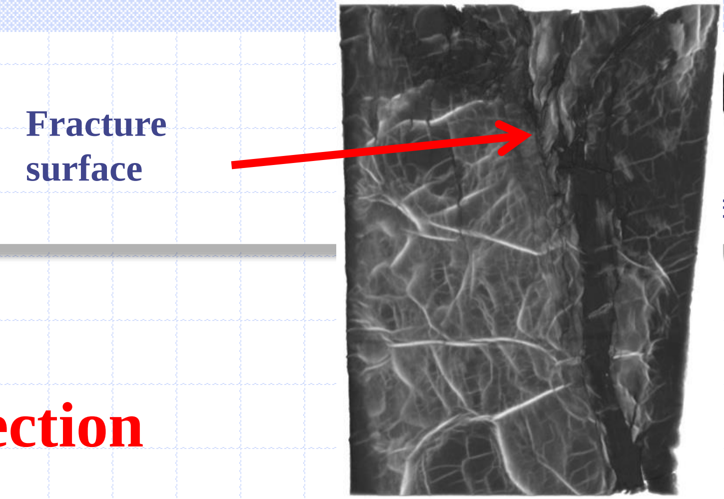




Stress-strain curve

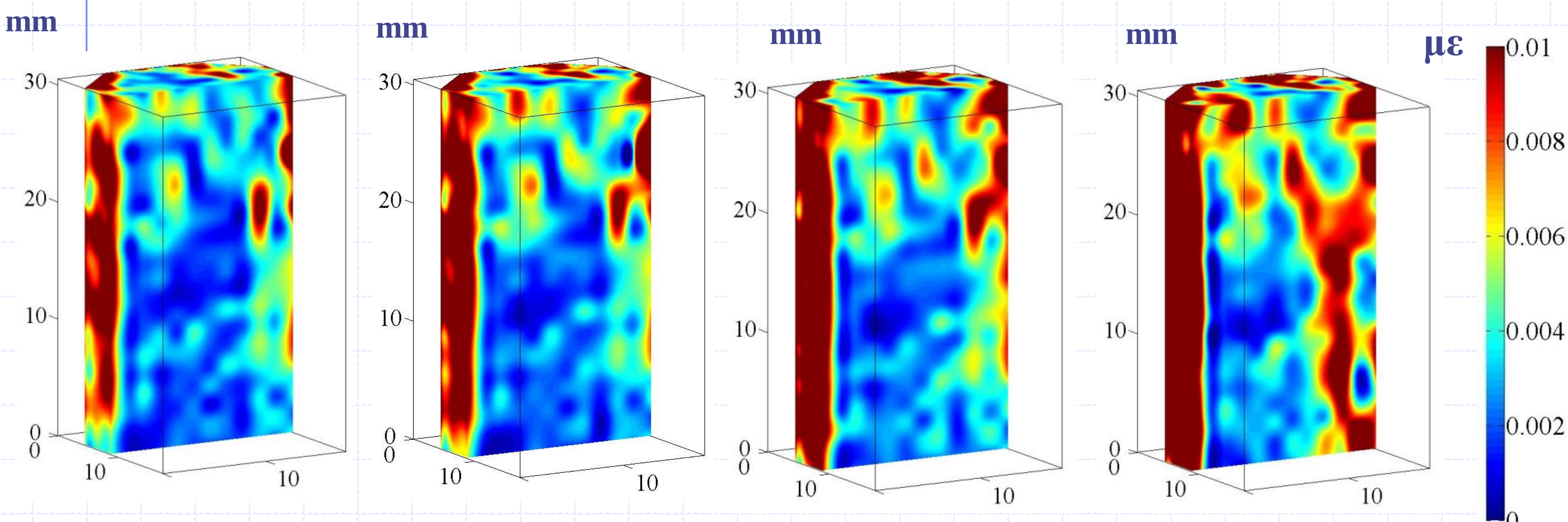
Section image along *x*=12.5mm

Application of DVSP



- Internal Strain Analysis of Coal

Von Mises equivalent strain of the section along *x*=12.5mm



(a) **(b)** **(c)** **(d)**

(a) 4.07MPa (Step2); (b)6.10MPa(Step3); (c)8.14MPa (Step4); (d) 9.98MPa (Step5);

Applications of DVSP

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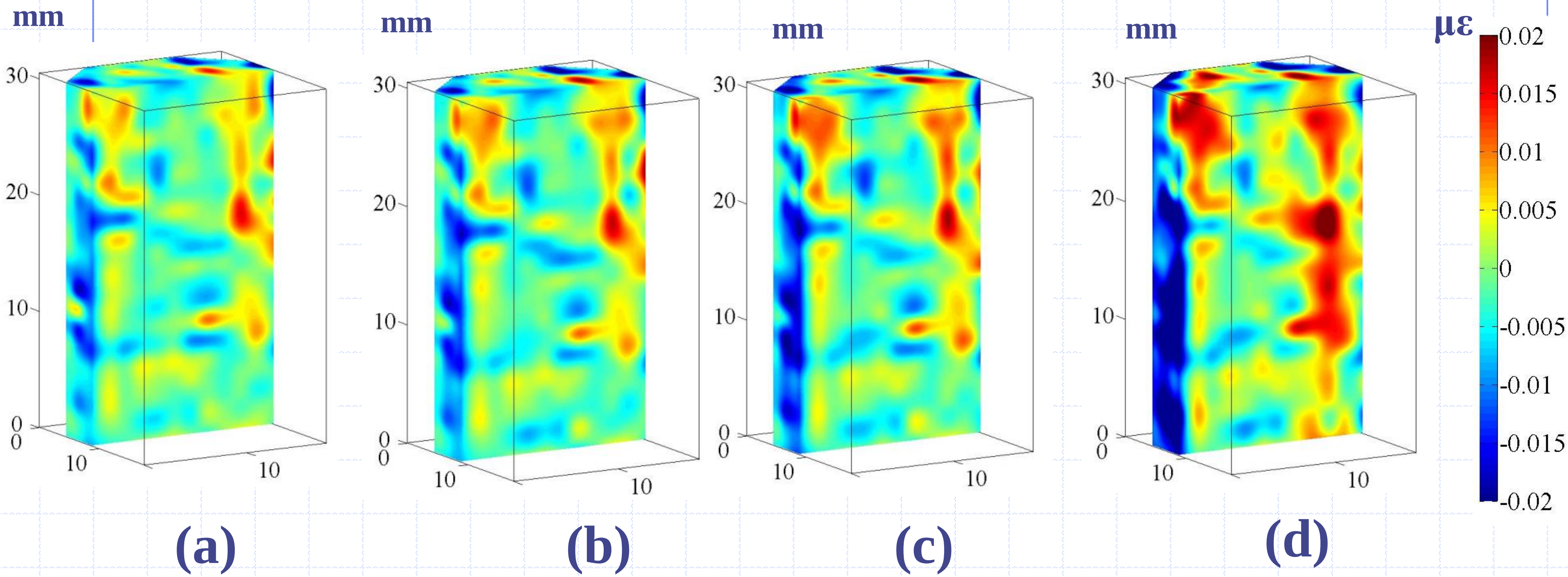
- Internal Strain Analysis of Coal

Volumetric strain of the section along *x*=12.5mm



(a) 4.07MPa (Step2); (b)6.10MPa(Step3); (c)8.14MPa (Step4); (d) 9.98MPa (Step5);

Compared with red sandstone, the internal structure of coal cannot be viewed as high quality speckle. We also observe the strain localization development.

Thank You: to all my students and visiting scholars, the work are all yours

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National Science Foundation,
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National Institute of Health,
Department of Transportation,
&
Industrial companies

- ***Dedicated with love and gratitude***

to

my wife and my children