Fatigue and Fracture of Engineering Materials

GIAN Course
Lecture 1
November 7, 2016

Instructor:
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Retired from
University of Tennessee
Knoxville, TN USA

Course Outline and Schedule
Day 1

- November 7, 2016

- Lecture 1: 1400-1500
- Fracture mechanics background and analytical tools

- Lecture 2: 1530-1630

- Workshop 1: Determining fracture mechanics parameters

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Day 2

- November 8, 2016

- Lecture 3: 1400-1500
- Fracture toughness testing

- Lecture 4: 1530-1630
- Workshop 2: Fracture toughness data and properties

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- Lecture 20: 1530-1700

- Examination/Assessment/Evaluation

Day 3

- November 9, 2016

- Lecture 5: 1400-1500
- Fatigue concepts, testing and properties

- Lecture 6: 1530-1630
- Workshop 3: Analysis of fracture and fatigue data

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Day 4

- November 10, 2016

- Lecture 7: 1400-1500
- Environmental effects in fracture and fatigue

- Lecture 8: 1530-1630

- Fracture mechanics applications

Day 5

- November 11, 2016

- Lecture 9: 1400-1500
- Workshop 4: Fracture and fatigue analysis of engineering structures

- Lecture 10: 1530-1630
- Case studies in fracture and fatigue

Day 6

- November 14, 2016

- Lecture 11: 1400-1500
- Nonlinear fracture mechanics parameters

- Lecture 12: 1530-1630
- Nonlinear fracture and fatigue testing

Day 7

- November 15, 2016

- Lecture 13: 1400-1500
- Workshop 6: Analyzing nonlinear fracture mechanics test results

- Lecture 14: 1530-1630
- Transition fracture toughness and analysis

Day 8

- November 16, 2016

- Lecture 15: 1400-1500
- Nonlinear fracture mechanics applications

- Lecture 16: 1530-1630
- Workshop 5: Using nonlinear fracture mechanics applications

Day 9

- November 17, 2016

- Lecture 17: 1400-1500
- Standard updates, sortware and new trends

- Lecture 18: 1530-1630
- New trends in research

Day 10

- November 18, 2016

- Lecture 19: 1400-1500
- Workshop 6: Discussion of problems contributed by students

- Lecture 20: 1530-1700
- Examination/Assessment/Evaluation

Practical Fracture Mechanics and Fractography - Nomenclature

(This nomenclature is not unique or used consistently in practice)

a = crack size

a_o = initial crack size

a_f = final crack size

a_{cr} = critical crack size

Δa = crack extension increment

b = width (used by the Stress Analysis Handbook)

b, c = material constants (fatigue)

b = (W - a) = uncracked ligament

B = thickness

C = compliance = v/P

da/dN = fatigue crack growth rate

E = elastic modulus

f(a/W), Y = dimensionless geometric parameter for K solution (given in tables or graphs)

F(a/b) = dimensionless geometric parameter for K solution

(given in the Stress Analysis of Cracks Handbook)

$\mathcal{G}$ = strain energy release rate (Griffith theory)

I_n = constant from HRR stress field

J_{Ic} = critical value of J integral, initiation fracture toughness

J_{el} = elastic part of J

J_{pl} = plastic part of J

K = crack-tip stress intensity factor

K_{Ia} = crack arrest fracture toughness

K_{Ic} = plane strain fracture toughness (from ASTM E 399, considered to be a materials property)

K_{Iscc} = threshold stress intensity factor for stress-corrosion cracking

$K_{Ic(t)}$ = fracture toughness for dynamic loading

K_{IR} = fracture toughness reference curve (ASME)

$K_R = K_{app}/K_{Ic}$ (K ratio used in failure analysis diagram)

K_Q = provisional fracture toughness value for K_{Ic} test

$\Delta K = (K_{max} - K_{min})$ = range of the stress intensity factor in fatigue loading

ΔK_{TH} = threshold value of ΔK below which there is no da/dN

k_t = stress concentration factor

m, C = materials constant from the Paris' Law

n = strain hardening exponent (monotonic stress-strain curve)

n' = strain hardening exponent (cyclic stress-strain curve)

N_f = number of cycles to failure

P = applied load

P_Q = provisional load for K_Q evaluation in K_{Ic} test

P_5 = load at 5% secant in K_{Ic} test

Q = calibration factor for K as a function of a/2c shape in surface flaw

Q = secondary stress, residual or thermal (used in CTOD design curve approach)

r = distance from the crack tip to stress measurement point

r^*, r_y = plastic zone size

r_p = ratio of distances in CTOD evaluation

R = stress ratio, $\sigma_{min}/\sigma_{max}$ (used in cyclic loading)

RT_{NDT} = reference temperature for K_{IR} curve (ASME)

S = applied stress amplitude (fatigue)

S = span

$S_R = \sigma_{app}/\sigma_{ys}$ (stress ratio used in failure analysis diagram)

T = surface tension (Griffith theory)

T = tearing Modulus (J-R curves)

T = temperature

T = stress vector in J integral

T_0 = reference temperature used in ASTM E1921 fracture transition master curve

t = thickness (Griffith theory)

$\mathbf{u}$ = displacement vector in J integral

U = total potential energy

U_0 = potential energy without a crack

U_a = potential energy due to a crack

U_t = surface energy per unit area

v = displacement

v_{LL} = load-line displacement

v_{el} = elastic part of the displacement

v_{pl} = plastic part of the displacement

W = specimen width

W = strain energy density in J integral

Z = distance from crack beginning to displacement measurement point in CTOD evaluation

δ = crack tip opening displacement, CTOD

δ_c = CTOD without stable crack growth

δ_m = CTOD at maximum load

δ_u = CTOD with some stable crack growth before unstable crack propagation

$\delta_R = \delta_{app} / \delta_c$ (CTOD ratio used in failure analysis diagram)

ε_a = strain amplitude in fatigue

ε_{ae} = elastic strain amplitude

ε_{ap} = plastic strain amplitude

ε_0 = yield strain

ν = Poisson's ratio

σ_a = stress amplitude in fatigue testing = $\Delta\sigma/2$

σ'_f = constant (fatigue)

$\sigma_{yy}, \sigma_{xx}, \tau_{xy}$ = stresses

$\sigma_Y = (\sigma_{uts} + \sigma_{ys})/2$

σ_{ys}, σ_0 = yield strength

σ_{uts} = ultimate tensile strength

σ_u = ultimate tensile strength in Goodman equation

σ_m = mean stress in fatigue loading

σ_m = membrane stress (CTOD design approach)

σ_b = bending stress (CTOD design approach)

$\Delta\sigma$ = stress range in fatigue loading

θ = angle between the crack plane and the point considered

K solutions

1. Load format; compact, etc.

    Use $f = KB\sqrt{W}/P$ tables

$$K = \frac{Pf}{B\sqrt{W}}$$

2. Stress format, CCT, SE(T), etc.

    Use graphs of F(a/b)

$$K = \sigma\sqrt{\pi a}\,F(a/b)$$

- Center Cracked; CCT; F = 1 for an infinite plate

- Single edge notched SE(T); F = 1.122 for a semi-infinite plate

Reference Books

1. D. Broek, <u>Elementary Engineering Fracture Mechanics</u>, Fourth Revised Edition, Martinus Nijhoff Publishers, 1987.

2. H. L. Ewalds and R. J. H. Wanhill, <u>Fracture Mechanics</u>, Edward Arnold, 1986.

3. M. F. Kanninen and C. H. Popelar, <u>Advanced Fracture Mechanics</u>, Oxford University Press, 1985.

4. J. M. Barsom and S. T. Rolfe, <u>Fracture and Fatigue Control in Structures, Applications of Fracture Mechanics</u>, Second Edition, Prentice Hall, 1987.

5. R. W. Hertzberg, <u>Deformation and Fracture Mechanics of Engineering Materials</u>, Fourth Edition, John Wiley & Sons, 1983.

6. J. F. Knott, <u>Fundamentals of Fracture Mechanics,</u> John Wiley & Sons, 1973.

7. T. L. Anderson, Fracture Mechanics, Fundamentals and Applications, Second Edition, CRC Press, 1995.

8. H. Tada, P. Paris and G. Irwin, The Stress Analysis of Cracks Handbook, Paris Productions, 1985 (new edition due 1998)

9. A. Saxena, <u>Nonlinear Fracture Mechanics for Engineers</u>, CRC Press, Boca Raton, FL, 1998.

10. N. E. Dowling, Mechanical Behavior of Materials, second edition, Prentice-Hall, 1999

Fracture and Fatigue Journals

1. Engineering Fracture Mechanics, Elsevier

2. International Journal of Fracture, Kluwer Academic Publishers

3. International Journal of Fatigue and Fracture of Engineering Materials and Structures, Blackwell

4. International Journal of Fatigue, Elsevier

5. Journal of Testing and Evaluation, ASTM

Course Objectives

1. Learn the importance of using a fracture mechanics approach

2. Understand some basic principles

3. Learn basic methods of testing and data analysis

4. Solve basic problems like critical defect size and life prediction

5. Learn where to get help with fracture problems

Introduction to Fracture Mechanics

- Definition: Technology that deals with the effect of defects on the load bearing capacity of materials and structures.

- Assumptions

    1. Defects may be present in materials and structures

    2. Approaches to predicting failure that do not consider these defects are not adequate
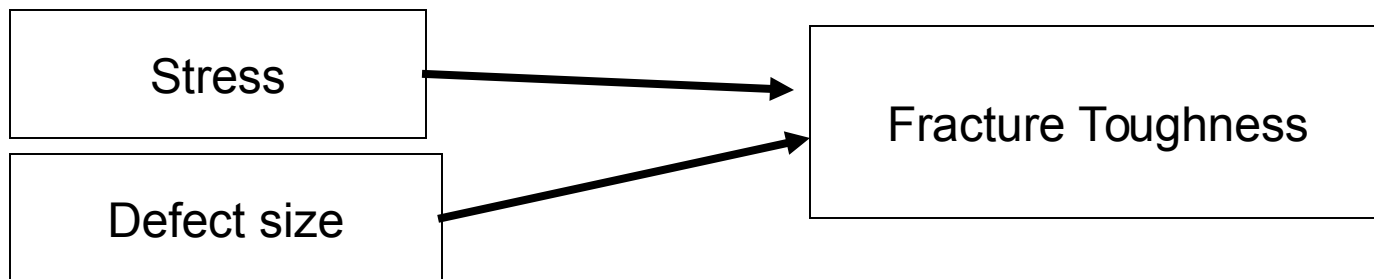
Fracture Mechanics versus Conventional Approaches

1. Conventional approach

| Stress | → | Yield Strength Ultimate tensile Strength |
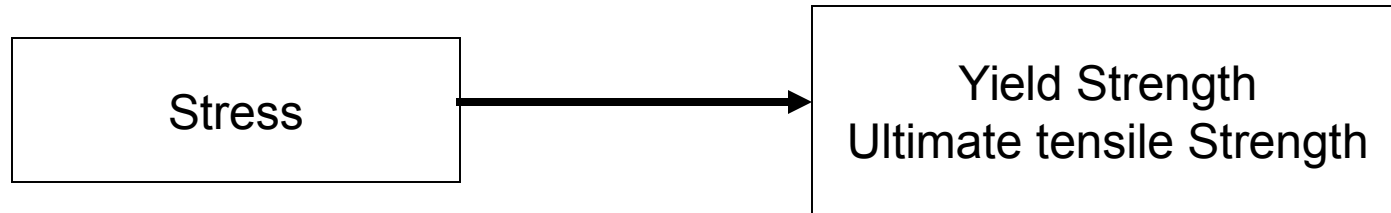
No consideration of the defect in the material

2. Fracture mechanics approach

| Stress | Fracture Toughness |
| Defect size | |

Defect is considered

Types of Defects

A. Microstructural
   Dislocations, voids, inclusions, grain boundaries, second phase particles

B. Macrostructural

   1. Notches, discontinuities, material boundaries

   2. Sharp cracks

Types of Defects, Cont'd

- Technology is not available to treat each case separately; defects are treated as

   a) Notches - stress riser

   b) Sharp crack - stress singularity (this is a fundamental assumption of fracture mechanics)

Need for Fracture Mechanics

1. Economic
    - Cost of failures in the USA 1982 - $132B/yr
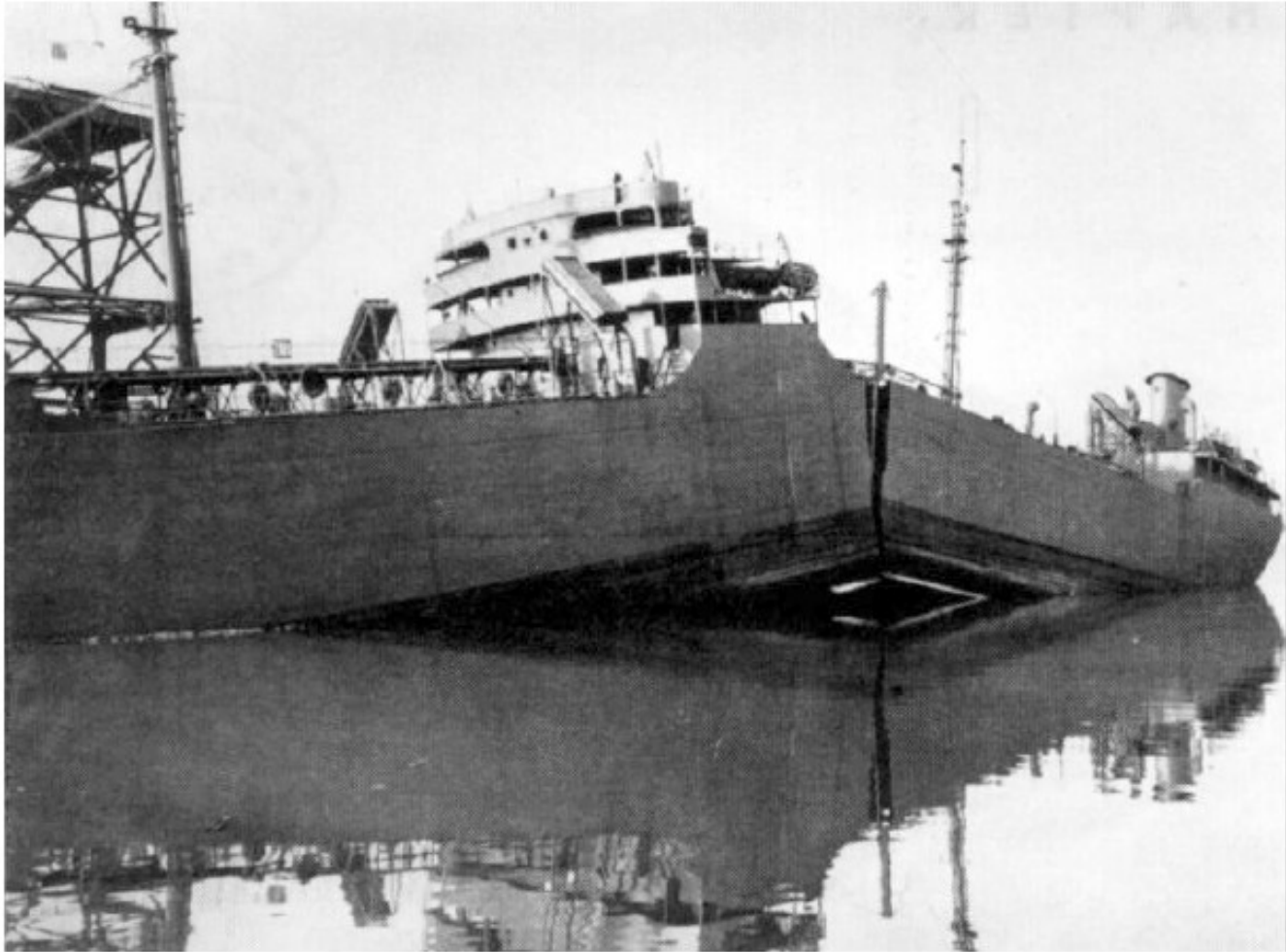   - Savings possible -> 50% using new technology
2. Failures
    - Historical - Molasses tank
    - World War II ships
    - Modern

Boston Molasses Tank Failure
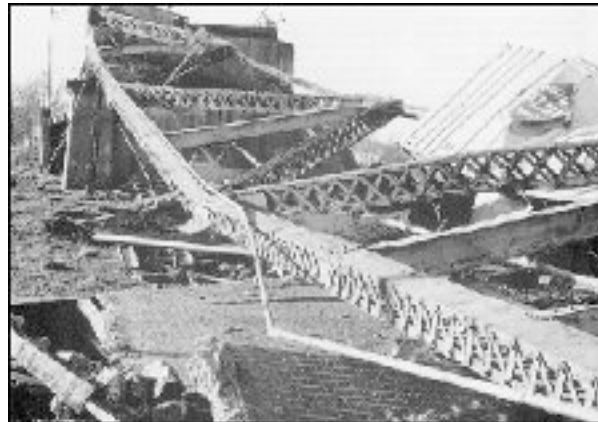
Barge Failure

Post WW II Failures

1. 1950's Comet Aircraft
2. 1967 Point Pleasant Bridge, Ohio - W. VA
3. 1972 IOS Barge
4. 1960's Polaris Missiles
5. 1960's Submarine pressure vessels
6. 1970's F-111 aircraft
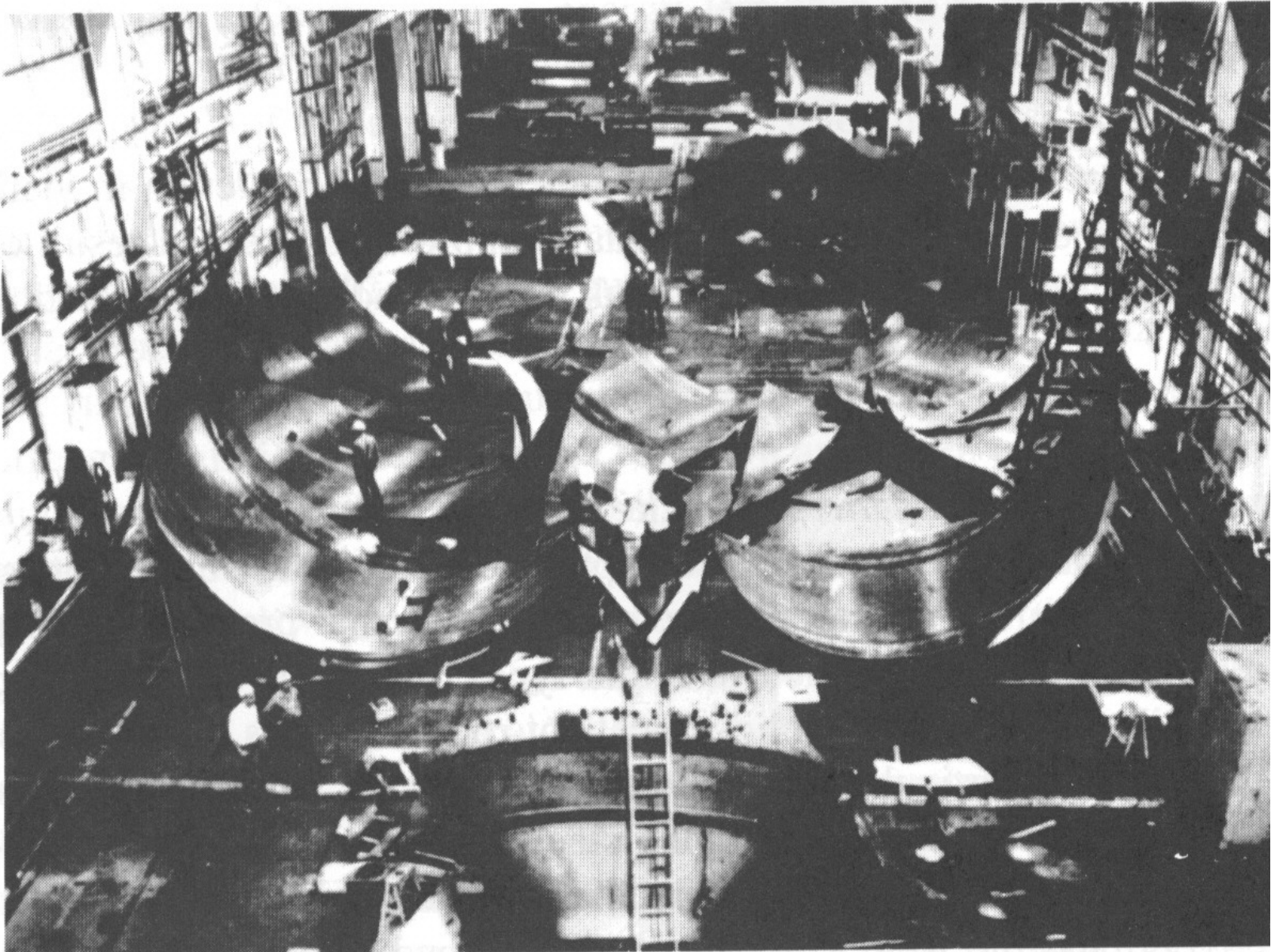7. Minneapolis I-35 W bridge

Fatigue Failure of a 737 Airplane

Point Pleasant Bridge Collapse
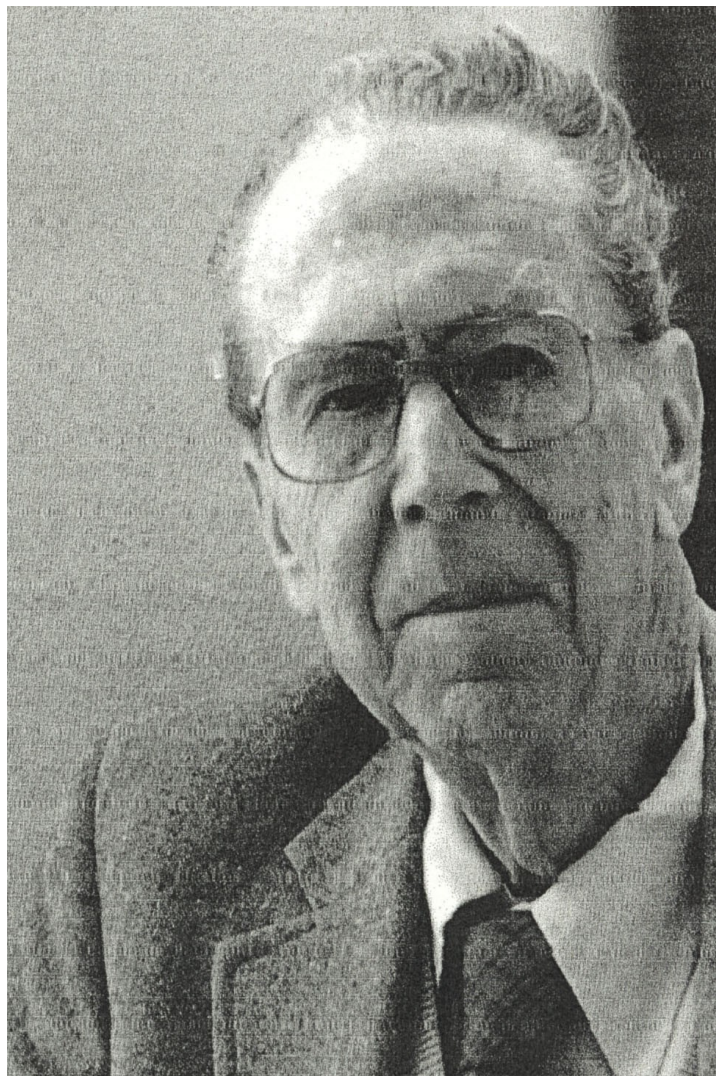
Bridge similar to
Point Pleasant

Bridge after collapse

NASA rocket motor casing failure

George Irwin

Advantages of Fracture Mechanics

1. Quantitative analysis
2. Allows assessment of:
   a) Structural life
   b) Safety factors
   c) Inspection criteria
3. Combines design information
   a) Defect characterization
   b) Stresses
   c) Materials properties