Image Cover Sheet

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TITLE

MODELING THE INITIATION AND PROPAGATION OF FATIGUE CRACKS IN WELDED STEEL STRUCTURES

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Modeling the Initiation and Propagation of Fatigue Cracks In Welded Steel Structures

by

S.B. Lambert[1], G. Glinka[1], and R.D. Yee[2]

[1]Department of Mechanical Engineering, University of Waterloo
[2]Fleet Technology Limited, Kanata, Ontario

ABSTRACT

In recent years, classification societies and naval design authorities have introduced explicit fatigue design criteria for welded structural details in merchant and naval ships. These criteria, which are largely based on well-established fatigue design procedures for welded joints in bridges and offshore structures are intended to ensure that there is a low probability of fatigue failures occurring during the design life of a ship, where failure is generally considered to be the initiation of a through-thickness crack several inches long. However, premature fatigue cracking as a result of fabrication or design errors can still occur. Furthermore, some fatigue cracking can still be expected in properly designed and fabricated ships. Therefore, quantitative techniques for predicting the residual life and residual strength of cracked structural welded details are needed to develop safe but cost-effective inspection schedules at the design stage. These techniques could also be used to optimize the scheduling of repairs for cracks found in service, to assess whether the operation of existing ships can be extended beyond their original design lives, and to assess the relative effects of environment and detail configuration on fatigue performance.

Fatigue cracking in welded details is a complex process that usually involves the initiation of multiple cracks along a weld toe in a pseudo-random manner, and the growth and coalescence of these cracks. Over the past decade, researchers at the University of Waterloo have developed probabilistic models for predicting the initiation and propagation of fatigue cracks in welded marine structures, including notch strain models for fatigue crack initiation and linear elastic fracture mechanics analysis for fatigue crack propagation. These models have been verified against experimental data on the initiation and propagation of fatigue cracks in large scale welded details.

This paper discusses the analytical basis of the models including the strain energy density approach to notch strain analysis, the weight function method for the efficient calculation of crack tip stress intensity factors, algorithms for simulating the coalescence of multiple cracks, and probabilistic methods to account for the variability of local weld geometry and material properties. In addition, developments currently underway to account for three-dimensional stress distributions and load shedding effects in ship structures are presented.

Outline

- Fatigue in Naval Structures
- Fatigue Modeling
  - Initiation
  - Propagation
  - Simulations
- T-Plate Example
  - Geometry and Loading
  - Input Data
  - Results

Fatigue in Naval Structures

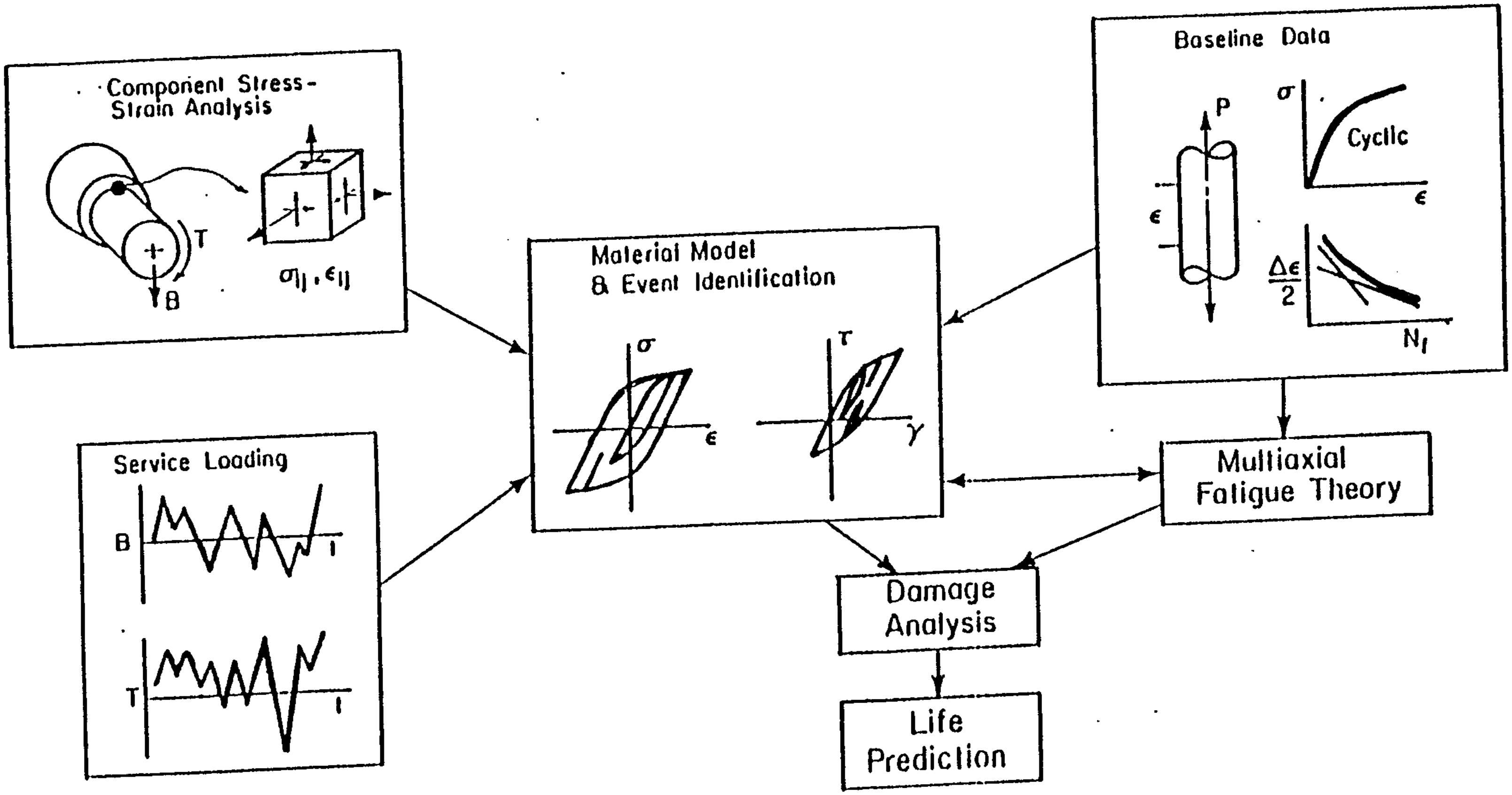
- Fatigue Loading
  - *wave loading* - longitudinal and transverse bending, torsion
  - *fluctuating hydrostatic pressure* - tank walls, cargo holds
  - *machinery and hull vibration*
- Corrosive Environment
  - *seawater, sour crude oil*
  - *corrosion fatigue, localized thinning*

Fatigue in Naval Structures (con't)

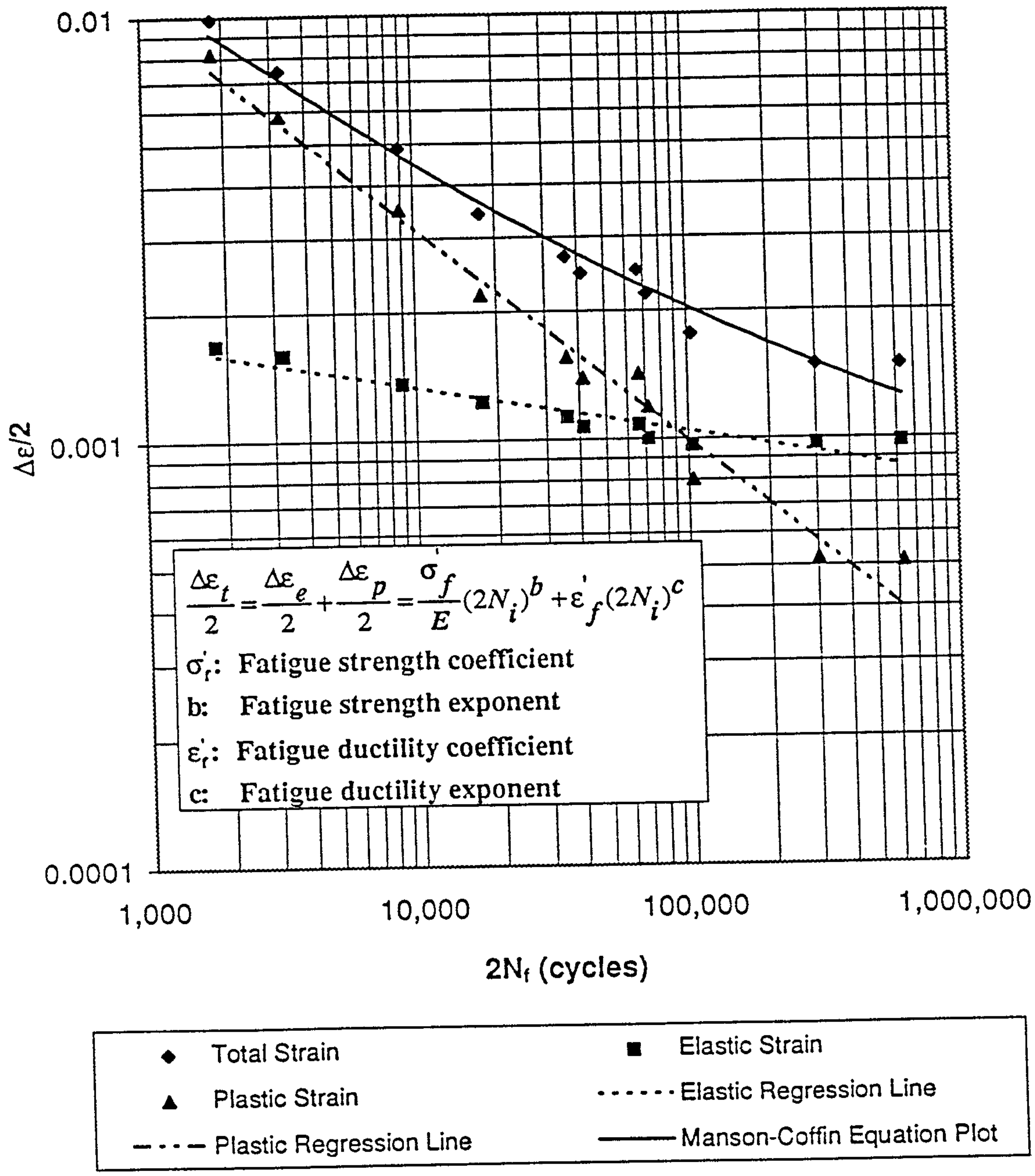
- Welded Connections
  - hatch corners, bulkhead intersections, end connections
  - stress concentrations, residual stresses, weld defects, redundant load paths
- Fatigue Analyses
  - damage tolerant design
  - scheduling of inspections
  - fabrication or design errors

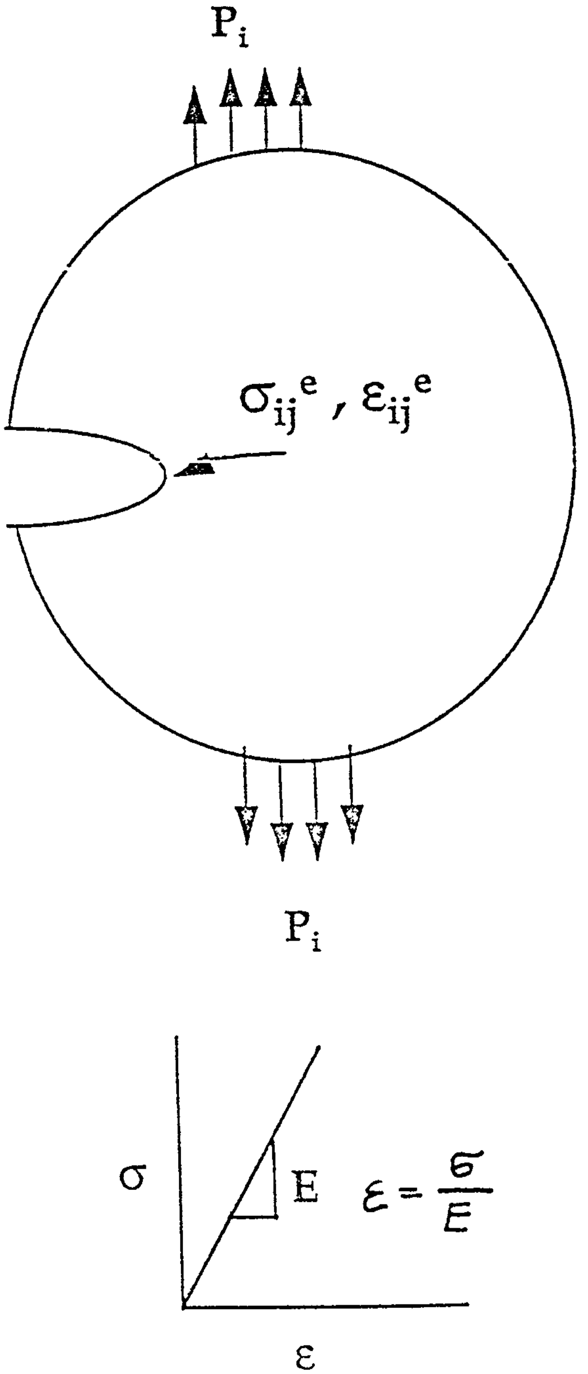
Fatigue Modeling

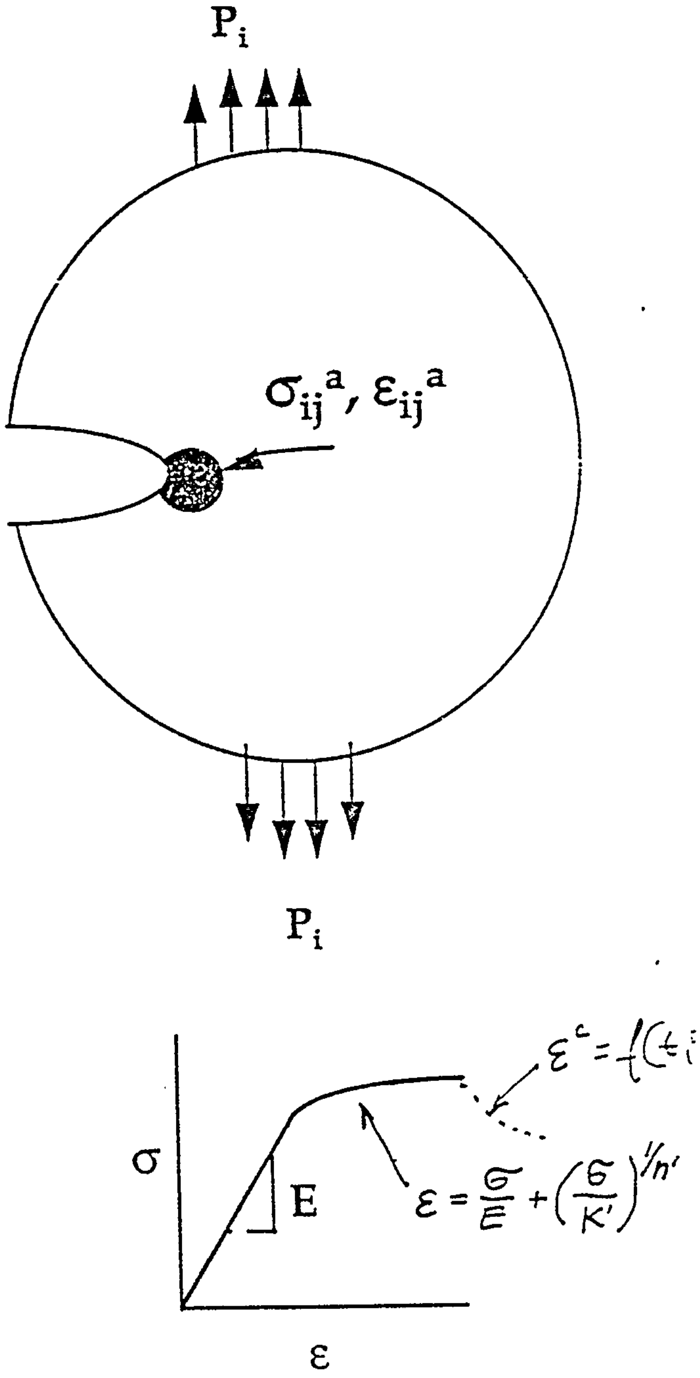
- Initiation
  - strain-life analysis
  - notch analysis
- Propagation
  - crack growth data
  - stress intensity factor calculations
  - crack shape development
- Simulations
  - initiation and propagation
  - Monte Carlo Techniques
  - input data

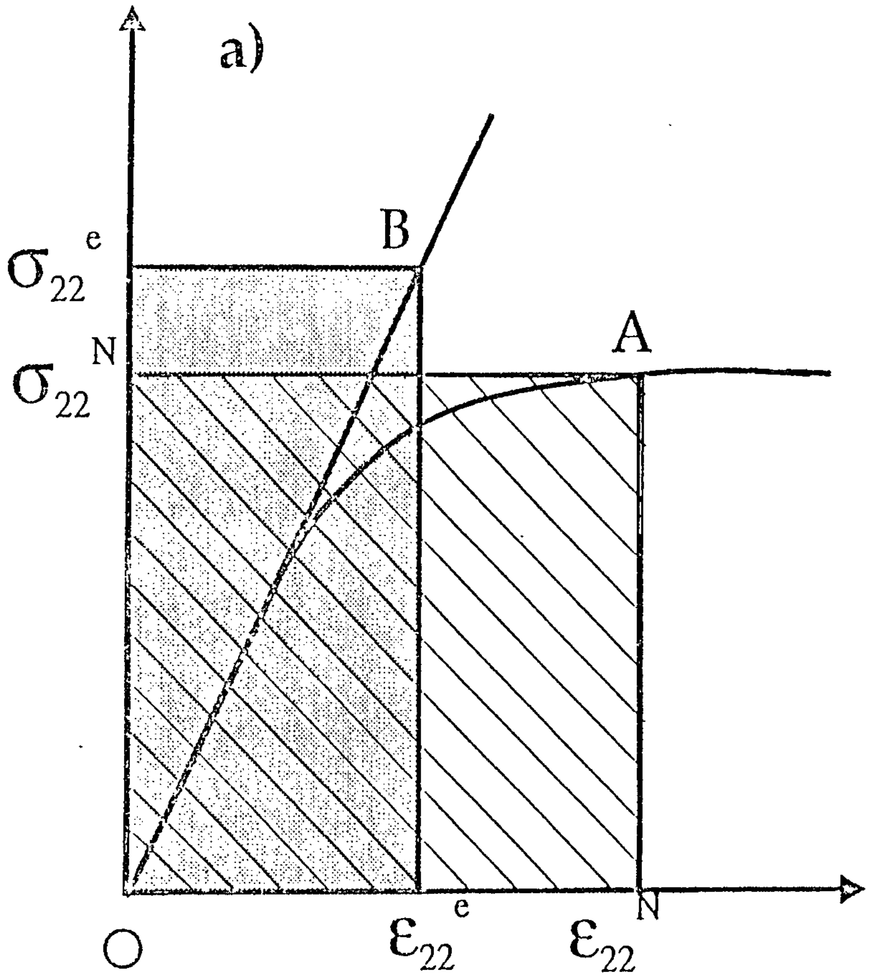


Schematic of Component Fatigue Analysis by the Local Stress-Strain Approach

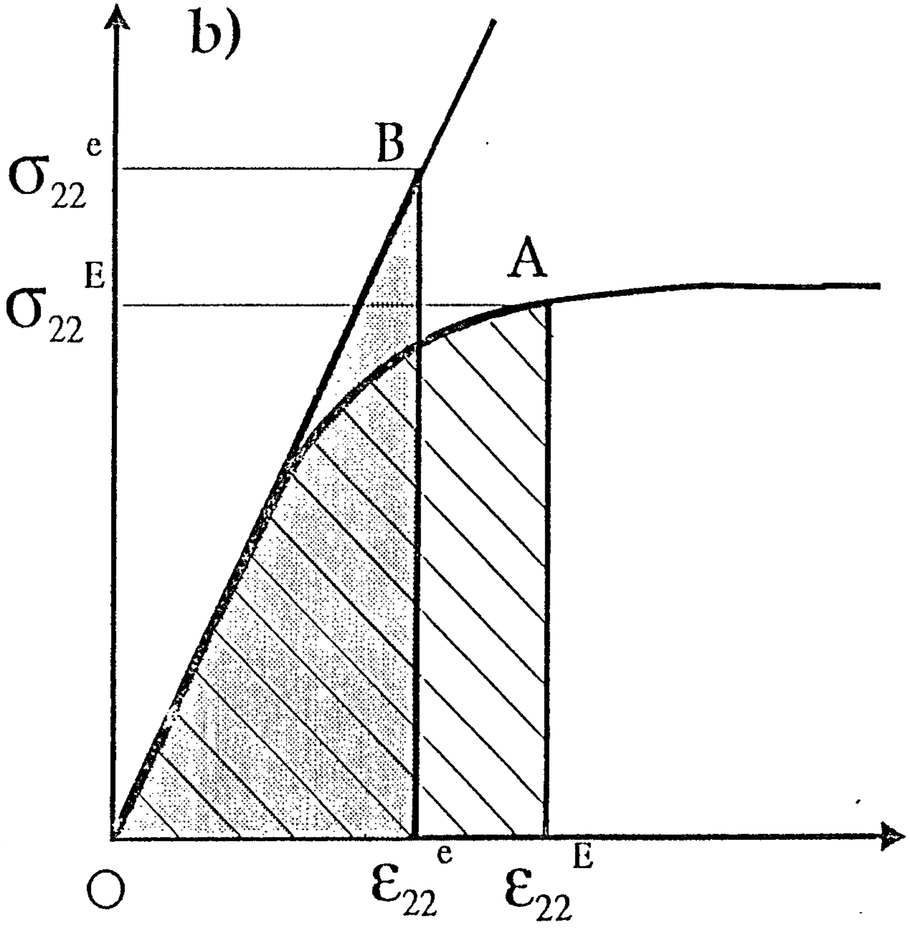

0.01
0.001
0.0001
Δε/2
1,000
10,000
100,000
1,000,000
2N$_f$ (cycles)
$\frac{\Delta\varepsilon_t}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma'_f}{E}(2N_i)^b + \varepsilon'_f(2N_i)^c$
σ'_f: Fatigue strength coefficient
b: Fatigue strength exponent
ε'_f: Fatigue ductility coefficient
c: Fatigue ductility exponent
◆ Total Strain
▲ Plastic Strain
– - - – Plastic Regression Line
■ Elastic Strain
- - - - - - Elastic Regression Line
——— Manson-Coffin Equation Plot


P_i
$\sigma_{ij}^e, \varepsilon_{ij}^e$
P_i
σ
E
$\varepsilon = \frac{\sigma}{E}$
ε

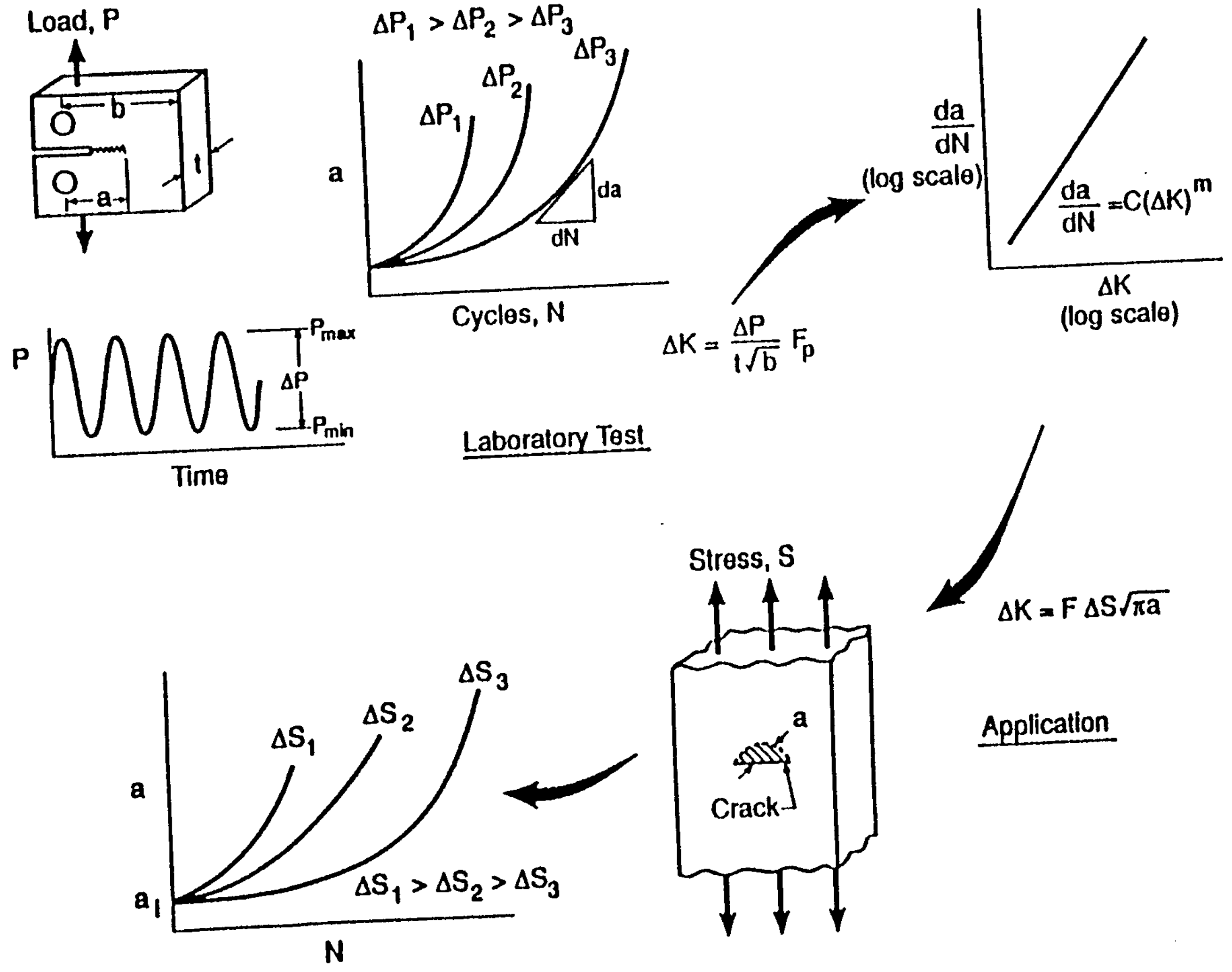

P_i
$\sigma_{ij}^a, \varepsilon_{ij}^a$
P_i
$\varepsilon^c = f(t;$
σ
E
$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{1/n'}$
ε



$$\sigma^e_{22}\varepsilon^e_{22} = \sigma^N_{22}\varepsilon^N_{22}$$



$$\frac{1}{2}\sigma^e_{22}\varepsilon^e_{22} = \int_0^{\varepsilon^E}\sigma^E_{22}\,d\varepsilon^E_{22}$$



Steps in obtaining da/dN vs. ΔK data and using it for an engineering application.

Crack Propagation

- Stress Intensity Factor (K) Calculations

$$K = Y\sigma\sqrt{\pi a}$$

  - Y - geometry correction factor
  - σ - nominal (remote) stress
  - a - crack depth
- handbooks, finite element methods, weight functions

Weight Functions: *m(x, a)*

$$K = \int_0^a m(x,a)\sigma(x)dx$$

$\sigma(x)$ - uncracked stress distribution on the prospective crack plane

Example: through crack in an infinite plate

$$m_A(x,a) = \frac{1}{\sqrt{\pi a}}\sqrt{\frac{a+x}{a-x}}$$

Weight Functions for semi-elliptic cracks in a flat plate:

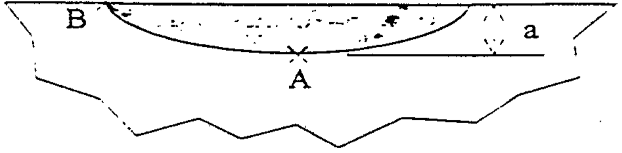
$$m_A(x,a)=\frac{2}{\sqrt{2\pi(a-x)}}\left[1+M_{1A}\left(1-\frac{x}{a}\right)^{1/2}+M_{2A}\left(1-\frac{x}{a}\right)+M_{3A}\left(1-\frac{x}{a}\right)^{3/2}\right]$$

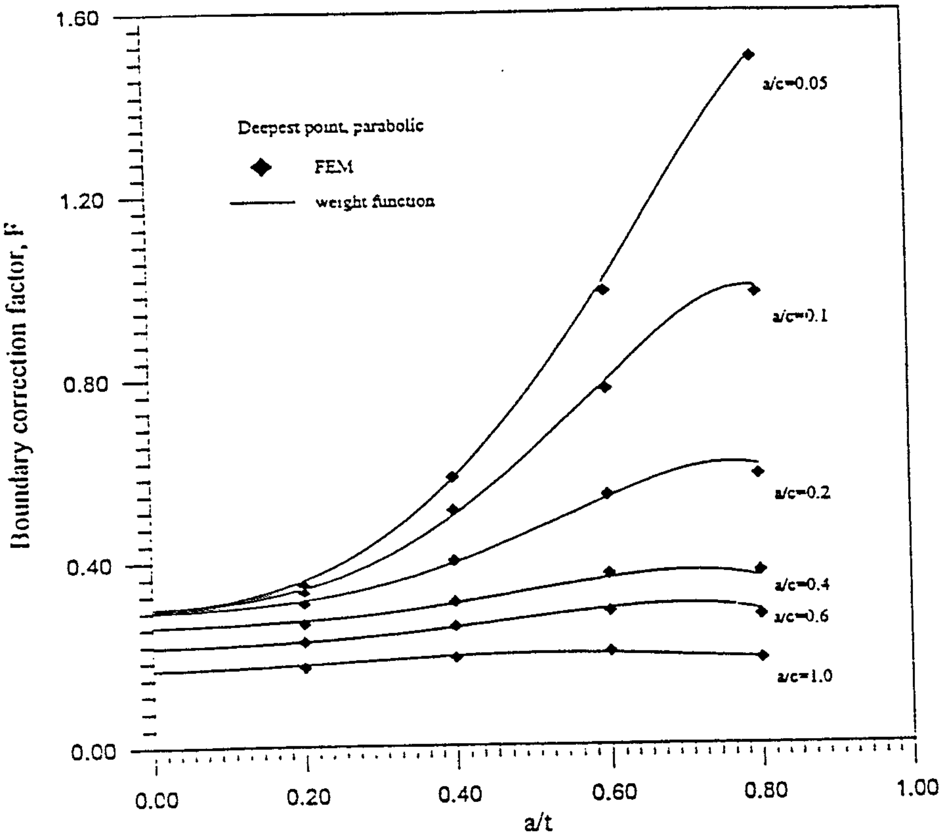
at the deepest point, *A*, and

$$m_B(x,a)=\frac{2}{\sqrt{\pi x}}\left[1+M_{1B}\left(\frac{x}{a}\right)^{1/2}+M_{2B}\left(\frac{x}{a}\right)+M_{3B}\left(\frac{x}{a}\right)^{3/2}\right]$$

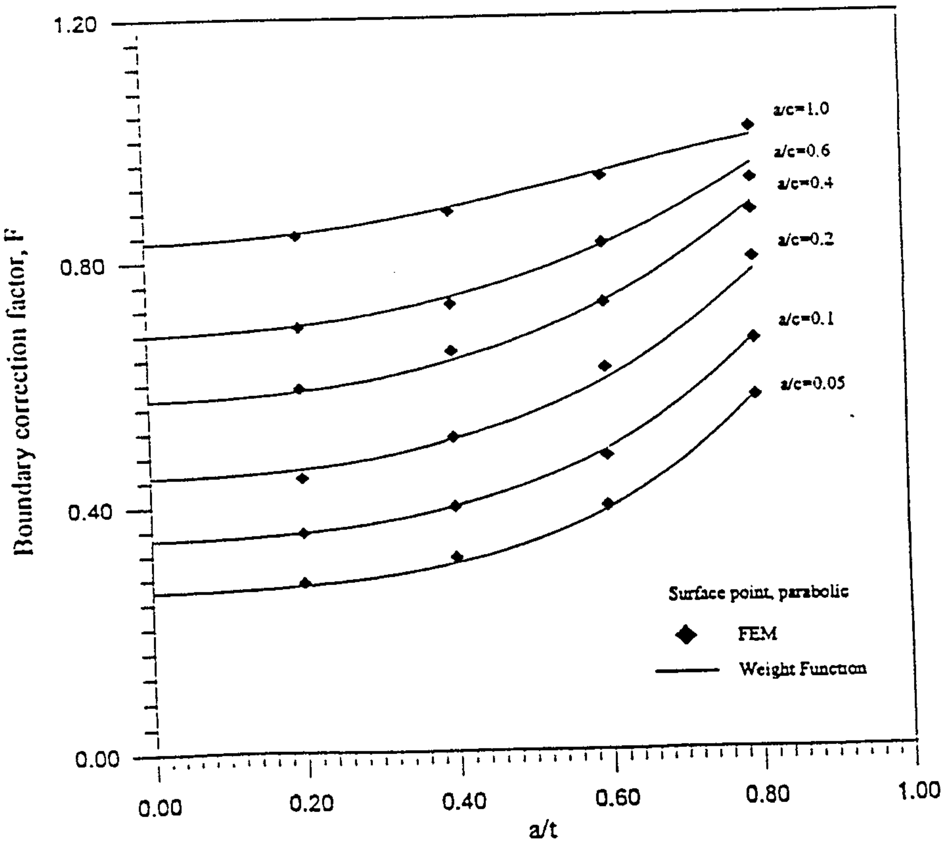
at the surface point, *B*.

See Wang and Lambert, *Engineering Fracture Mechanics*, Vol. 51, No. 4, pp. 517-532, 1995.





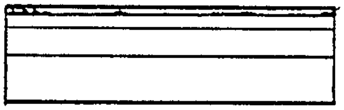
Deepest point, parabolic
FEM
weight function
Boundary correction factor, F
a/t
1.60
1.20
0.80
0.40
0.00
0.00
0.20
0.40
0.60
0.80
1.00
a/c=0.05
a/c=0.1
a/c=0.2
a/c=0.4
a/c=0.6
a/c=1.0



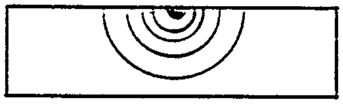
Surface point, parabolic
FEM
Weight Function
Boundary correction factor, F
a/t
1.20
0.80
0.40
0.00
0.00
0.20
0.40
0.60
0.80
1.00
a/c=1.0
a/c=0.6
a/c=0.4
a/c=0.2
a/c=0.1
a/c=0.05

Crack shape development assumptions should be based on physical observations.

Example: T-plate welded joint:
Edge crack is the most conservative (shortest predicted life).



Single surface crack with 'natural' development is the least conservative.

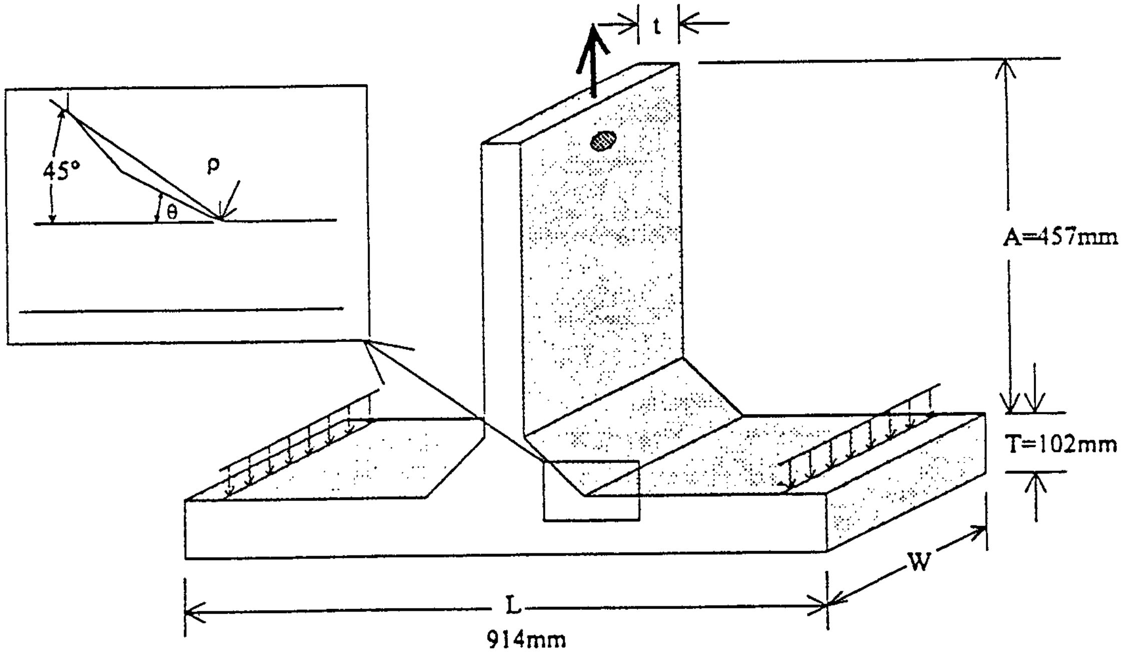


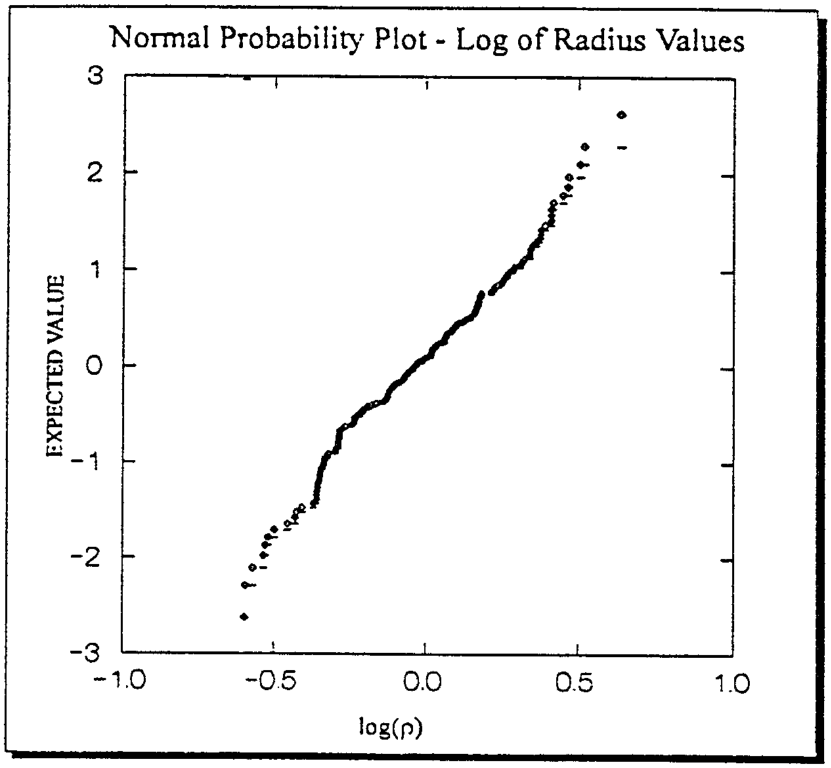
Single surface crack with a prescribed aspect ratio (forcing function) based on physical observations is more accurate.

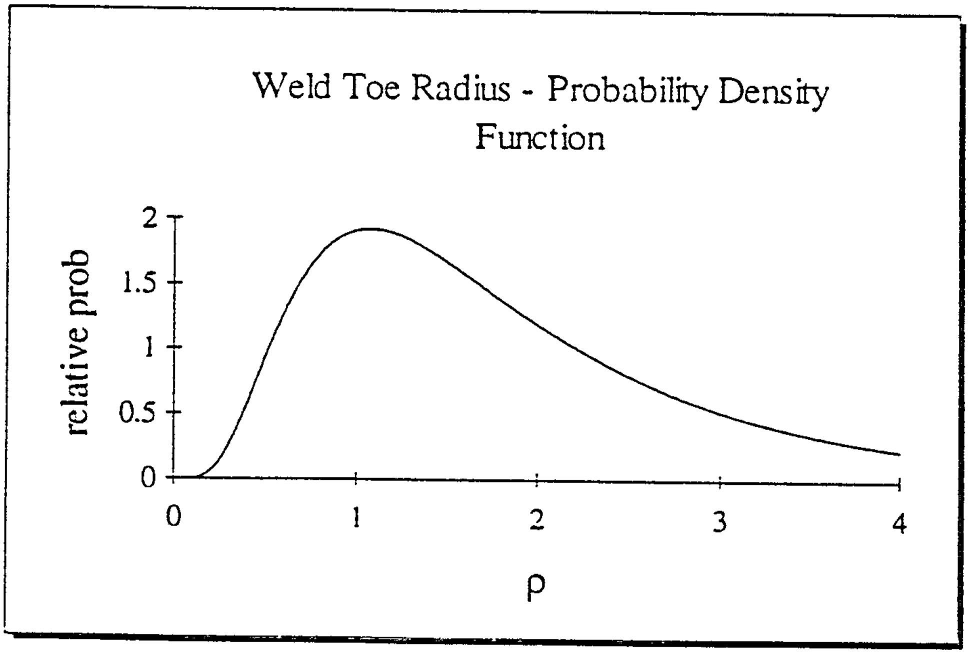
Multiple surface crack with simple coalescence rules is most accurate.

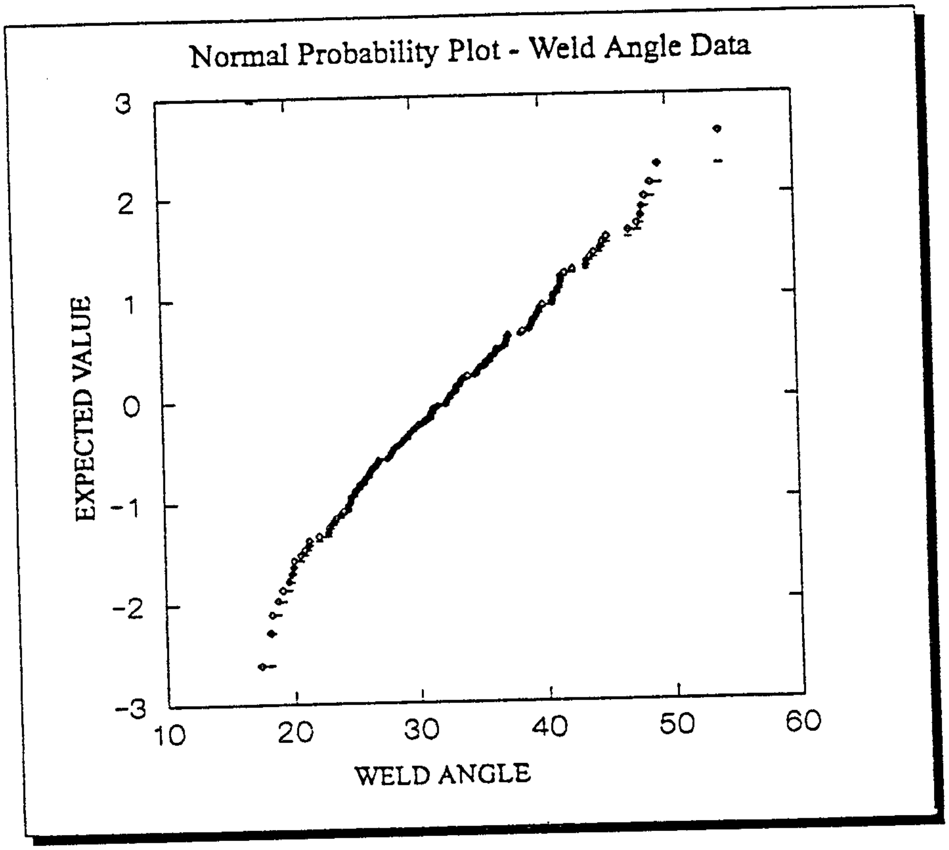
Example: T-Plate Welded Joint

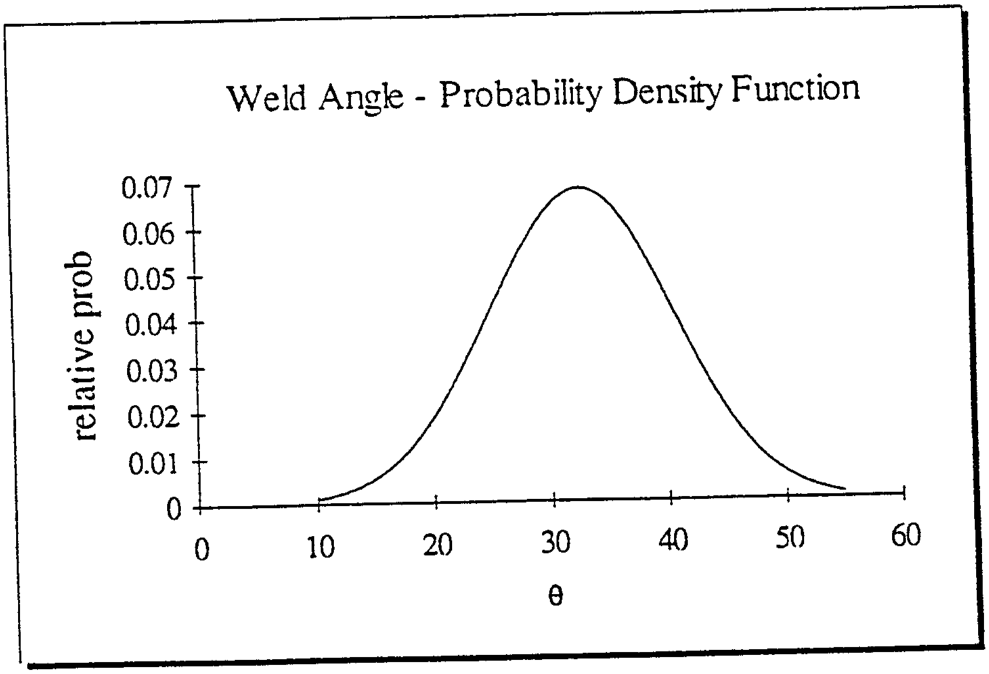
See: R.L. Lecsek, R. Yee, S.B. Lambert and D.J. Burns, “A Probabilistic Model for Initiation and Propagation of Surface Cracks in Welded Joints”, *Fatigue & Fracture of Engineering Materials and Structures*, Vol. 18, No. 7/8. pp. 821-831, 1995.

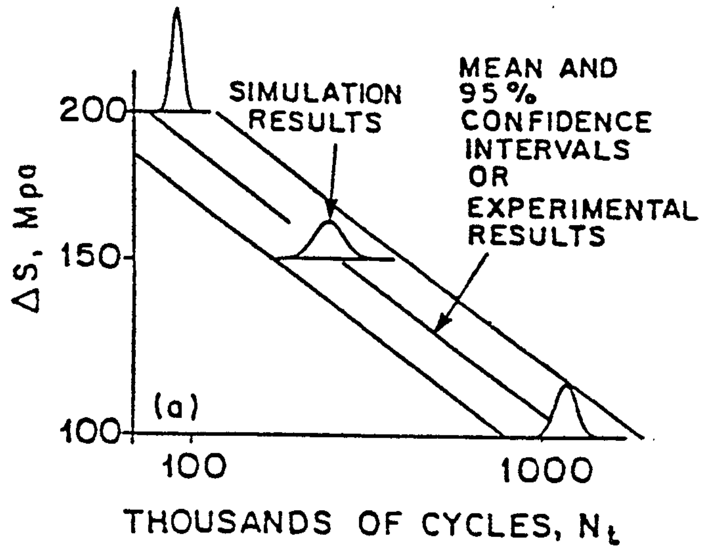



Normal Probability Plot - Log of Radius Values
EXPECTED VALUE
3
2
1
0
-1
-2
-3
-1.0
-0.5
0.0
0.5
1.0
log(ρ)

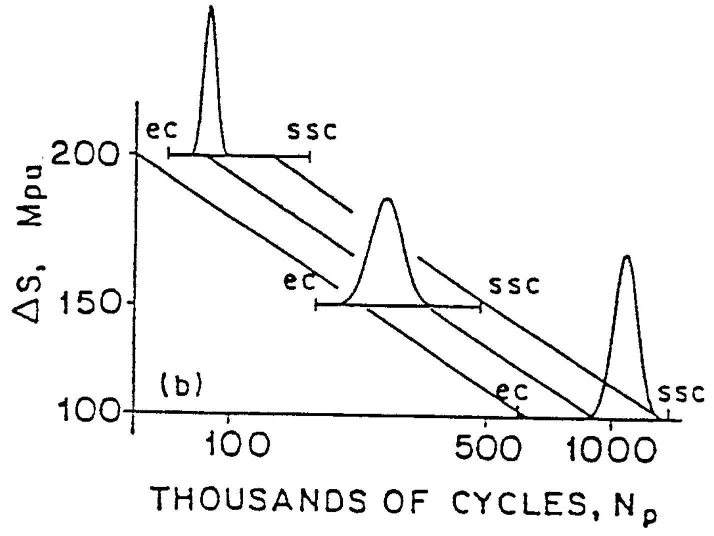

Weld Toe Radius - Probability Density Function
relative prob
2
1.5
1
0.5
0
0
1
2
3
4
ρ


Normal Probability Plot - Weld Angle Data
EXPECTED VALUE
3
2
1
0
-1
-2
-3
10
20
30
40
50
60
WELD ANGLE

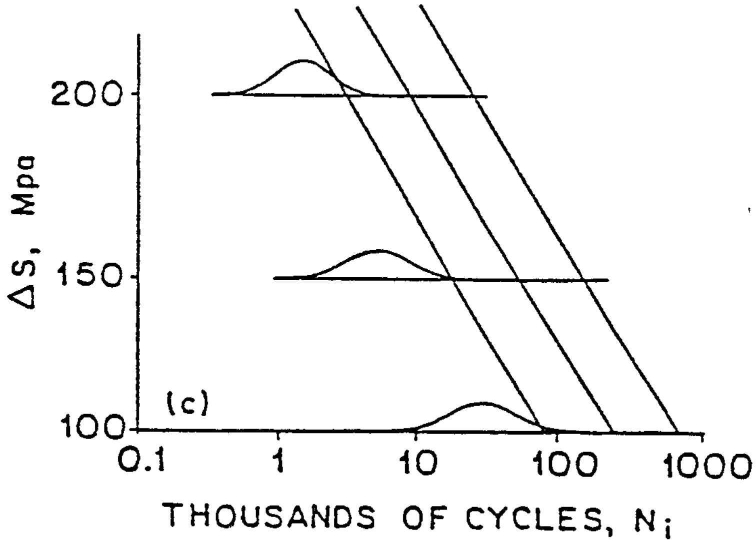

Weld Angle - Probability Density Function
relative prob
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
10
20
30
40
50
60
θ



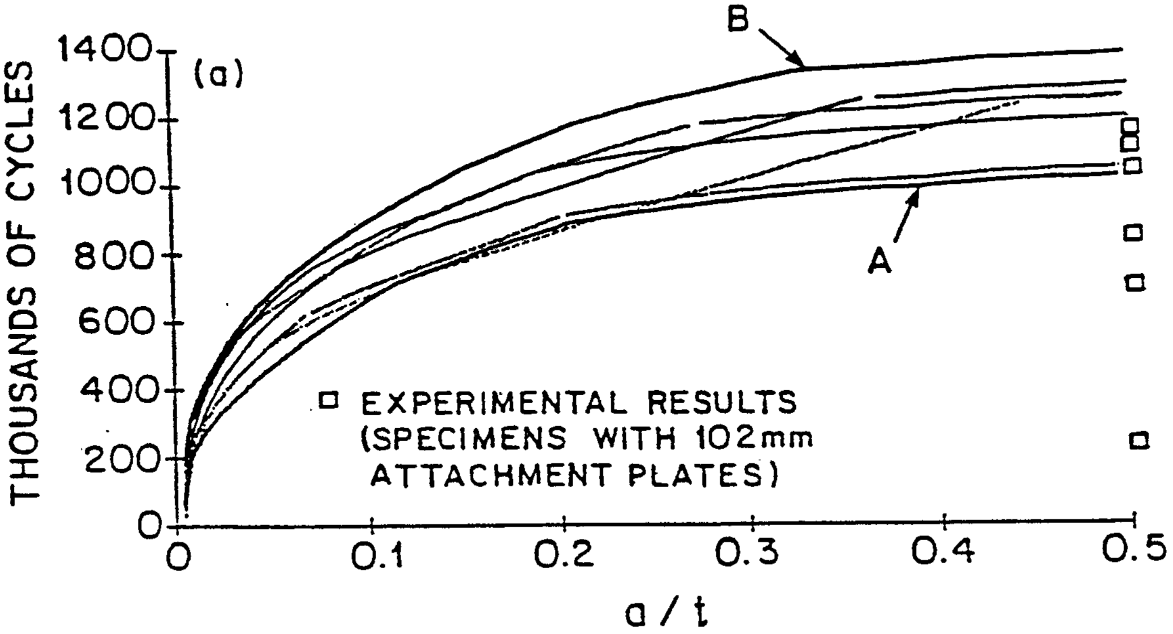
SIMULATION RESULTS
MEAN AND 95% CONFIDENCE INTERVALS OR EXPERIMENTAL RESULTS
ΔS, Mpa
200
150
100
(a)
100
1000
THOUSANDS OF CYCLES, N_t

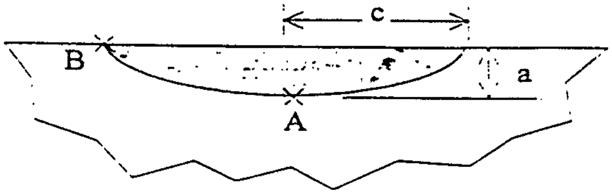


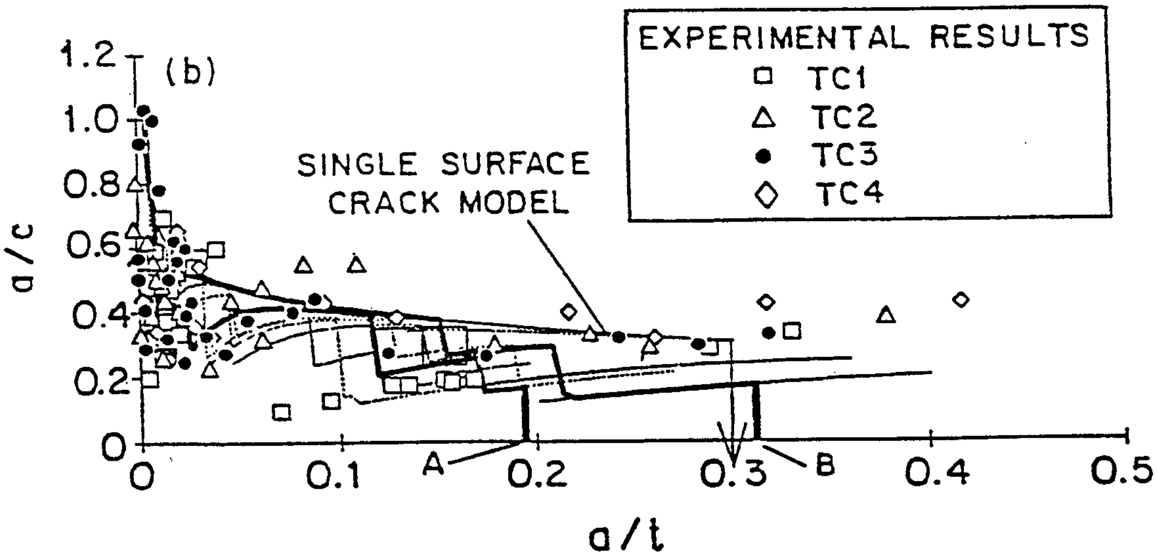
ec
ssc
ec
ssc
ec
ssc
ΔS, Mpa
200
150
100
(b)
100
500
1000
THOUSANDS OF CYCLES, N_p



ΔS, Mpa
200
150
100
(c)
0.1
1
10
100
1000
THOUSANDS OF CYCLES, N_i


B
A
(a)
THOUSANDS OF CYCLES
1400
1200
1000
800
600
400
200
0
0
0.1
0.2
0.3
0.4
0.5
a / t
EXPERIMENTAL RESULTS (SPECIMENS WITH 102mm ATTACHMENT PLATES)


c
B
a
A


(b)
a/c
1.2
1.0
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
a / t
A
B
SINGLE SURFACE CRACK MODEL
EXPERIMENTAL RESULTS
□ TC1
△ TC2
● TC3
◇ TC4