Discussion of Open Issues on Cracks Versus Notches

R. Bruce Thompson, Center for NDE
D. Forsyth, TRI
E. Lindgren, AFRL

Outline

- Slides from February, 2005 MAPOD Meeting
- Controlling Factors
- Past Eddy Current Data
- Past Ultrasonic Data

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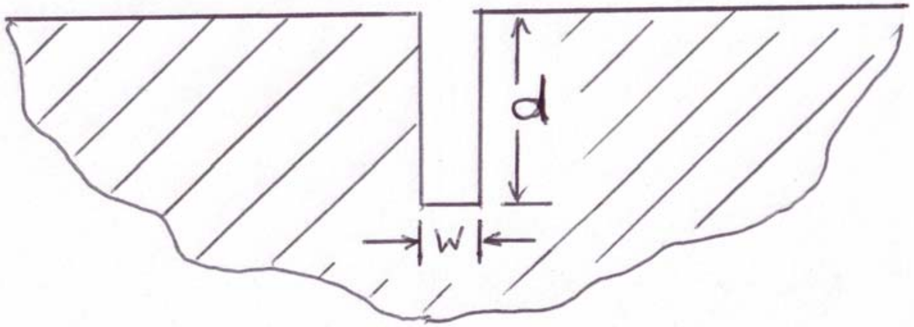
Notch

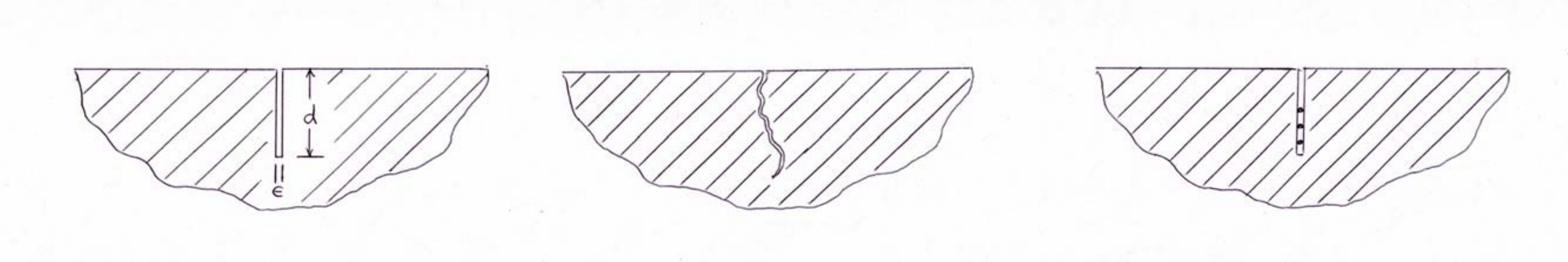


Cracks

Ideal Mathematical Crack

Morphology Effects

Electrical/Mechanical Contact Effects



Material Mechanisms

- Growth along grain boundaries
- Non-uniform residual stresses

- Oxides and other debris
- Contacting asperities
- Sheared faces

Ultrasonics

Response as Compared to Notch Response

Measurement	Ideal Crack	Morphology Effects	Mechanical Contact Effects
Specular Reflection	Equivalent	Reduced Due to Interference	Reduced Due to Transmission
Tip Diffraction	Different; Often Less	Different; Often Less	Different; Often less
Through Transmission	Equivalent	Equivalent	Increased

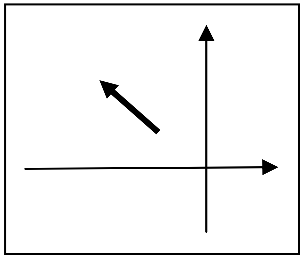
Eddy Currents

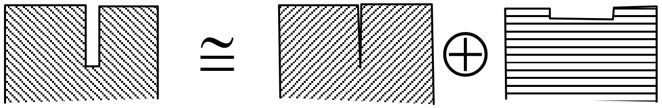
General Comments

- Electrical contacts (bridging) will always have an effect if currents, following along crack faces, are "short circuited"
- Morphology effects are less significant than for UT
- Open cracks have greater "inductance" than ideal mathematical crack because of stored energy in magnetic fields
- The difference increases with frequency
- In the impedance plane, this is similar to, and hard to differentiate from, lift-off effect

Notch vs. Crack: EC Model

- Notch-Crack difference appears
  - ☐ Strongly in impedance amplitude
  - ☐ Weakly in vertical components (when lift-off is horizontal)
- Reason
  - ☐ The volume effects behave similarly to the lift-off effect
    - More volume energy = higher reactance
    - Less material = lower resistance





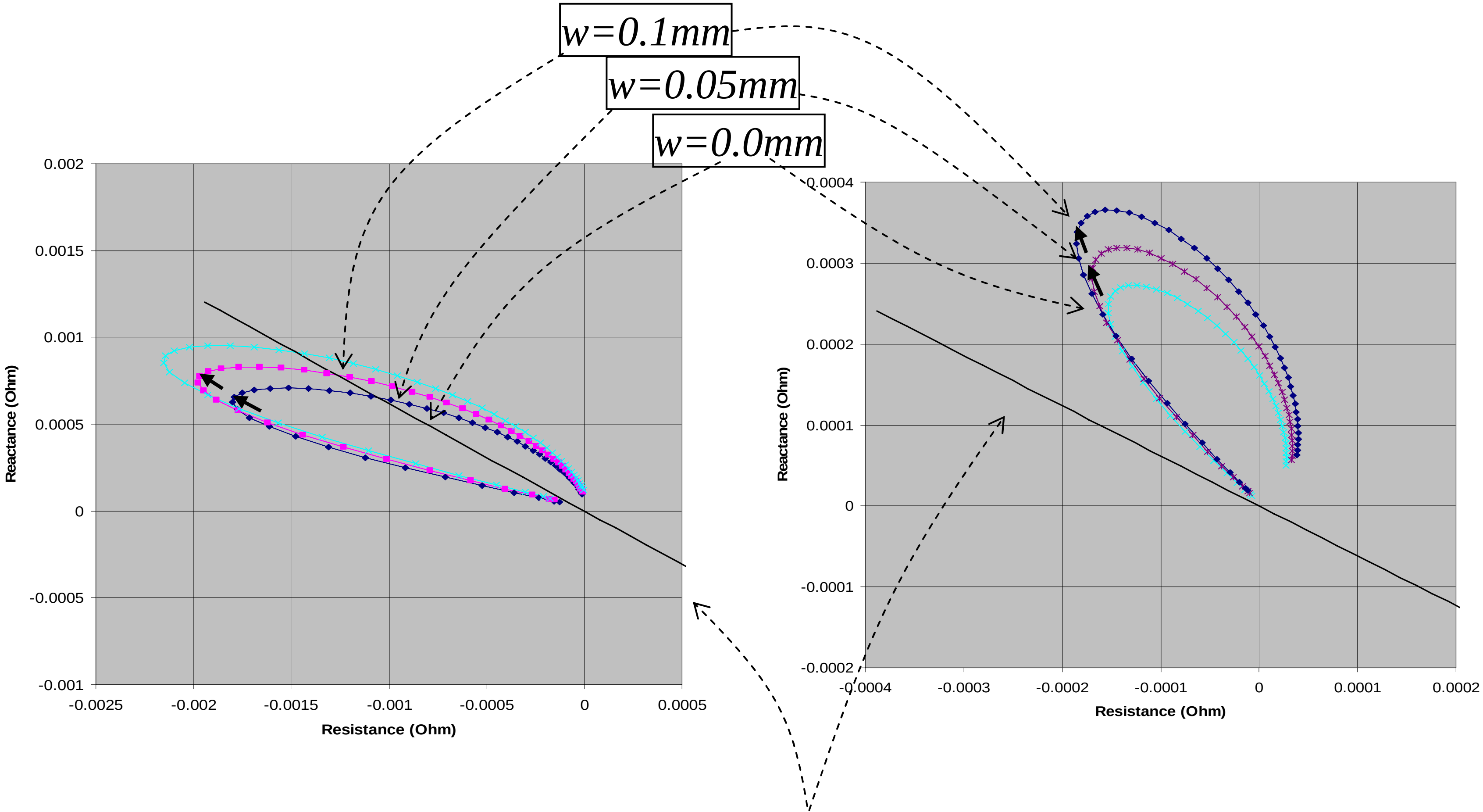
Example Calculation

Model Parameters

- Notch *l*ength×*d*epth×*w*idth
  - *l*=1mm, *d*=0.5mm
  - *w*=0.0, 0.05, 0.1mm
- Solenoid coil
  - *ID*=1.07mm, *OD*=2.62mm
  - *L*=2.79mm
  - Lift off=0.73mm
  - *F*=100kHz
- Part = a plate
  - Inconel 600 (1.02x10^6 S/m)
  - 1.27mm thick

- In two configurations
  - “ID” (same side)
  - “OD” (opposite side)
- Results
  - ~20% increase in amplitude with 10% opening (i.e. *w*/*l*=0.1)
  - Increase in the lift-off direction
  - Vertical components are insensitive to notch openings.

Calculated Opening Effects



w=0.1mm

w=0.05mm

w=0.0mm

ID

Lift-off direction

OD

Eddy Currents

Measurement	**Ideal crack response as compared to notch response**
Absolute coil - Lift-off rotated to horizontal - "Response" taken as vertical response	**Difference often small** - Ideal crack can have greater or less response
Differential coil - "Response" taken as magnitude of impedance change	Significant Difference $\left\|\Delta Z_{NOTCH}\right\| > \left\|\Delta Z_{CRACK}\right\|$

Suggested Strategy

- Use physics-based models to correct notch data for difference between ideal cracks and notches
- Create database of deviations of responses real cracks from expectations for ideal cracks
  - Include salient materials variables specifying growth factors controlling morphology
    - HCF vs LCF
    - Closure
    - Etc.
- Long term goal
  - Develop “knock down factors” that can be confidentially used in new studies

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- Slide from February, 2005 MAPOD Meeting
- **Controlling Factors**
- Past Eddy Current Data
- Past Ultrasonic Data

Controlling Factors for Signal – EC
(to be checked against INCITE list)

- Correlation between signal and noise sources
- Notches
  - Wire
  - HAZ
  - Tool condition
  - Processes to generate (feeds, speeds)
  - Tool materials and dimensions
  - Tool shape
  - Notch shape

Controlling Factors for Signal – EC (to be checked against INCITE list)

- Cracks
  - Opening
  - Contacting asperities
  - Roughness
  - Surface condition (shot peening, smeared metal
  - Presence of fretting
  - Morphology (shape, orientation, depth, length)
  - Multiple cracks vs. single crack

Controlling Factors for Signal – EC
(to be checked against INCITE list)

- Root causes
  - Growth conditions
    - $\sigma/\sigma y$ time history
      - Constant amplitude
      - Overloads
      - High or low cycle
      - Mode I, II, III or ?
  - Initiation conditions
    - Stress corrosion vs. fatigue vs. corrosion fatigue, etc.
    - Intergranular vs. transgranular
    - Scratches, dings
    - Fretting
    - Surface vs. subsurface initiation

Controlling Factors for Signal – EC (to be checked against INCITE list)

- Material issues
    - Toughness
    - Grain size
    - Grain boundary condition
    - Mechanism of contact (sliding, oxide debris, plastic deformation)
    - Contacts conducting
    - Roughness

Controlling Factors for Noise - EC

- Scratches, dents, dings
- Roughness
- Surface geometry features (edges, corners, etc.)
- Out of roundness
- Corrosion, pitting
- Dirt
- Liftoff variations
- Microstructure
- Thermal drift
- Fastener/part interface and material

System/Operator Issues

Consider relevance to model inputs some of which will be modeled and some of which will be characterized empirically

- Probes, instrumentation, cables, etc.
- Scan plan (speed)
- Quality control of inspection system
- Human factors

Challenge: Variable for Fastener Sites (Aldrin, et. al)

- NDE technique (measurement system):
  - NDE method
  - Transducer/probe design
  - Contact condition with part (direct, immersion)
  - Scan plan (directions, resolution, orientation)
- Part Geometry, material and condition:
  - Layer material, number, and thickness (shims)
  - Outer layer surface condition (paint, corrosion)
  - Fastener material/type/head condition

Challenge: Variable for Fastener Sites (Aldrin, et. al)

- Hole geometry (oblong, off-angled, surface conditions, scratches, chatter, tool marks)
- Fastener hole fit (asymmetric fit, irregular contact conditions/loading, sealant)
- Gaps/sealant between layers (aging)
- Presence of metal shavings
- Bushings, residual stress around holes
- Proximity of adjacent fasteners and edges
- Presence and condition of repairs

Challenge: Variable for Fastener Sites (Aldrin, et. al)

- Flaw characteristics:
  - Flaw number (number of cracks per site)
  - Flaw type (cracks, EDM notch)
  - Flaw location (layer, location in layer: surface, mid-bore, eye-brow cracks)
  - Flaw orientation (around fastener site, skew angle from normal)
  - Flaw dimensions (length, aspect ratio)
  - Material within flaw (sealant/paint/fluids)
  - Flaw morphology (regular, irregular)
  - Flaw conditions at crack faces (contact conditions, residual stress)

Controlling Factors for Signal – UT (surface breaking cracks)

- Correlation between signal and noise sources
- Notches
  - Wire
  - HAZ
  - Tool condition
  - Processes to generate (feeds, speeds)
  - Tool materials and dimensions
  - Tool shape
  - Notch shape

Controlling Factors for Signal – UT (surface breaking cracks)

- Cracks
  - Opening
  - Contacting asperities
  - Roughness
  - Surface condition (shot peening, smeared metal)
  - Presence of fretting
  - Morphology (shape, orientation, depth, length, branching)
  - Multiple cracks vs. single crack

Controlling Factors for Signal – UT (surface breaking cracks)

- Root causes
  - Growth conditions
    - $\sigma/\sigma y$ time history
      - Constant amplitude
      - Overloads
      - High or low cycle
      - Mode I, II, III or ?
  - Initiation conditions
    - Stress corrosion vs. fatigue vs. corrosion fatigue, etc.
    - Intergranular vs. transgranular
    - Scratches, dings
    - Fretting
    - Surface vs. subsurface initiation
    - Multiple indications in the area of interest

Controlling Factors for Signal – UT (surface breaking cracks)

- Material Issues
  - Toughness
  - Grain size
  - Grain boundary condition
  - Mechanism of contact (sliding, oxide debris, plastic deformation)
  - Contacts conducting
  - Roughness

Controlling Factors for Noise - UT

- Scratches, dents, dings
- Roughness
- Surface geometry features (edges, corners, etc.)
- Out of roundness
- Corrosion, pitting
- Dirt
- Micro/macro structure (anisotrophy, attenuation
- Sealant variation, bladders, foam
- Surface protectants (paint, coatings, etc.)
- Couplant variation
- Interface contaminants
- Thermal drift
- Fastener/part interface and material

System/Operator Issues

Consider relevance to model inputs some of which will be modeled and some of which will be characterized empirically

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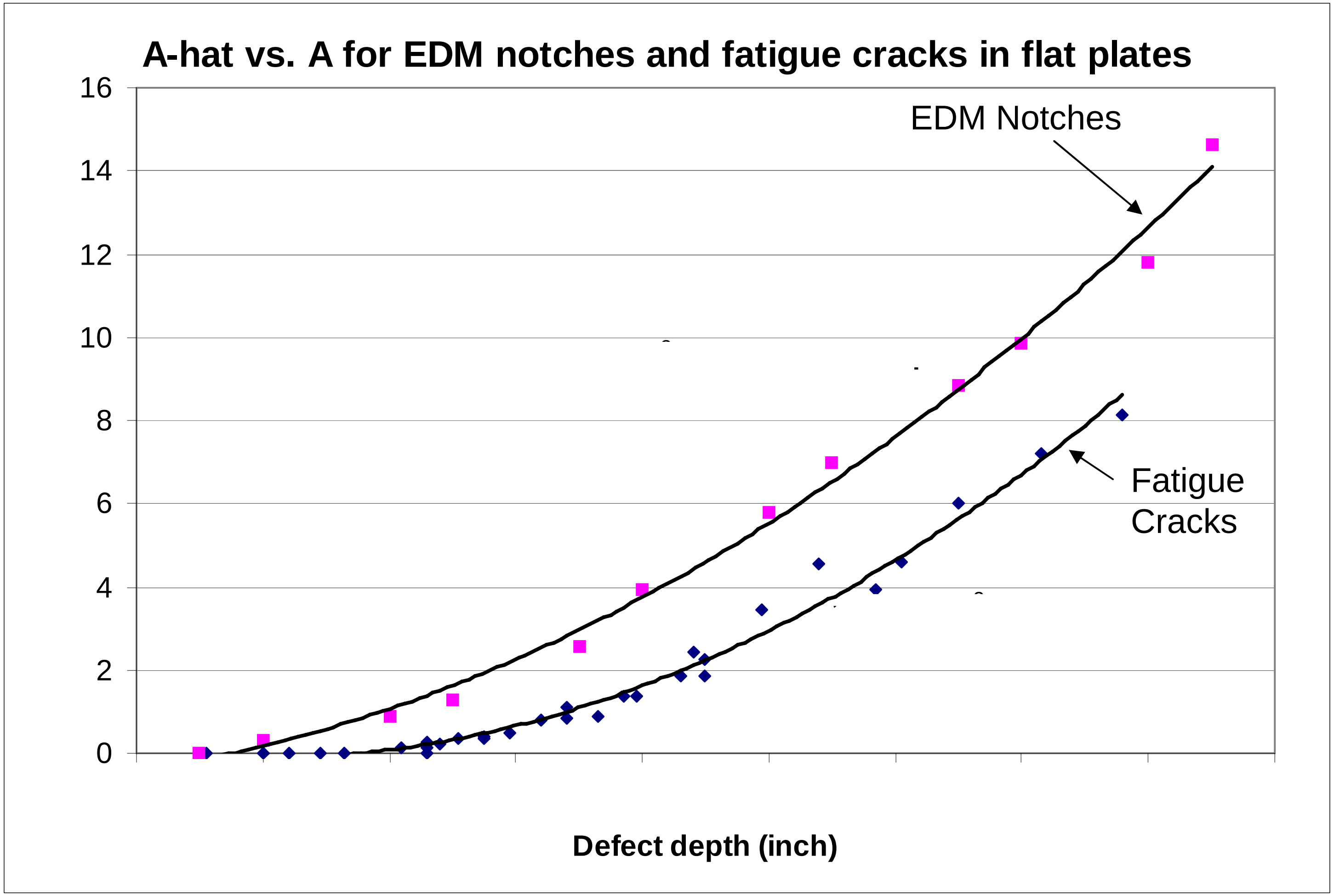
Transfer Function Example

From Smith (Pratt & Whitney) – February 2005 MAPOD Meeting



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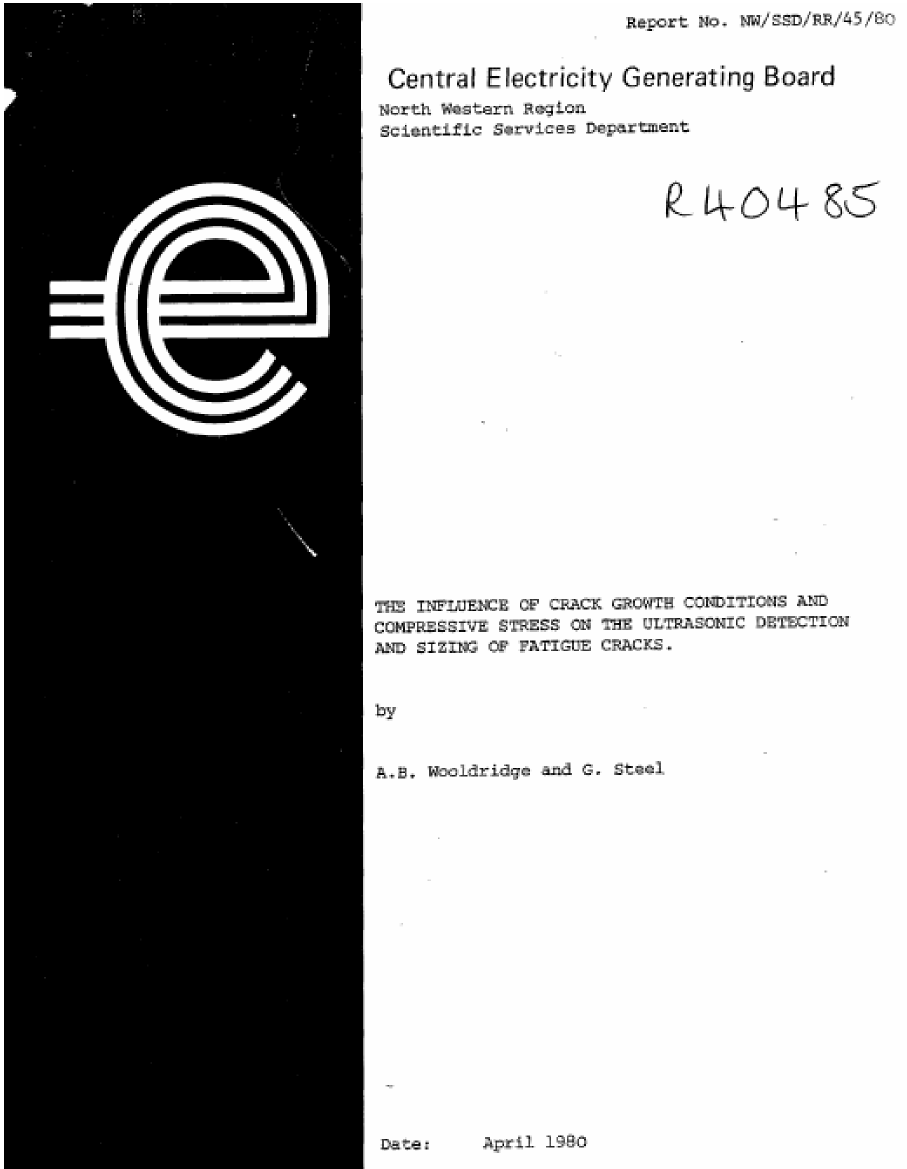
Fatigue Crack Growth and Compressive Stress



Report No. NW/SSD/RR/45/80

Central Electricity Generating Board
North Western Region
Scientific Services Department

R40485

THE INFLUENCE OF CRACK GROWTH CONDITIONS AND COMPRESSIVE STRESS ON THE ULTRASONIC DETECTION AND SIZING OF FATIGUE CRACKS.

by

A.B. Wooldridge and G. Steel

Date: April 1980

Fatigue Crack Growth and Compressive Stress

- Summary
  - ☐ A series of fatigue cracks in mild steel parent metal and weld metal grown under constant stress intensity conditions have been examined ultrasonically for compressive stresses up to 150 MN m^{-2}. Various angles of shear waves and the Delta technique were employed to study the corner echoes. Reductions in reflectivity at zero load and under stress have been shown to correlate with the crack growth conditions and with the roughness of the crack faces. We also measured the ultrasonic echoes from the crack tips which are small even at zero load and become undetectable for small compressive stresses. The detectability with shear waves of cracks containing liquid has been measured and compared with theoretical predictions derived from a thin parallel-sided gap model.

Fatigue Crack Growth and Compressive Stress

- Conclusions
  - The growth conditions of fatigue cracks have a significant affect on their ultrasonic response, both at zero load and when under compressive stress. The cyclic change in stress intensity factor during crack growth correlates well with the roughness of the fatigue crack surfaces and this is believed to cause the changes in ultrasonic response.
  - Both increasing crack roughness and increasing compressive stresses reduce the specular reflection from cracks but the roughest cracks show the least variation with stress.

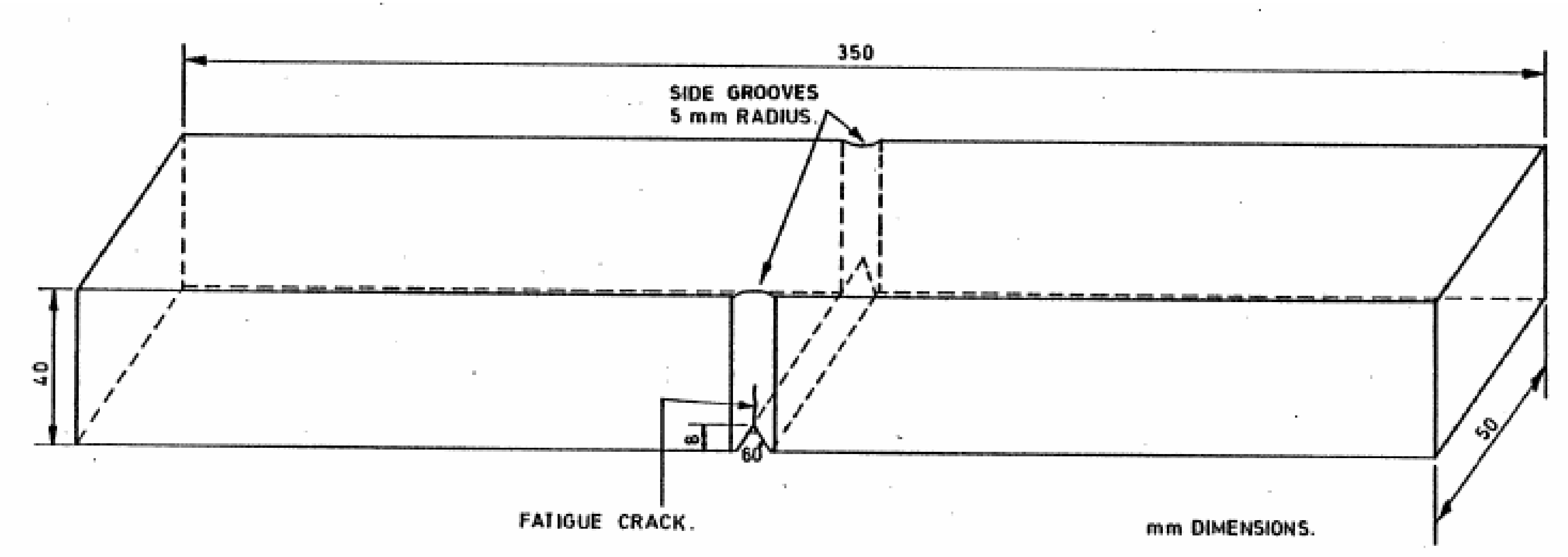
Fatigue Crack Growth and Compressive Stress

- Conclusions
  - Crack tip echoes are small; typically they are 50 dB down on a back wall echo at the same range when using a compression wave probe at grazing incidence, and they are practically impossible to identify reliably if the cracks are in compression or if the material contains other defects such as inclusions.
  - The errors in sizing cracks in clean material by detecting the tip echoes are typically ± 1 mm if averaged for several probes. Individual readings, however, may be in error by several millimeters.

Fatigue Crack Growth and Compressive Stress

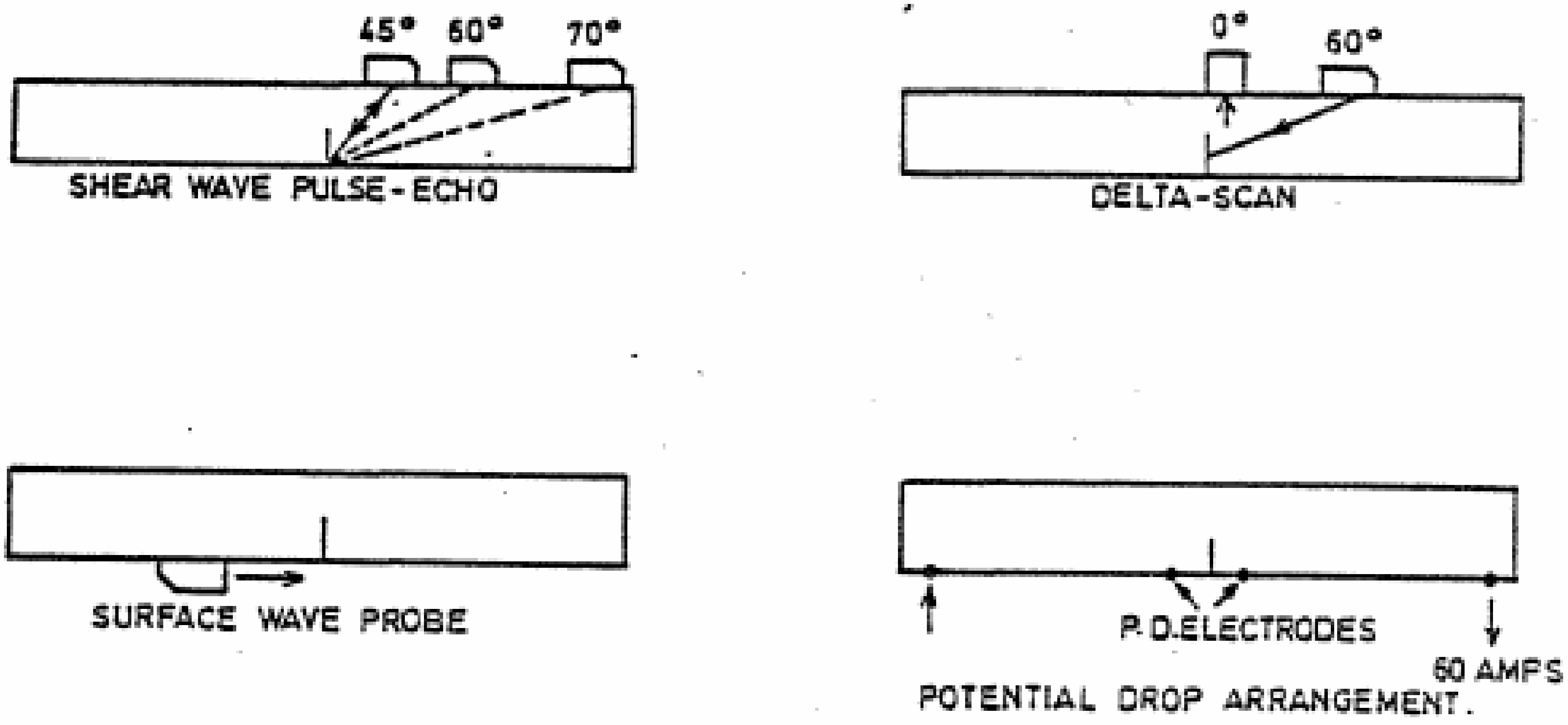
- Conclusions
  - The presence of liquid in a crack causes a marginal increase in reflection for shear wave beams incident at 20° to the crack normal. Modest decreases in reflection occur for beams incident at 45°, while considerable decreases are likely at 30° incidence.

Fatigue Crack Growth and Compressive Stress



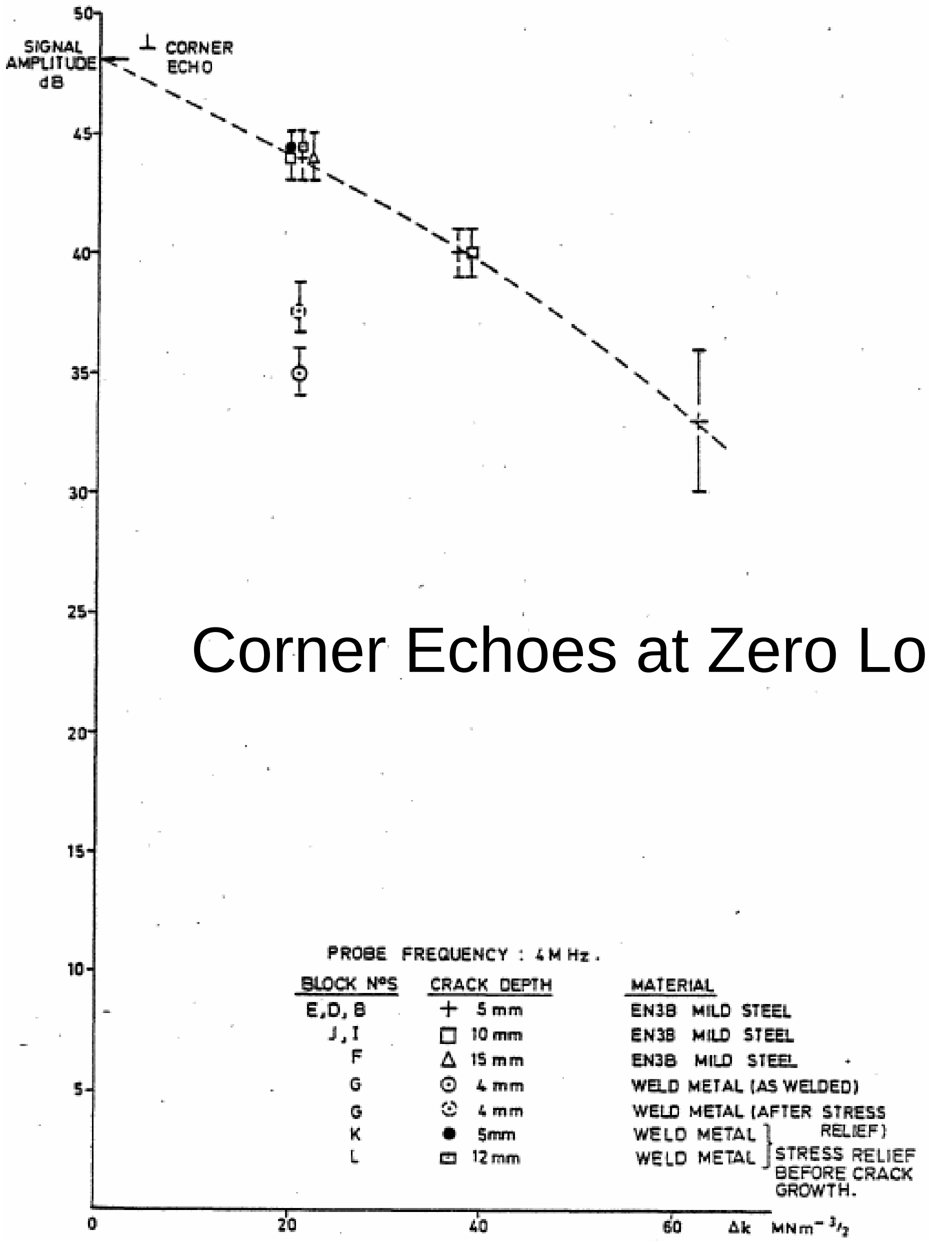
Initial Fatigue Crack Specimen

Fatigue Crack Growth and Compressive Stress

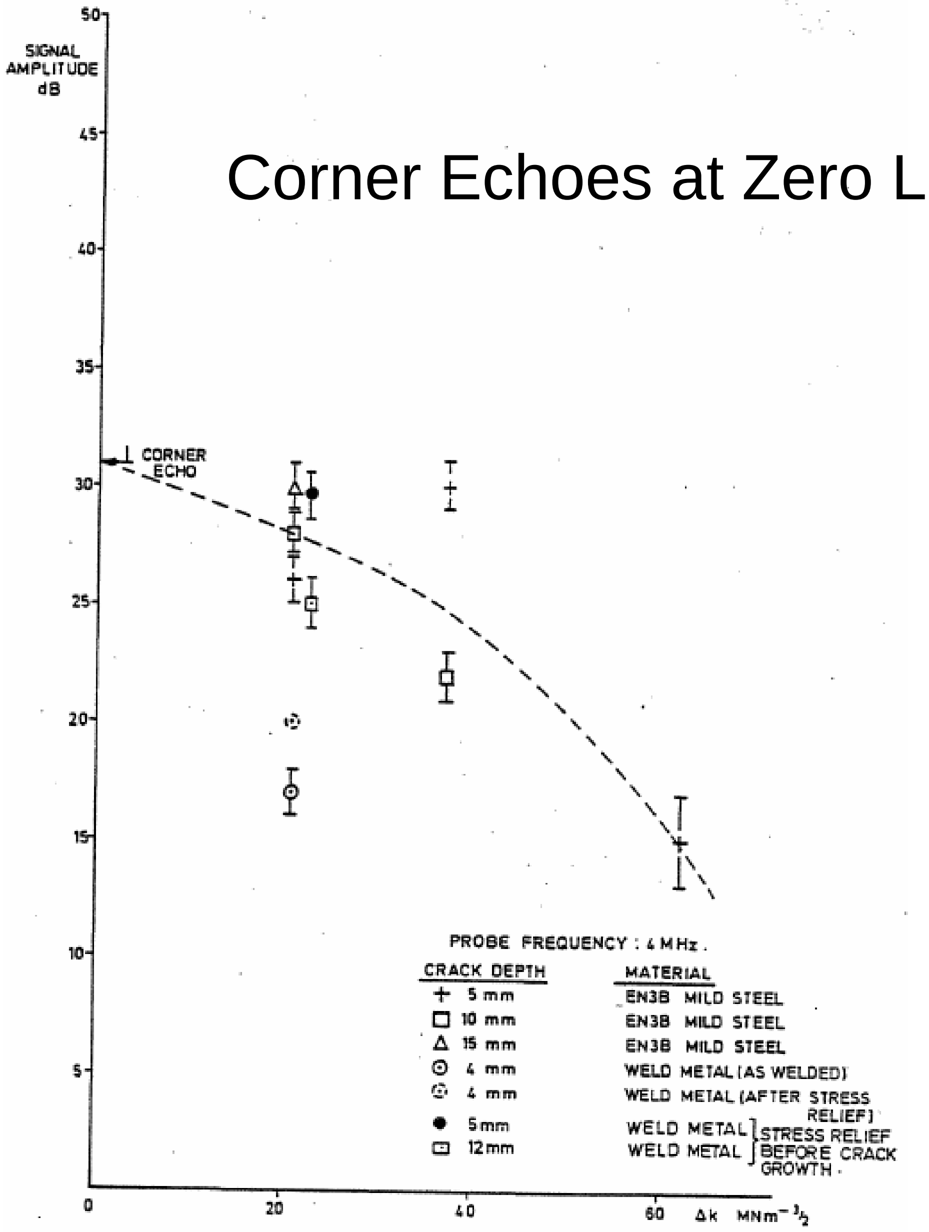


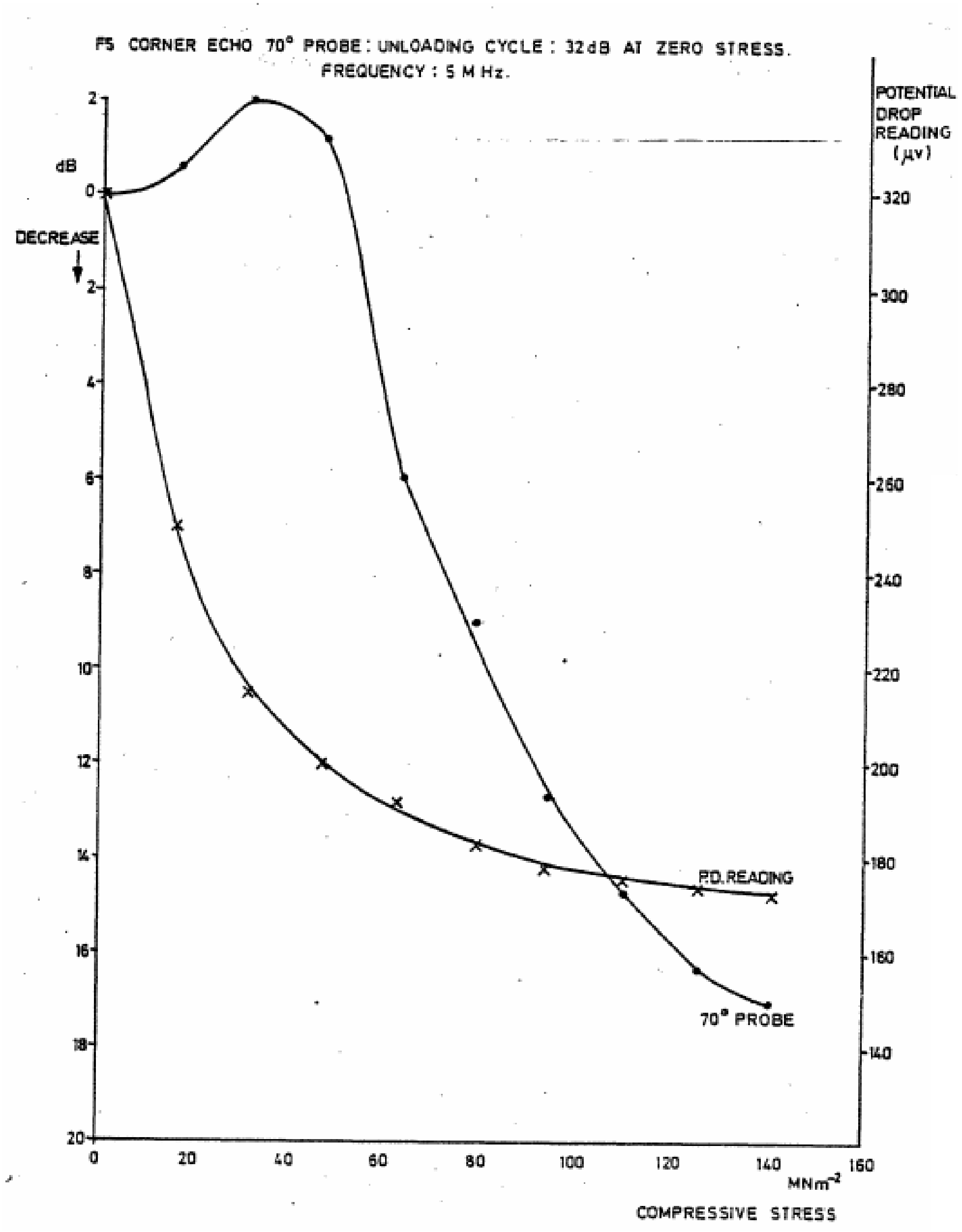
Ultrasonic Probe Arrangements

Corner Echoes at Zero Loads Versus Δk: 45° Probe



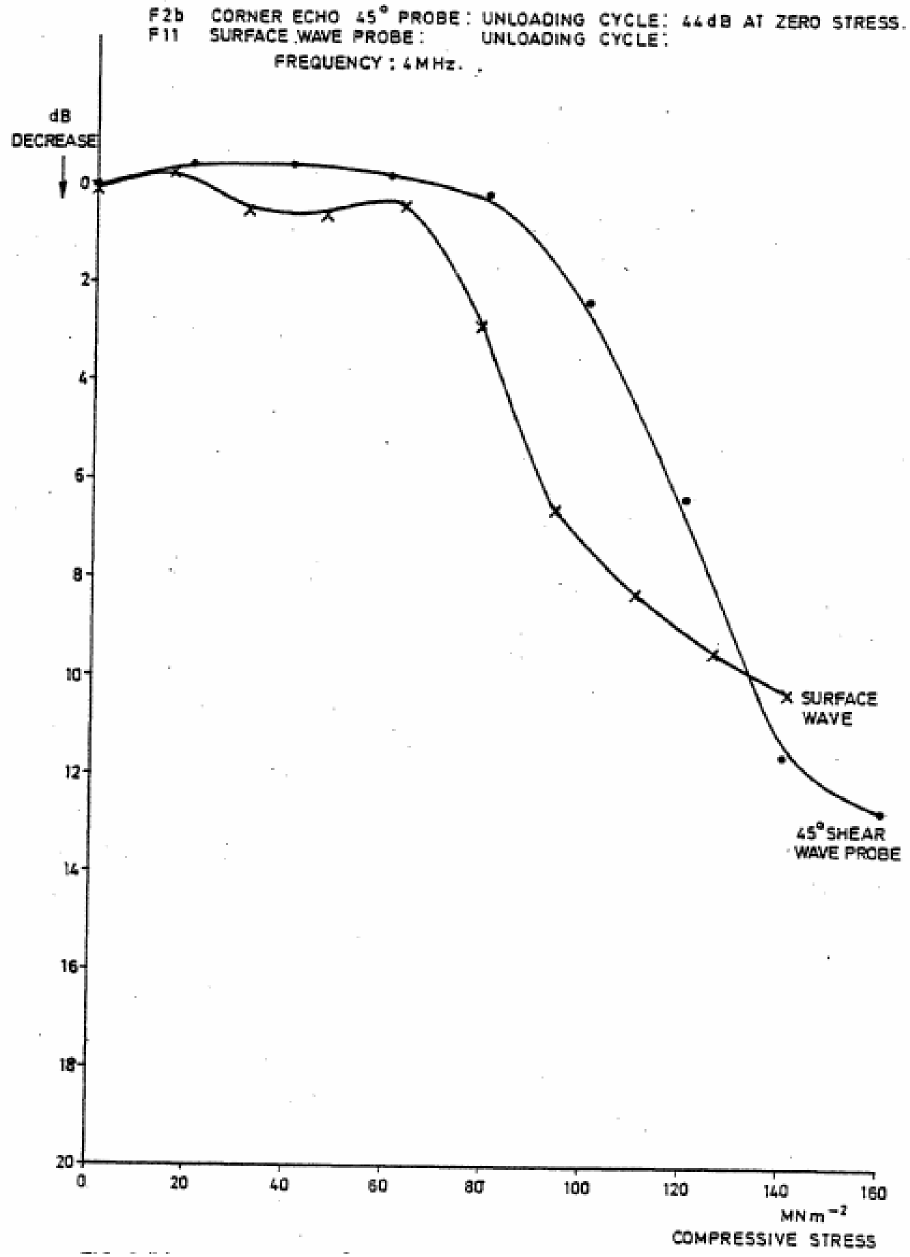
Corner Echoes at Zero Loads Versus Δk: 60° Probe



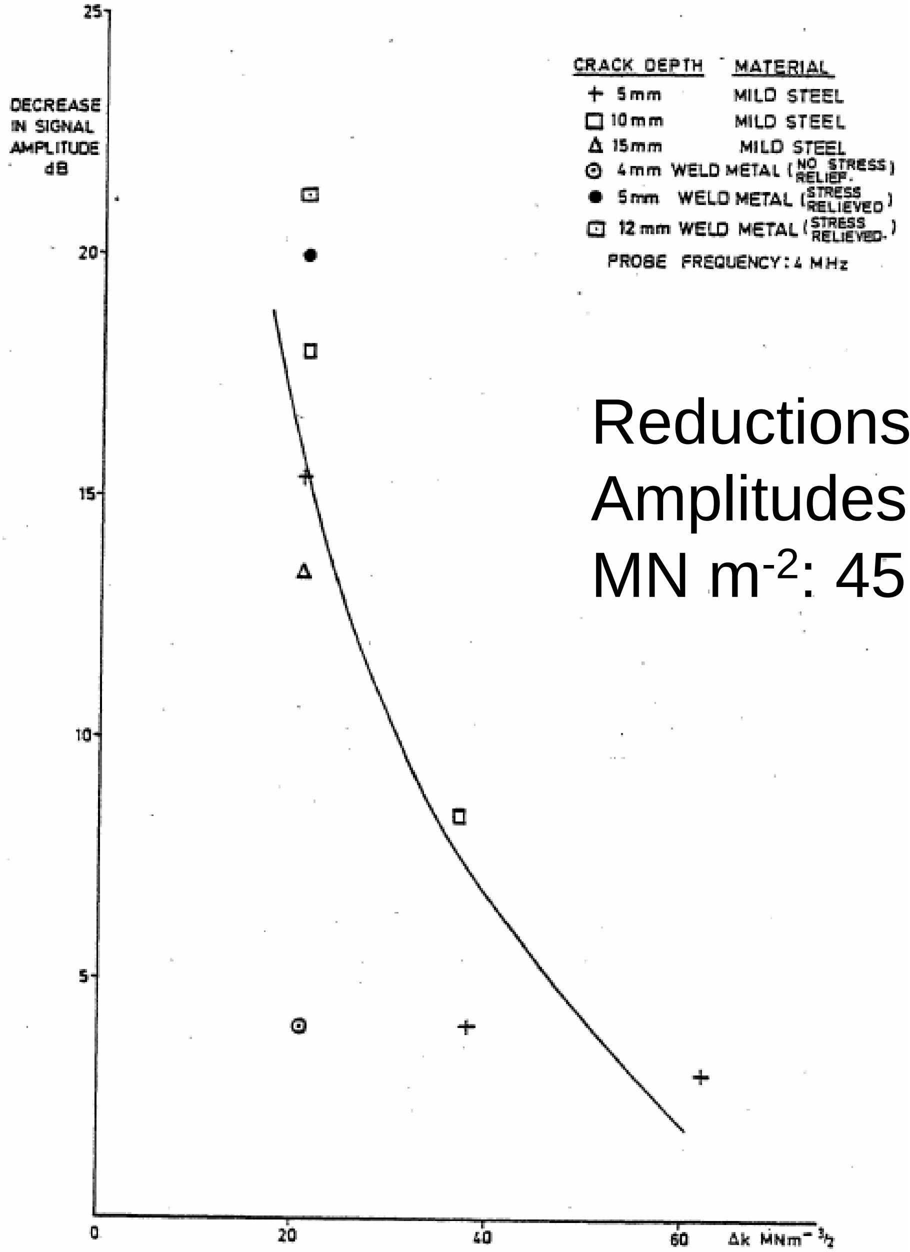


Block F: 70° Shear Wave Probe Echo and Potential Drop Reading

Block F: 45° Shear Wave and Surface Wave Echo



Reductions in Corner Echo Amplitudes for a Stress of 160 MN m^{-2}: 45° Probe



Reductions in Corner Echo Amplitudes for a Stress of 160 MN m^{-2}: 60° Probe