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Fatigue crack growth in 350WT steel subjected to intermittent tensile overloads and compressive underloads

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Fatigue Crack Growth in 350WT Steel Subjected to Intermittent Tensile Overloads & Compressive Underloads

by
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Abstract

Previous investigations have shown that significant crack growth retardation in 350WT steel may be realized through the application of tensile overloads. However, the application of compressive underloads may appreciably reduce the retardation produced by previous tensile overloads. Unfortunately, compressive underloads are commonly neglected in practice, or, at best, dealt with via an empirically adjusted stress ratio (R). Therefore, a combined experimental and analytical/numerical fatigue testing program was undertaken with the objective of investigating the effects of intermittently applied tensile overloads (OL) and compressive underloads (UL) on fatigue crack growth in center-cracked 350WT steel specimens. A significant amount of knowledge has been gained regarding this overload/underload interaction, the subsequent fatigue crack growth behavior, and the analytical and numerical characterization of such behavior.

Experimental fatigue testing was performed on a total of 16 specimens, in which the stress ratio (R), the overload ratio (OLR), and the overload-to-underload ratio (OL/UL) were systematically varied. Modifications to the commonly used Wheeler model were proposed, allowing consideration of compressive underloading effects. The results of the proposed modifications will be included in a future publication.

A previously proposed exponential delay model was revised to include the effects of not only overload ratio, but also stress ratio and overload/underload ratio. Although seemingly complex, the resulting delay model may be easily incorporated into any existing crack growth model for constant amplitude loading, and has been shown to yield fatigue life predictions which are generally in good agreement with the experimental data. Details of the revised delay model are to be included in a future publication.

In addition to a discussion of the experimental program, the current briefing will focus on a nonlinear FE analysis (using the NISA FE package) which was also performed, subjecting a typical specimen to a simple OL/UL sequence. The results of this FE investigation validated the proposed existence of a crack tip ‘compressive plastic zone’ under compressive loading, the size of which is typically smaller than that produced by an equivalent tensile overload. The analysis also predicted a zone of tensile yielding at the crack tip upon removal of this compressive underload, further substantiating the experimentally observed phenomena of crack growth acceleration and reduction in retardation. The size of these compression-induced ‘yield zones’ were found to depend not only on the relative magnitude of the compressive underload and preceding tensile overload, but also on the assumed crack face separation (δ_o).

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Outline

- Introduction
- Brief Review of Fracture Mechanics
- Motivation for Research
- Approach
  - Experimental
  - Analytical/Numerical
- Discussion of Results
  - Experimental
  - Analytical/Numerical
- Conclusions
- Acknowledgements

Introduction: Why Consider Research on Fracture?

- Cost of Fracture is Enormous ($$$)
- Consequences of Fracture Worse Today
- Knowledge of Crack Growth Behavior Essential
  - Safer, More Cost-Effective Design Practices
  - Improve Fabrication & Quality Control Measures
  - Assess Inspection, Maintenance & Repair
- Interaction of Tensile & Compressive Loading
  - Compressive Loading Data is Scarce
  - Effects of Compressive Loading Often Neglected
  - May Yield Unconservative Life Predictions

Theories of Fracture Mechanics

- Two Main Branches of Fracture Mechanics
  - Linear Elastic Fracture Mechanics (**LEFM**)
  - Elastic Plastic Fracture Mechanics (**EPFM**)
- LEFM w/Linear Elastic Materials (Minimal Yielding)
  - Stress Intensity Factor (K):

$$K = \sigma Y \sqrt{\pi a} \quad (\mathrm{MPa}\sqrt{\mathrm{m}})$$

- EPFM Used w/Large-Scale Plastic Deformation
  - J-Integral (Rice): Accounts for N/Linear Material Behavior

$$J \approx \frac{K_{EQ}^{2}}{E}$$

Fatigue Crack Propagation

- Small Cracks & Flaws Inevitable
- Some Type of Crack Growth Analysis Required
  - Establish Intervals for Inspection, Maintenance/Repairs, etc.
  - Project/Forecast Remaining Useful Life of Components
  - Ultimately, Maintain Structural Integrity

Fatigue Crack Propagation

- FCP Models Describe Growth Rate, **$da/dN = f(\Delta K, R)$**
  - Most Describe Stable Region II Growth
  - Model Disadvantages: Number & Nature of Curve Fitting Parameters Used to Describe $f(\Delta K, R)$
  - Most Parameters Lack Physical Significance
- **Paris' Law** (Early 1960's): $\frac{da}{dN} = C_P(\Delta K)^{m_P}$
  - Simple ⇒ Only 2 Parameters (m_P= Slope, C_P= Intercept)
  - Does Not Account for Near-Threshold$^{(I)}$ Growth, Rapid/Unstable Growth$^{(III)}$, or Stress Ratio ($R=\sigma_{min}/\sigma_{max}$)
  - Additional Capabilities ⇒ More Parameters (Forman, Walker)

Fatigue Crack Propagation

- **Zheng & Hirt Model** (1983):
  - Δa_i = Distance Over Which Max. Normal Stress Exceeds Material Fracture Stress
  - No Empirical Parameters ⇒ Simple Tensile Testing Req'd

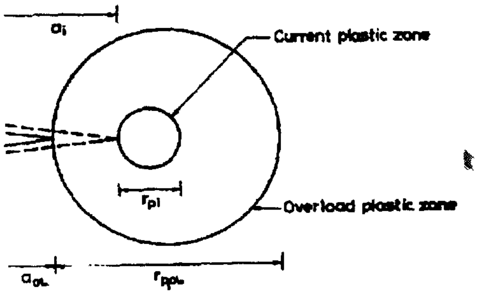
$$\frac{da}{dN} = \frac{(\Delta K - \Delta K_{th})^2}{2\pi E \sigma_{ult}(1+RA)[-\ln(1-RA)]}$$

- **Effects of Load Interaction** is an Important Aspect to Consider:
  - Tensile Overloads (OL) ⇒ Crack Growth Retardation
  - Compressive Underloads (UL) ⇒ Crack Acceleration
  - OL + UL ⇒ Combination of Retardation & Acceleration

Fatigue Crack Propagation

- **Wheeler Model** (1972):
  - Quantifies Crack Growth Retardation Using Factor ϕ_R
  - Retardation IF Current PZ Lies w/in Boundary of a Previous PZ
  - Applied to <u>ANY</u> FCP Model ⇒ **$(da/dN)_R = \phi_R \cdot f(\Delta K, R)$**
  - **Empirical** Shaping Exponent 'm': Value That "Best Fits" Data

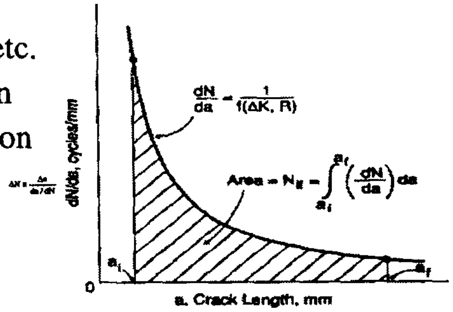
$$\phi_R = \begin{cases} \left[\dfrac{r_{pi}}{a_{OL} + r_{pOL} - a_i}\right]^m & , a_i + r_{pi} \le a_{OL} + r_{pOL} \\ 1 & , a_i + r_{pi} \ge a_{OL} + r_{pOL} \end{cases}$$



Fatigue Life Assessment Techniques

- Closed Form Integration of da/dN = f (ΔK, R)
- Numerical Integration:
  - 1% Rule, Midpoint Rule, etc.
  - Cycle-by-Cycle Integration
  - Piecewise-Linear Integration

$$\Delta N \cong \frac{\Delta a}{da/dN}$$



- Cumulative Damage Theories
  - Failure Based On Progressive Damage Accumulation (D_1)

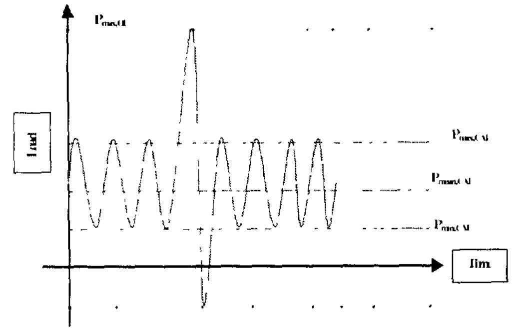
Motivation for Research

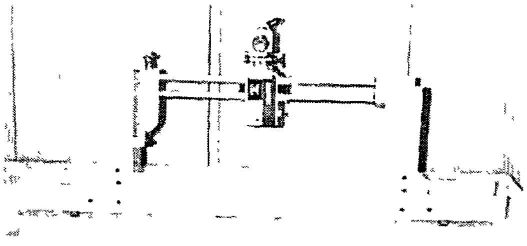
- DREA: Fatigue Problems w/350WT, No da/dN-ΔK Data
- Phase I: Obtain Baseline CAL Data for 350WT
  - Zheng & Hirt Shown Promising But Highly Dependent on K_{th}
  - Intermittent Tensile Overloads (OLR=$\sigma_{max,OL}/\sigma_{max,CAL}$)
  - Delay Model Proposed to Quantify Retardation (N_D)
- Phase II: Semi-Random Loading
  - Investigate Tensile & Compressive Loading
    - Effects of Compressive Loading on Retardation
    - Insight Into Load Interaction Effects in 350WT
    - Improve Fatigue Life Predictions
  - Evaluate K_{th} (Zheng & Hirt)

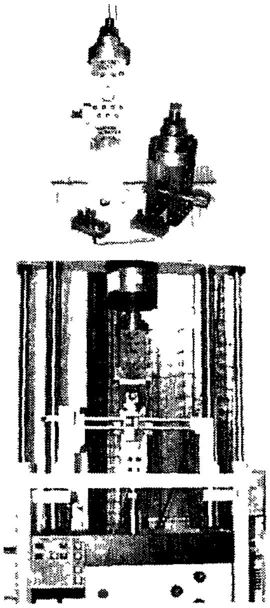
Experimental Approach

- Specimens: 300mmx100mmx5mm Plates w/EDM Starter Notch of 2a = 20mm
- Category 5 Steel Common in Bridges, Offshore Structures, and Hulls of Halifax Class Frigates
- All Testing Performed iaw ASTM E647
  - Threshold Testing to Evaluate K_{th}
  - Tensile & Compressive Overloading: Variations in R, OLR and OL/UL Ratio
- Instron UTM (±100kN Dynamic Capacity)
- Mitutoyo Travelling Microscope (10X Magnification)

Experimental Approach: Loading Sequence & Test Setup

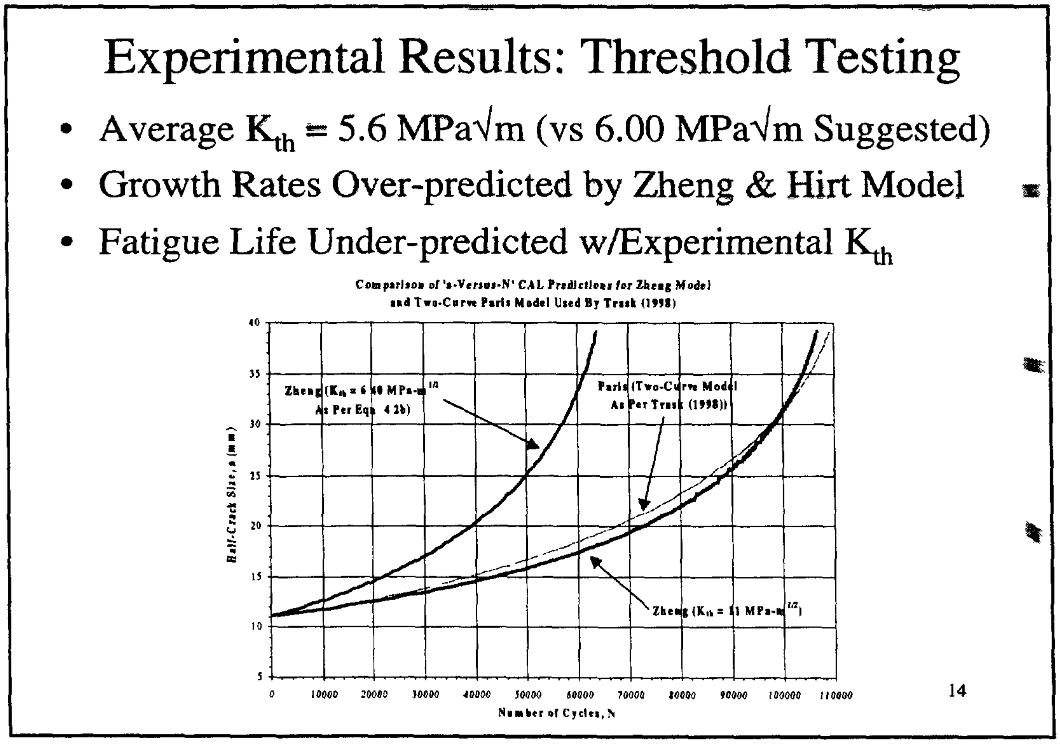






Numerical Approach

- Quantify Effects of Load Interaction
  - Correlate Experimental Results w/Predictions Using Existing Models
- Propose Modifications to Better Account for Compressive Loading Effects
- FE Analysis: Investigate Crack Tip Plasticity Under Typical Overload - Underload Sequence
- Revise Previous Delay Model Incl. OLR, R, & OL/UL



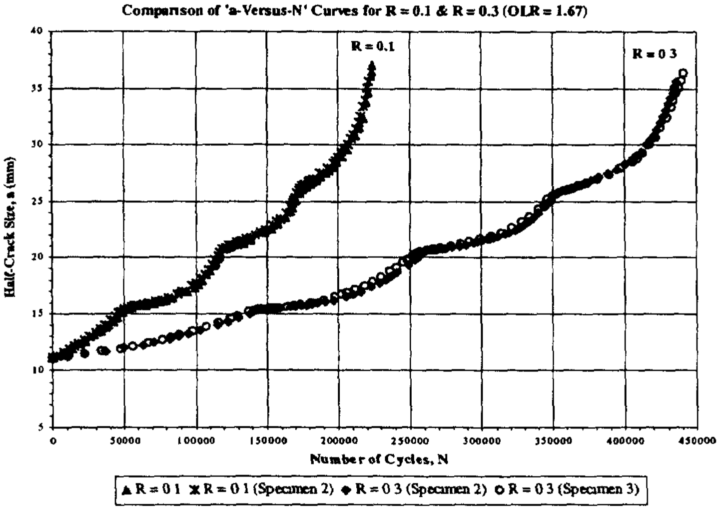
Experimental Results: Threshold Testing

- Average K_{th} = 5.6 MPa√m (vs 6.00 MPa√m Suggested)
- Growth Rates Over-predicted by Zheng & Hirt Model
- Fatigue Life Under-predicted w/Experimental K_{th}

Comparison of 'a-Versus-N' CAL Predictions for Zheng Model and Two-Curve Paris Model Used By Trask (1998)

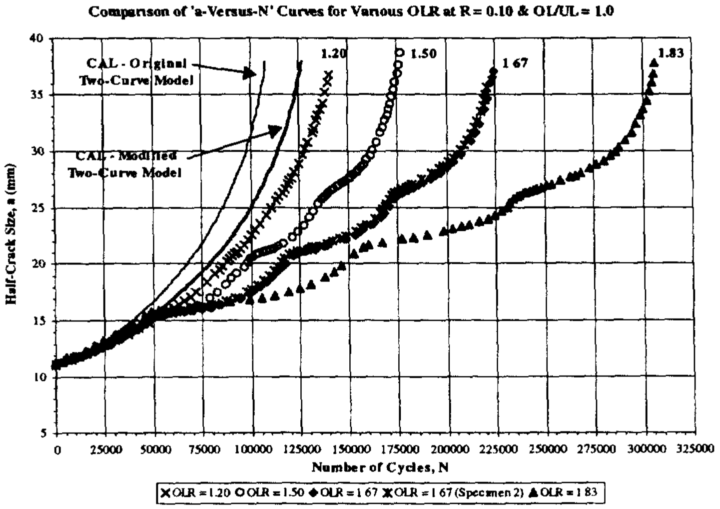
Experimental Results: Semi-Random Testing

- Larger ‘R’ Corresponds to Reduced Stress Range (Δσ)
  ⇒ ∴ Lower Growth Rate ⇒ **Longer Life**



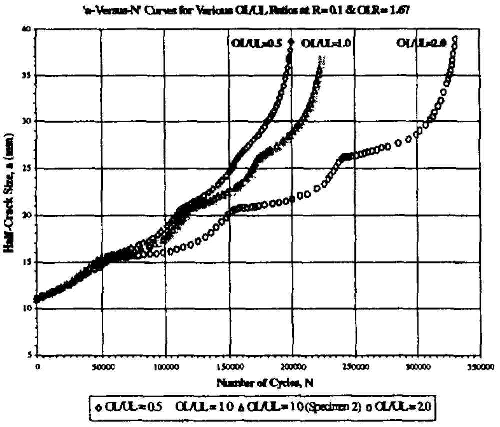
Experimental Results: Semi-Random Testing

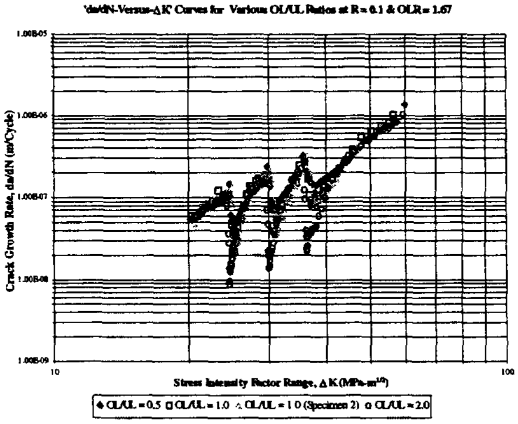
- OL/UL Constant ⇒ Increased Retardation w/Larger OLR
- Inflection Point In Fatigue Rate Data ⇒ ∴Bi-Linear Paris



Experimental Results: Semi-Random Testing

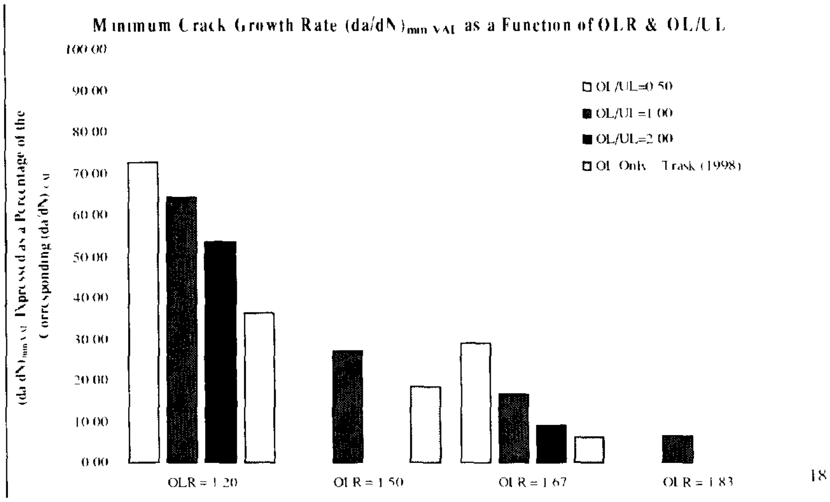
- Maintained Constant OLR & Varied OL/UL Ratio
  - Post-Overload Retardation Was Greatly Affected
  - Suggests a **Compressive Plastic Zone** @ Crack Tip





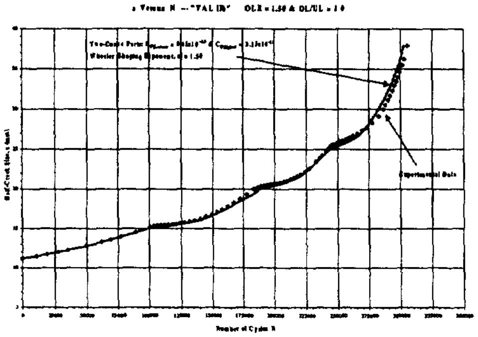
Numerical Results: Semi-Random Testing

- Larger UL's (ie., Smaller OL/UL) ⇒ Less Retardation
  - Min. Post-OL Growth Rate is Higher % of Equiv't. CAL Rate



Numerical Results: Wheeler Predictions

- Excellent Fatigue Life Predictions Obtained w/Wheeler Model & Bi-Linear Paris Approximation
  - <1% Error in 11 of 16 Specimens, >5% Error for 2 Specimens

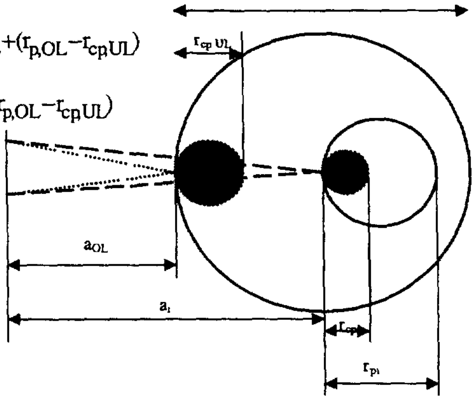


- Shaping Exponent ‘m’ **Empirical** in Nature
  - Trial & Error to Determine ‘Best Fit’ to Data
  - Potential Shown in Polynomial Regression of m=*f*(OLR)[19]

Numerical Results: Modified Wheeler Model

- Crack Growth Acceleration Typically Neglected in Practice
- Modifications: Account for Reduction in Retardation
  - Incorporate an ‘Effective’ Plastic Zone, $r_{eff} = r_p - r_{cp}$
  - Result: Smaller Overall PZ ⇒ Less Growth Retardation Predicted

$$\phi_R^{T-C} = \begin{cases} \left[\dfrac{r_{eff,i}}{(a_{OL}+r_{eff,OL}-a_i}\right]^m & , a_i+(r_{pi}-r_{cpi})<a_{OL}+(r_{p,OL}-r_{cp,UL}) \\ 1 & , a_i+(r_{pi}-r_{cpi})\geq a_{OL}+(r_{p,OL}-r_{cp,UL}) \end{cases}$$



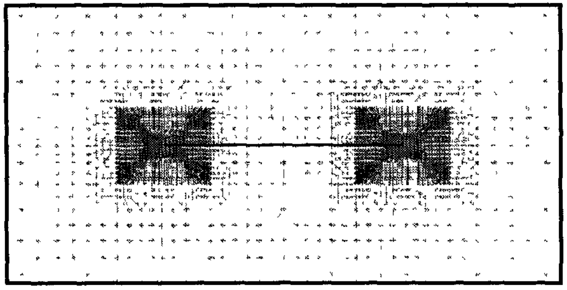
- Proposed Compressive PZ:

$$r_{cp} = \frac{1}{\alpha\ \pi}\left(\frac{\Delta K_{UL}}{2\cdot\sigma_{yld}}\right)^2$$

  - $\Delta K_{UL} \approx K_{min,CAL} - K_{UL}$
- <2% Error in Life Predictions

Numerical Results: FE Analysis

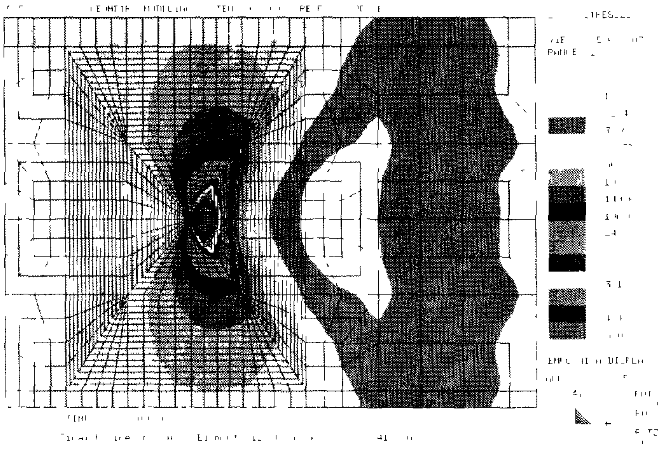
- Crack Tip Plasticity Under Compressive Loading
  - NISA: N/Linear Static (Elastic Perfectly Plastic Material)
  - P_{OL}= 120kN & P_{UL}= -120kN (OL/UL=1)
  - Corresponding Far-Field Stress, $\sigma=\pm 240$ MPa
  - 1st Order Plane Stress & Gap Elements (To Bridge Crack Faces)
  - Initial Crack Face Separation, $\delta_0 = 0.054$mm
  - Mesh Refined @ Crack Tips: 10/1000ths of Specimen Thickness

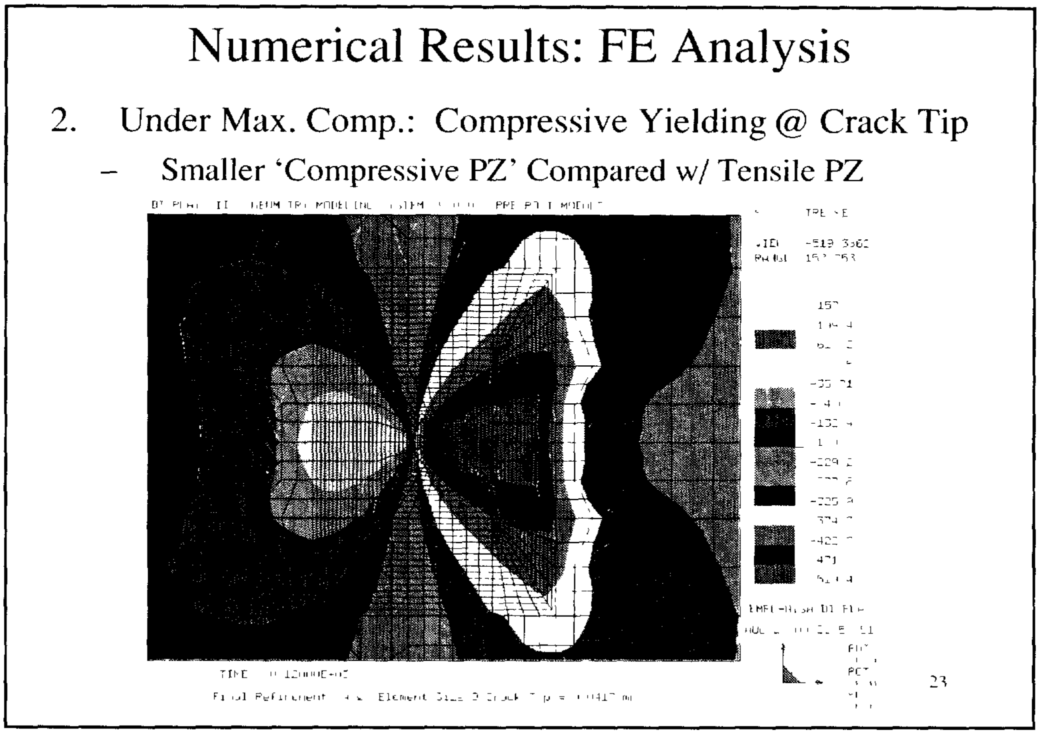


Numerical Results: FE Analysis

- Consider Stress Distributions @ Major Loading Points:

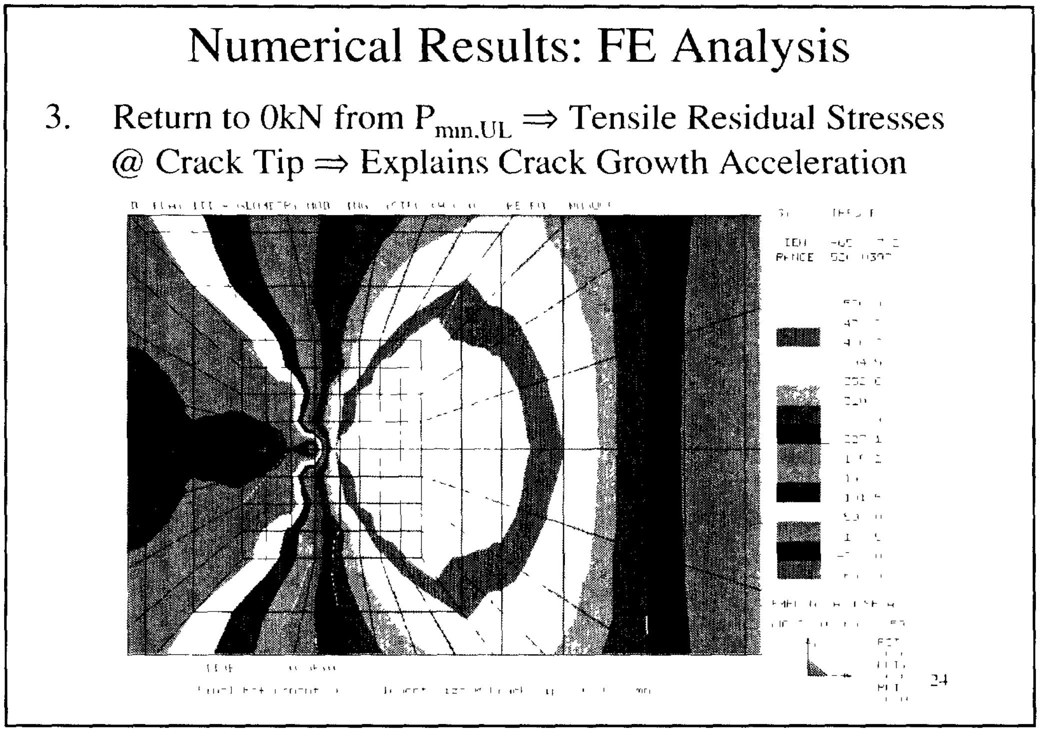
1. Return to 0kN from $P_{max.OL} \Rightarrow$ Compressive Residual Stresses @ Crack Tip $\Rightarrow$ Explains Growth Retardation





Numerical Results: FE Analysis

2. Under Max. Comp.: Compressive Yielding @ Crack Tip
   - Smaller 'Compressive PZ' Compared w/ Tensile PZ



Numerical Results: FE Analysis

3. Return to 0kN from $P_{min,UL}$ ⇒ Tensile Residual Stresses @ Crack Tip ⇒ Explains Crack Growth Acceleration

Numerical Results: FE Analysis

- Results Based on Crack Face Separation, $\delta_o = 0.054\text{mm}$
- $\therefore$Reduced Separation to $\delta = 0.0054\text{mm}$ (i.e., 1/10 δ_o)
  - Identical Trends Under Tensile Loading, As Expected
  - Smaller Plastic Zones Predicted Under Compression
- $\therefore$ Size of Compressive Yield Zones Depends on:
  - Magnitude of Both Compressive Underload (UL) & Preceding Tensile Overload (OL)
  - Assumption of Average Crack Face Separation, δ
    - ($\delta \approx 200\mu\text{m}$ May Be a More Realistic Assumption)

Numerical Results: Exponential Delay Model

- Trask (1998): Proposed an Exponential Delay Model To Predict Retardation (N_D) as f(OLR)
- In Conjunction w/Paris' Law, This Delay Model Yields a Life Prediction of:

$$N_{if} = \int_{a_i}^{a_f} \frac{da}{C_P \Delta K^{m_P}} + N_{OL} \cdot N_D$$

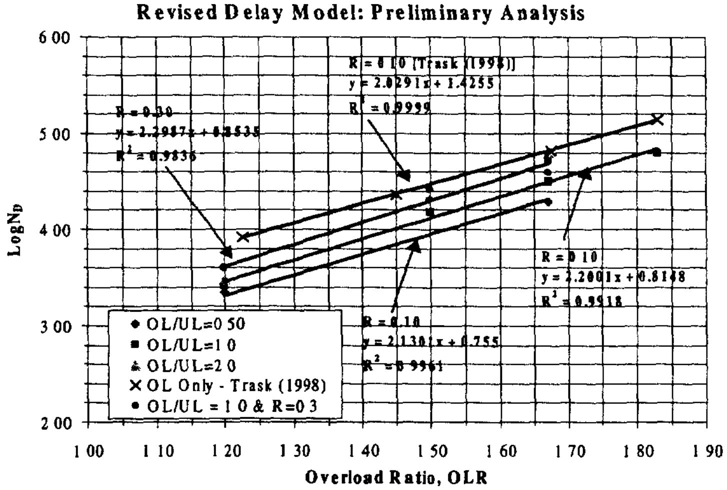
Where: $N_D = f(\text{OLR})$

- Objective: Revise This Delay Model Such That

$$N_D = f(\text{OLR, R, OL/UL})$$

Numerical Results: Exponential Delay Model

- First Plotted $\text{Log}_{10}[N_D]$ as a Function of OLR
  - Found Similar Slopes @ All Stress Ratios (R) & OL/UL Ratios

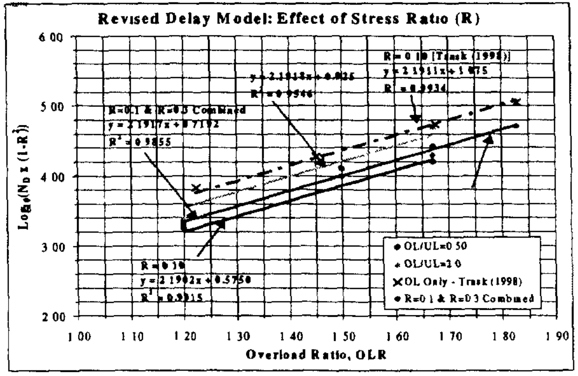


Numerical Results: Exponential Delay Model

- Suggested @ Constant OL/UL, Data for Different Stress Ratios (R) May Be Consolidated Onto a Single Curve:
  - $\text{Log}_{10}[N_D(1-R)^2]$ vs OLR ⇒ Consolidation Achieved (Red)

$$\text{Log}_{10}[N_D(1-R)^2] = \mu(\text{OLR}) + \beta$$

  - Resulting Curve w/Slope Similar to Unconsolidated Curves



Numerical Results: Exponential Delay Model

- Suggests That Each OL/UL May Have Unique Intercept
  - Express Intercept ‘β’ as *f*(OL/UL)
  - Least Squares Regression of β-vs-OL/UL
- Finally, $N_D = f(\mathrm{OLR}, \mathrm{R}, \mathrm{OL/UL})$ Expressed As

$$N_D = \frac{10^{m \cdot OLR + \left[a\left(\frac{OL}{UL}\right)^2 + b\left(\frac{OL}{UL}\right) + c\right]}}{(1-R)^2}$$

- Recall Paris’ Life Prediction: $N_{if} = \int_{a_i}^{a_f} \frac{da}{C_P \Delta K^{m_P}} + N_{OL} \cdot N_D$
- Average of 3.25% Error in Fatigue Life Predictions

Conclusions

- Threshold Testing: Average $K_{th} = 5.6$ MPa√m
- Valuable Insight Into Load Interaction in 350WT
- Excellent Life Predictions w/Wheeler & Paris
  - Potential in Expressing Wheeler ‘m’ as *f*(OLR)
- Variation in UL Greatly Affects Growth Retardation
  - @ Constant OLR, Larger UL Yields Less Retardation
    - Suggesting Crack Tip Plasticity Under Compressive Load
    - FE Analysis Confirmed Crack Tip ‘Compressive Plastic Zone’
- Revisions to Trask’s Exponential Delay Model
  - Multi-Parameter Model Includes OLR, R, and OL/UL
  - Life Predictions Agreed Well w/Experimental Data

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