Fatigue Life Prediction for Crenellated and Constant Thickness Steel Panels

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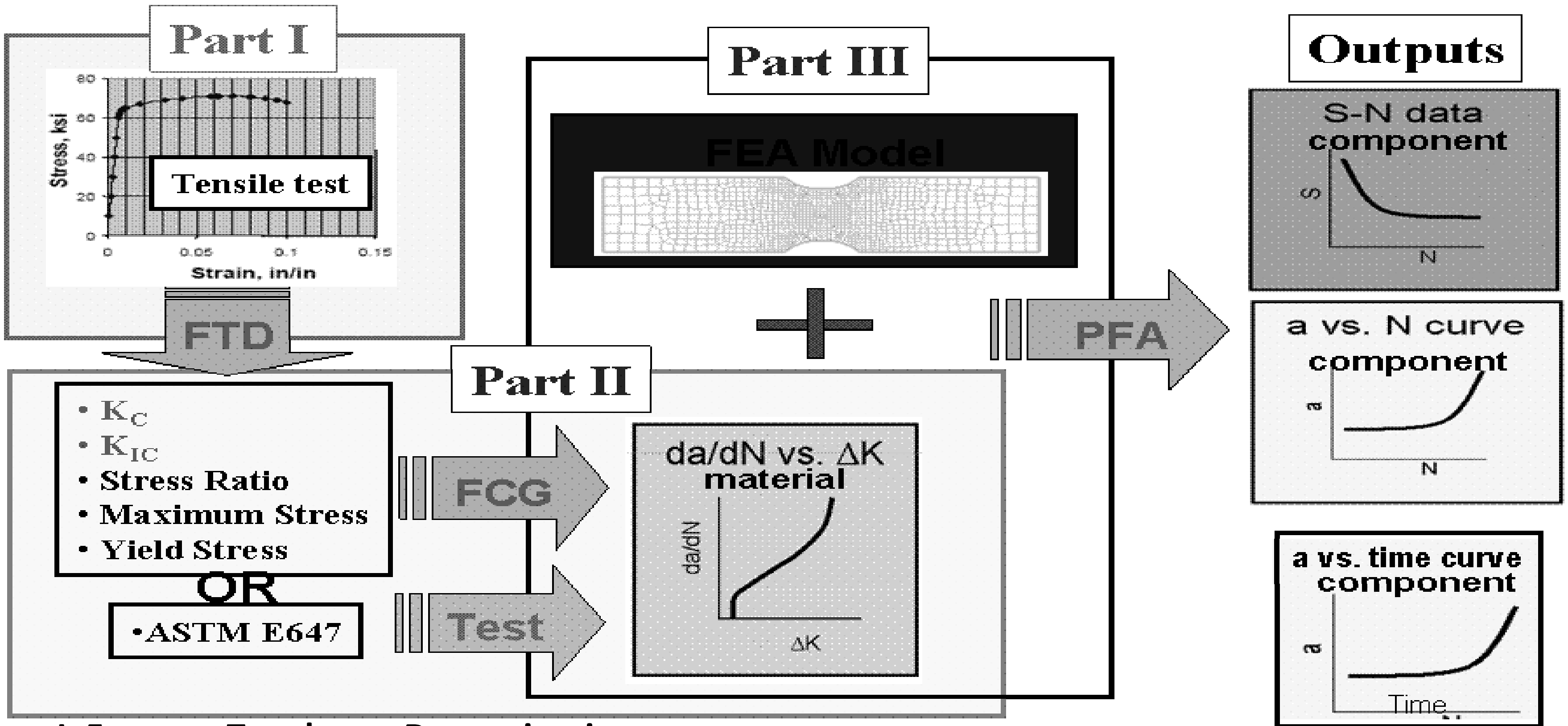
ASTM Committee E08

Agenda

- Paper Objective
  - Predict and test validate Fatigue Crack Growth:
    - Constant Thickness Panel
    - Delay Crack Growth in service by design of Crenellated panels
  - Materials: Steel (S420M, S690QL)
    - Fracture toughness Determination (FTD) Prediction
    - Fatigue crack growth (FCG) Prediction
  - Panels: Fatigue crack growth (a-N curve) Prediction
    - Constant Thickness Panel
    - Delay Crack Growth in service by design of Crenellated panels
    - Comparison of analytical and experimental test results
- Summary

Metal Lifing Approach for un-notched, and notched specimens

Three-Steps Fatigue Metal Approach



- **Part I: Fracture Toughness Determination**
- **Part II: Fatigue Crack Growth vs. stress Intensity factor**
- **Part III: a) Fatigue Strength-Life (S-N), a-N; b) Creep Time (a-t), da/dt; c) Fatigue creep Interaction**

References

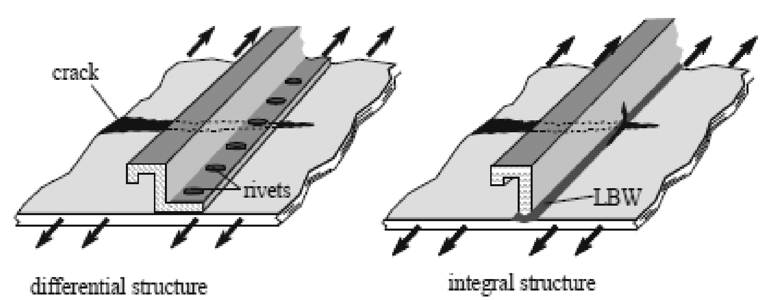
1. B. Farahmand, "Fracture Toughness Determinations (FTD) and Fatigue Crack Growth". Book Chapter - "Composites, Welded Joints, and Bolted Joints" Kluwer Academic Publisher, 2000.
2. Metal Probabilistic: Bob Farahmand, Frank Abdi, "Probabilistic Fracture Toughness, Fatigue Crack Growth Estimation Resulting From Material Uncertainties" ASTM Conference Paper 11569 November 6-7, 2002.

Crenellation

- **Crenellation as a novel solution to the growing fatigue crack**
  - hence integrity problem has emerged aiming to retard a growing crack towards the stringer, which has initiated in parent material.
  - Growing fatigue crack perpendicular to reinforcements, considered as "worst case" design scenario for thin-walled welded structures.
- **Joining stringers to main body of structure, by using two design philosophies:**
  - **differential design**: requiring use of rivets
  - integral design: requiring welding of the stringer to the main structure

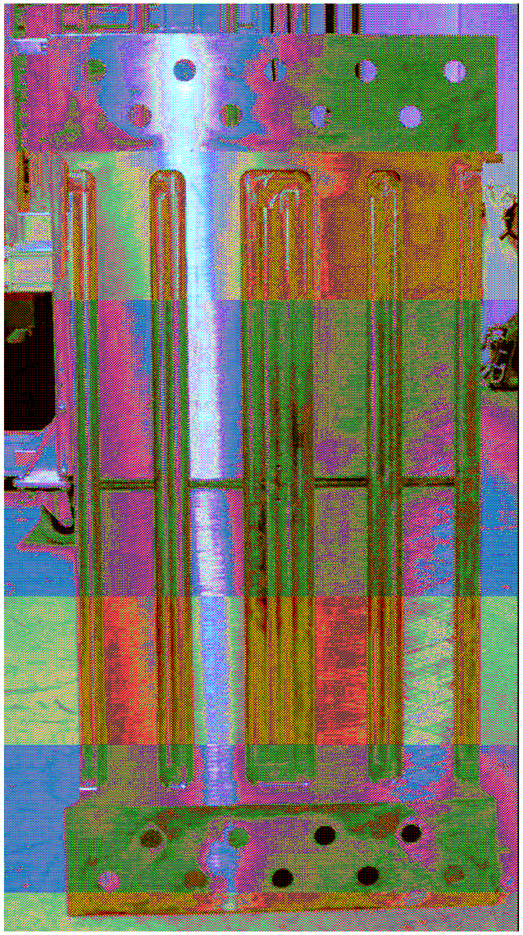
- In fracture mechanics, **differential design** is more advantageous, as a potential crack in main body of structure will continue extending under the stringer,
  - which may keep the stringer undamaged for a certain period
  - If a crack, evolves in a structure where stringer is joined by welding,
    - crack branching may occur leading to failure of stringer or separation of stringer from main structure

Crack paths in uniformly stressed differential and integral structures

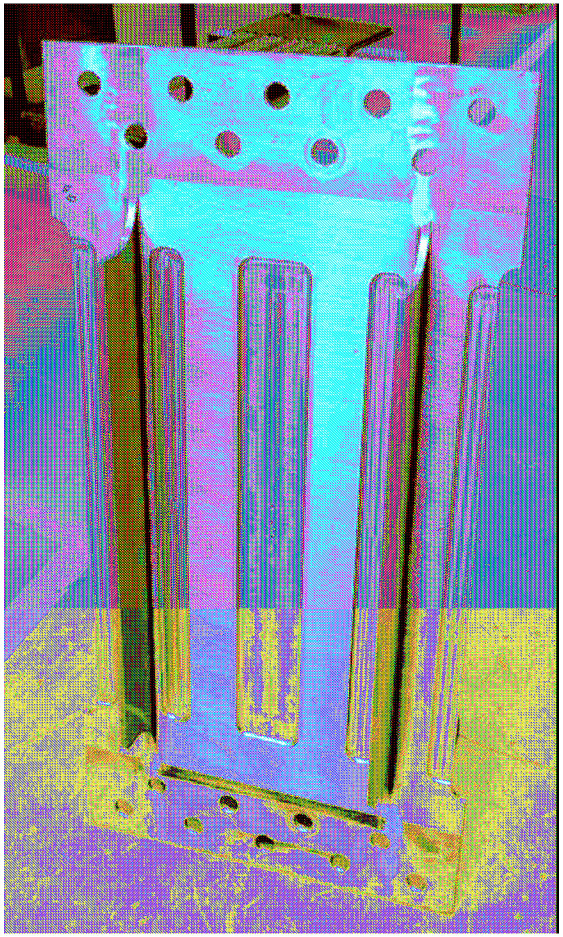


Crenellated wide plates

Crenellated wide plates containing butt & fillet welds



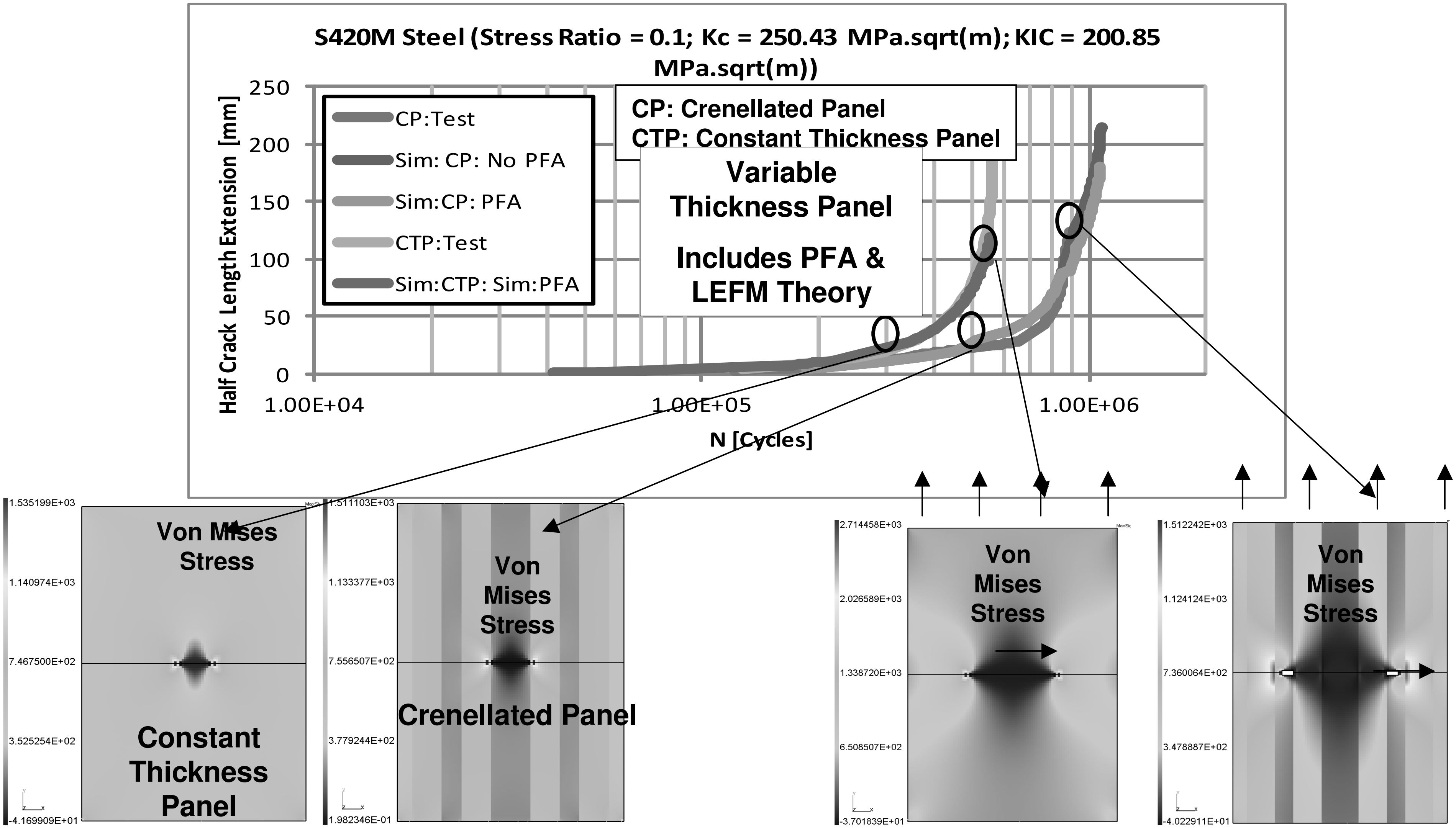
Butt weld specimen



Fillet weld specimen

Various crenellated wide plates

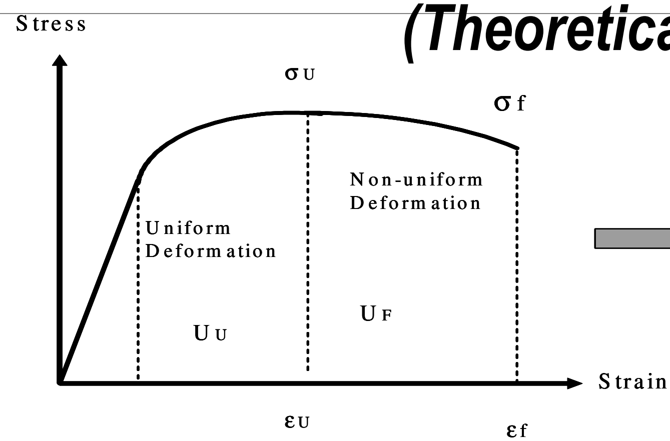
Summary of Results: Improvement of Fatigue Crack Growth in Crenellated Vs. Constant Thickness Steel Panels [S420M]



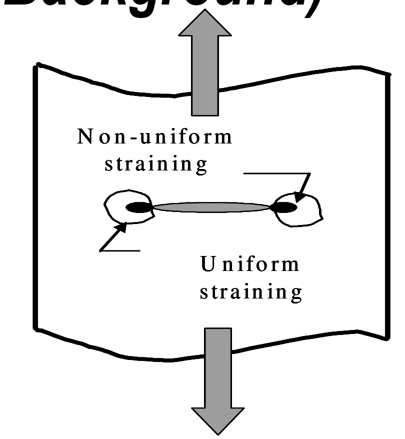
Ref: Sefika Elvin EREN, '**Advancing The Damage Tolerance Of Laser Beam Welded Steels Using Crenellation Technique**, 20.11.2011, Ph.D. Thesis in Structural Integrity, by Dipl.-Ing. Imperial College London, UK

PART 1: Fracture Toughness Determination

(Theoretical Background)



Areas associated with the uniform and Non-uniform straining



A center crack in a wide plate

$$\frac{\pi\sigma^2 c}{E} = 2T$$

Griffith Equation

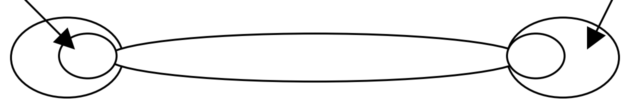
$$\frac{\pi\sigma^2 c}{E} = 2T + \frac{\partial U_F}{\partial c} + \frac{\partial U_U}{\partial c}$$

Extended Griffith equation to account for crack tip plasticity

Energy release rate at the crack tip for non-uniform straining

$U_P = U_F + U_U$

Energy release rate near the crack tip for uniform straining



U_P = Total energy per unit thickness absorbed in plastic straining around the crack tip, where U_F and U_U are the energy absorbed per unit thickness in plastic straining of the material beyond the ultimate at the crack tip and below the ultimate stress near the crack tip, respectively

PART I: Fracture Toughness Determination [FTD]

(Theoretical Background)

Residual Strength Capability Equation

(A Relationship Between Crack Length & Applied Stress)

$$\frac{\partial U_F}{\partial c} = h_F \, W_F$$

$$c = \frac{E}{\pi\sigma^2\mu}\left\{2T + \overline{\sigma}_{UF}\,\varepsilon_{PN}\,h_F k + \left(\frac{n}{n-1}\right)\sigma_{TU}\,\varepsilon_{TU}\left[1 - \left(\frac{\sigma_T}{\sigma_{TU}}\right)^{n+1}\right] h \left[\frac{\varepsilon_{TF}\,\varepsilon_{TL}}{\varepsilon_{TU}\,\varepsilon_T}\right] * \left[\left(\frac{\varepsilon_{TU}}{\varepsilon_{TL}}\right)^{\frac{n-1}{n}} - 1\right]\beta\right\}$$

$$\frac{\partial U_U}{\partial c} = W_U \, h_U$$

Mixed mode fracture and thickness parameters:

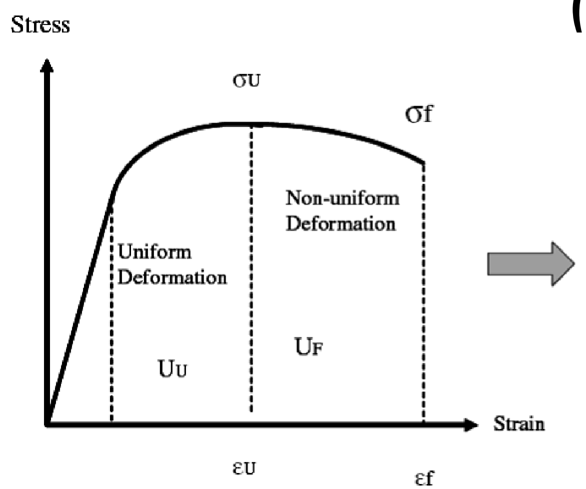
μ is the thickness correction factor

K is the thickness correction factor

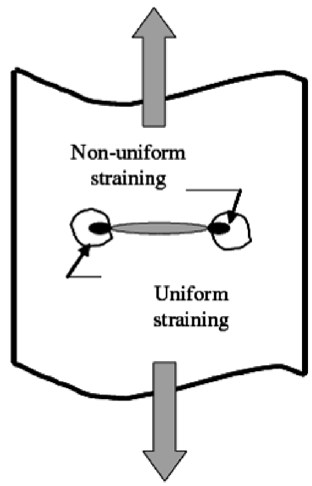
β is 1.3 and 0.127 for the plane stress and strain conditions, respectively

Fracture Toughness Determination

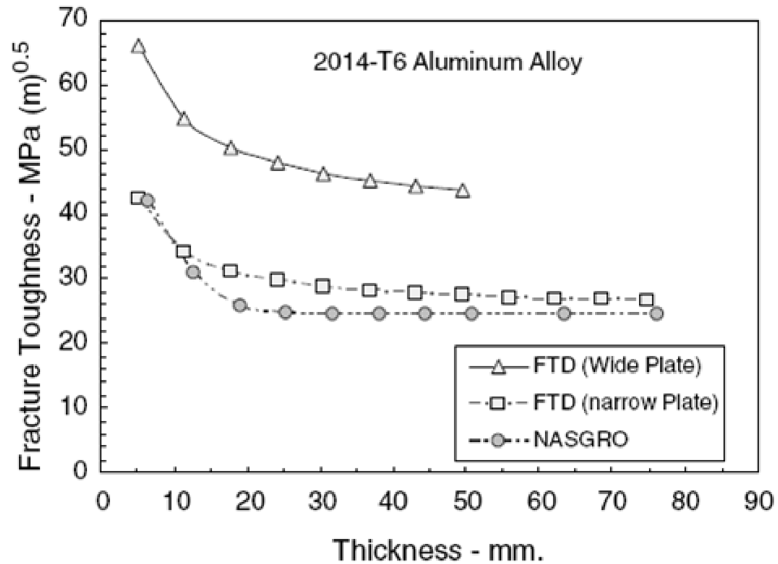
(Theoretical Background)



Areas associated with the uniform and Non-uniform straining



A center crack in a wide plate



$$K_\chi = \beta\sigma\sqrt{\pi c}$$

$$c = \frac{E}{\pi\sigma^2\mu}\{2T + g_1 + g_2\}$$

$$g_1 = \sigma_{UF}\varepsilon_{PN}h_F k$$

$$g_2 = \frac{n}{n-1}\sigma_{TU}\varepsilon_{TU}\left[1 - \left(\frac{\sigma_T}{\sigma_{TU}}\right)^{n+1}\right] h \left[\frac{\varepsilon_{TF}\varepsilon_{TL}}{\varepsilon_{TU}\varepsilon_T}\right]\left[\left(\frac{\varepsilon_{TU}}{\varepsilon_{TL}}\right)^{(n-1)/n} - 1\right]\beta$$

Ref: Bahram Farahmand a, Kamran Nikbin, Predicting fracture and fatigue crack growth properties using tensile properties, Engineering Fracture Mechanics 75 (2008) 2144–2155

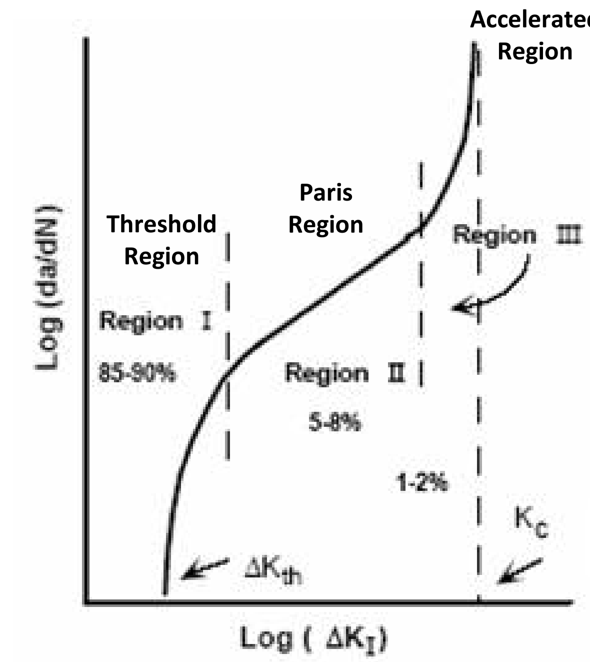
PART II: Fatigue Crack Growth [FCG]

(Theoretical Background)

$$\frac{da}{dN} = \frac{C(1-f)^n \Delta K^n \left(1 - \frac{\Delta K_{th}}{\Delta K}\right)^p}{(1-R)^n \left(1 - \frac{\Delta K}{(1-R)K_c}\right)^q}$$

Forman-Newman-de Koning (FNK)

Crack Growth Rate Empirical Relationship -NASGRO



FNK Equation Variables:

C, n, p, and q ~ empirically derived constants comes from tests or virtual testing

R ~ stress ratio

ΔK ~ stress intensity factor range

ΔK_{th} ~ threshold stress intensity factor

f ~ crack opening function (incorporates the effect of closure behavior on crack growth rate under constant amplitude loading for plasticity-induced crack closure, as defined by Newman)

Compute Stress Intensity Factor using FE and VCCT

$$\begin{array}{l} If\ \Delta K < \Delta K_{th} \ - No\ \ FCG\ \ \text{initiation} \\ If\ \Delta K > K_{c} \ - \text{fast fracture - stop} \end{array}$$

Initial crack length a

VCCT

$$G_I \cong \frac{F_{y12}(v_3 - v_4)}{2B\Delta a}$$

$$K_{\mathrm{Im}ax} = \sqrt{EG_I}$$

$$\Delta K = (1-R)K_{\mathrm{Im}ax}$$

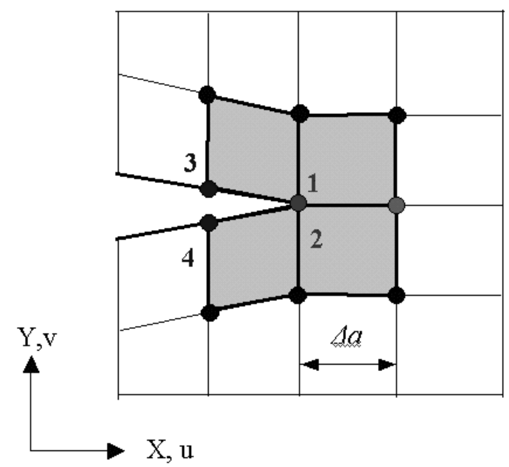
da is fixed (element size)

$$\frac{da}{dN}\ vs.\Delta K$$

dN

Release nodes:

$a = a + da \quad N = N + dN$



***G*: strain energy release rate**
***K*: stress intensity factor; *Kth*: threshold stress intensity factor; *Kc*: critical stress intensity factor, *N*: cycles; *a:* crack length**

Ref: B. Farahmand, C. Saff, De Xie and F. Abdi, "Estimation of Fatigue and Fracture Allowables For Metallic Materials Under Cyclic Loading". **AIAA-2007-2381, Honolulu, Hawaii, April, 2007.**

PART III - Methodology: Critical Damage and Fracture Events

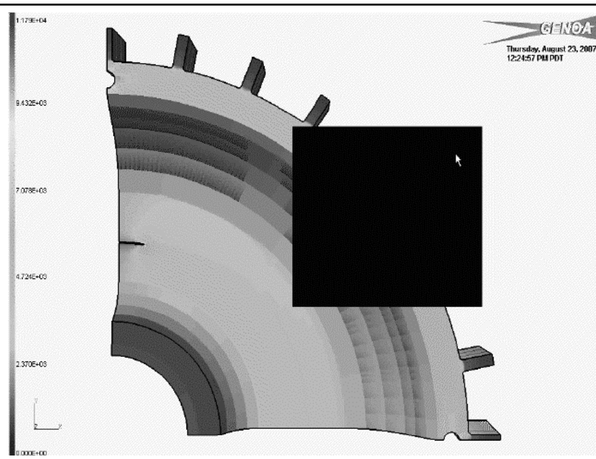
Damage Initiation/growth, and Fracture initiation/growth, Residual Strength

<u>PFA</u>

- Determine: 5 stages of damage mechanism, damage pattern & crack path, failure mechanisms.
- Advantage: not requires predefined crack path.
- Disadvantage: removing damaged elements can create stress singularity.

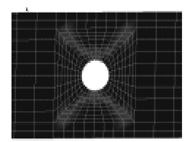
<u>Fracture Mechanics Theory</u>

- Disadvantage: predefined crack path, fracture toughness
- Advantage: stress singularity

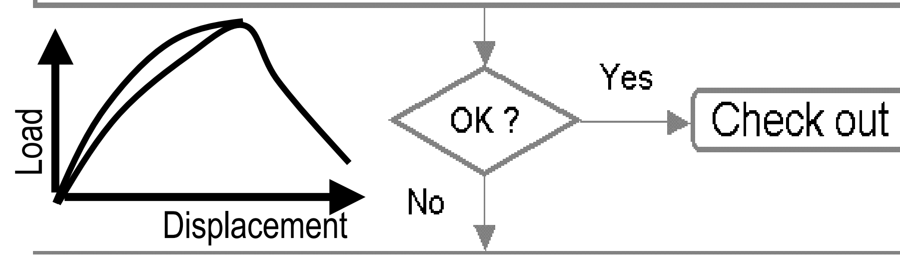


Crack growth strategy in composite under static loading with GENOA/PFA

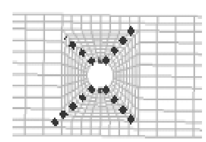
<u>Step 1: Run GENOA/PFA with *FAILURECRITERIA</u>



- **Damage Mechanism**
- **Damage Pattern**
- **Crack path**
- **<u>Load vs. displacement curve</u>**



<u>Step 2: Run GENOA/PFA with *DCZM</u>



- **<u>Load vs. displacement curve</u>**

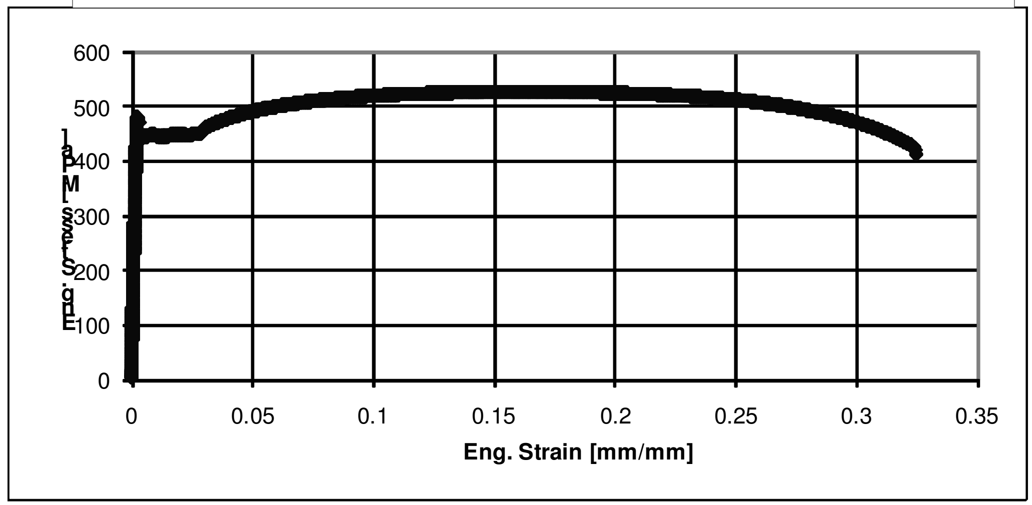
Ref: Xie D and Biggers, Jr. SB, "Progressive crack growth analysis using interface element based on the virtual crack closure technique, ", Finite Elements in Analysis and Design, 2006, Vol 42, page 977-984.

Part 1: Fracture Toughness Prediction Vs. Test (Steel S420M)

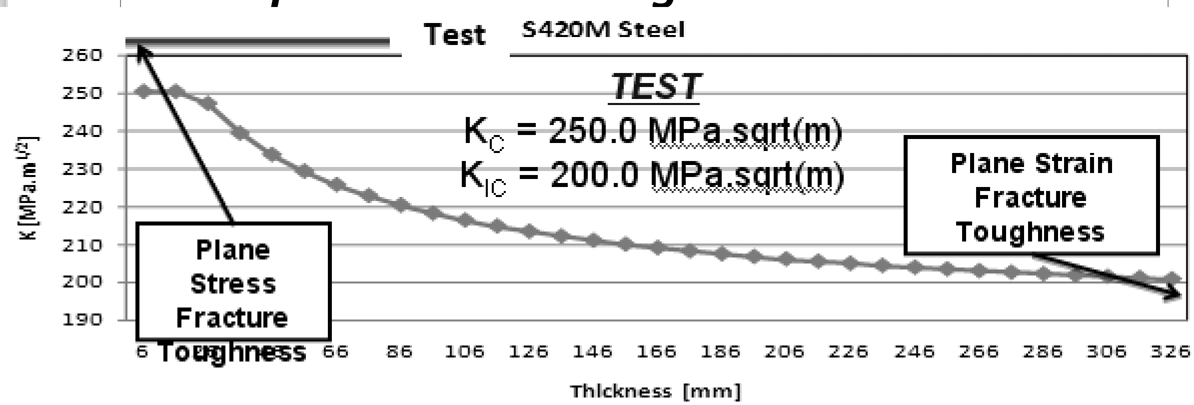
Input

Name	Value
Name	S420M_IMPERIAL
Category	Stainless_Steel
Description	Stainless_steel_bar-H1000_...
Unit System	International System (SI)
Material Properties	
Ultimate Strength (MPa)	514.700012
Yielding Strength (MPa)	4MPa99988
Rupture Strength (MPa)	400
Necking Strength (MPa)	506
Apply Stress	240
Normal Modulus (MPa)	219400
Poisson Ratio	0.3
Ultimate Strain	0.1722
Rupture Strain	0.33
Atomic Spacing (angstrom)	2.86
Geometric Values	
Specimen Thickness (mm)	6
Gauge Length (mm)	50
Plate Width (mm)	460
Plate Thickness (mm)	6
Range Thickness (mm)	327
Increments Range (mm)	10

Input: Stress-Strain Curve



Output: Fracture Toughness vs. Thickness



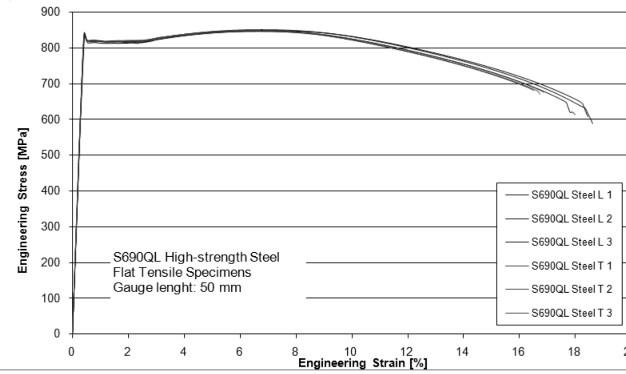
Ref: B. Farahmand, "Fatigue and Fracture Mechanics of High Risk Parts", Chapman and Hall, 1997

Part 1: Fracture Toughness [S690 QL]

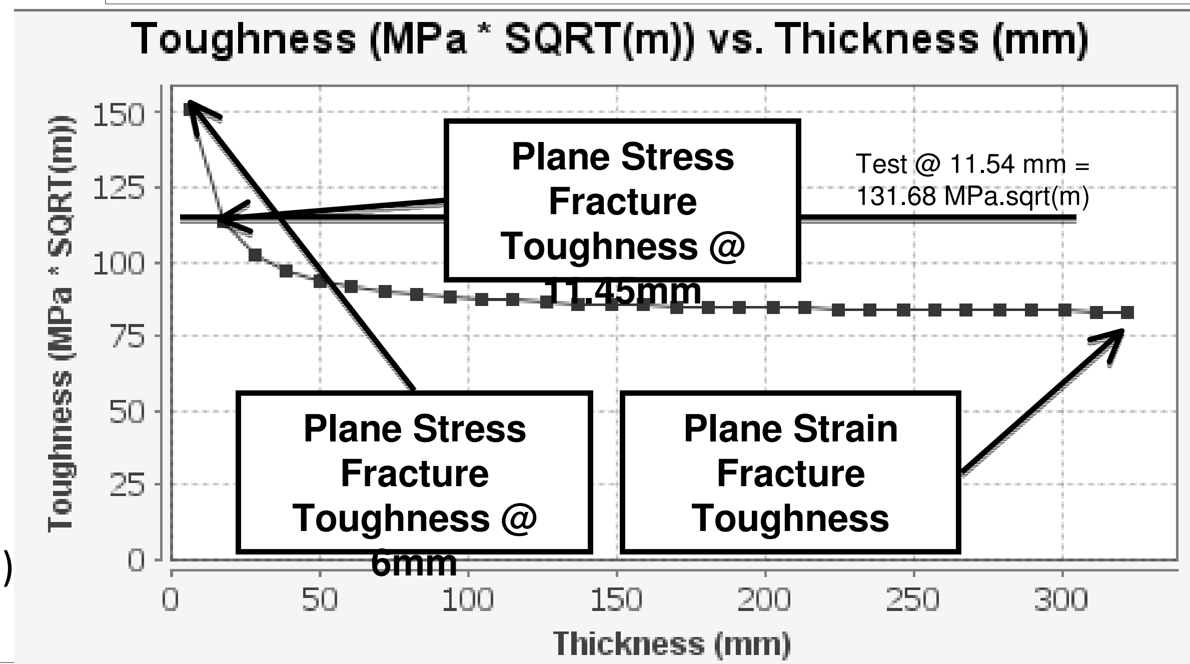
Input

- FTD Materials (1)
  - S690QL
    - **Description:**
      Steel_6_mm_thick-at_70F-longitudinal
    - **Material Properties**
      - Yielding Strength = 8.212E+02 MPa
      - Ultimate Strength = 8.491E+02 MPa
      - Necking Strength = 8.281E+02 MPa
      - Rupture Strength = 6.409E+02 MPa
      - Apply Stress = 5.000E+02 MPa
      - Normal Modulus = 2.092E+05
      - Poisson Ratio = 3.000E-01
      - Ultimate Strain = 6.585E-02 mm/mm
      - Rupture Strain = 1.618E-01 mm/mm
      - h Constants = 1.170E-04
      - Alpha Constants = 2.860E+00
    - **Geometry**
      - Specimen Thickness = 6.000E+00 mm
      - Gauge Length = 5.000E+01 mm
      - Plate Width = 4.600E+02 mm
      - Plate Thickness = 6.000E+00 mm
      - Range Thickness = 3.270E+02 mm
      - Increments Range = 5.450E+00 mm
    - Stress Strain Curve

Input: Stress-Strain Curve



Output: Fracture Toughness vs. Thickness

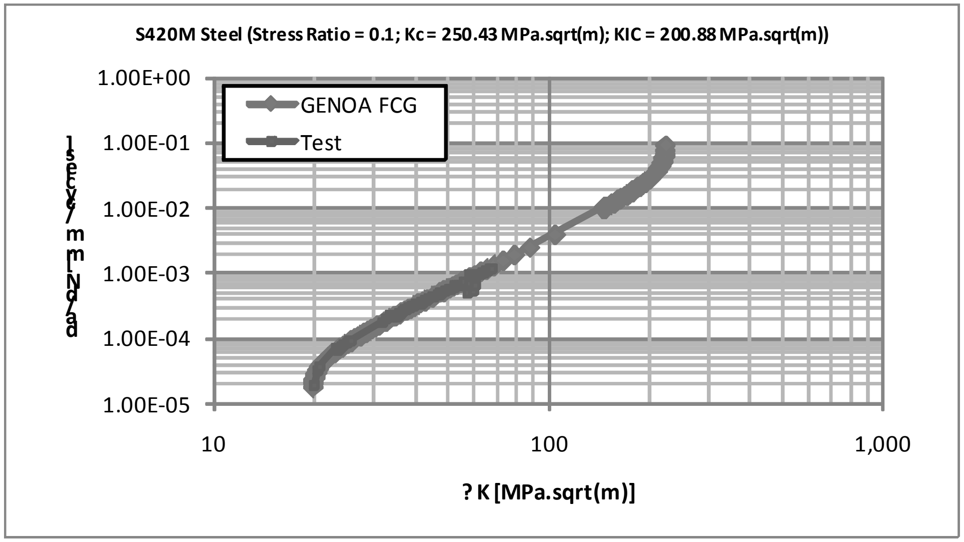


K_C @ 6.0mm = 151.6 MPa.sqrt(m)
K_C @ 11.54mm = 130.0 MPa.sqrt(m)
K_{IC} = 83.25 MPa.sqrt(m)

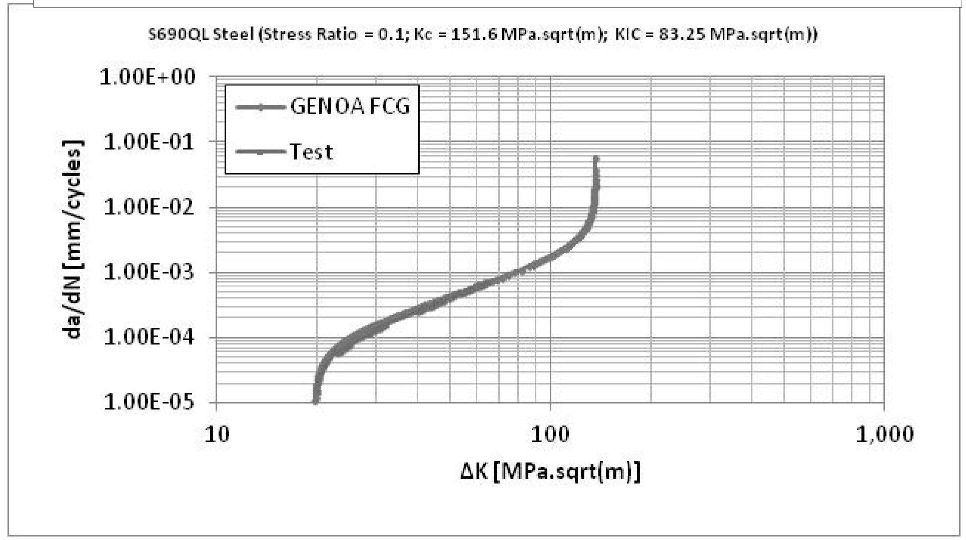
Part 2: Fatigue Crack Growth Prediction Vs. Test (Steel)

Prediction VS Test

S420M Steel,
R=0.1, K1C= 200.88 (MPa.sqrt(m))



S690QL Steel,
R=0.1, K1C= 83 (MPa.sqrt(m))



- Same FCG curve was used for both constant thickness and variable thickness panels.
- For FE Analysis the blue curve was used to predict the a-N curve for constant thickness and variable thickness panels.

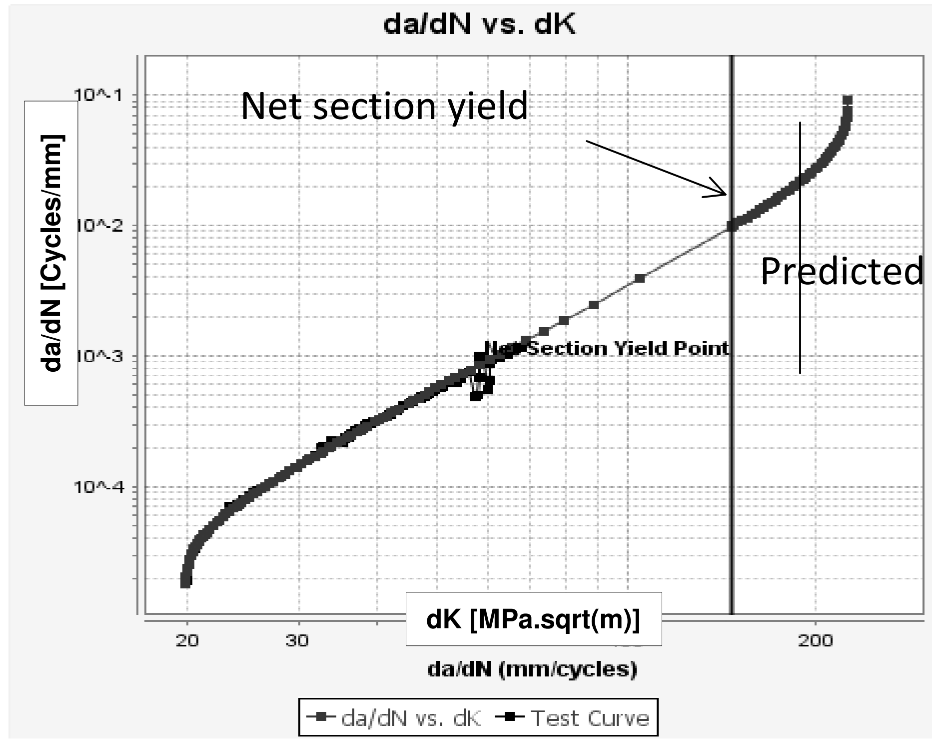
PART 2: Fatigue Crack Growth (Steel S420M)

Input

Material Setup

Name	Value
Name	S420M
Category	AISI_Steel
Unit System	International System (SI)
Material Properties	
P Constant	0.25
Q Constant	0.25
Kc (MPa*SQRT(m))	250.432907
Klc (MPa*SQRT(m))	200.880707
Stress Ratio	0.1
Plate Thickness	6
Plate Width (mm)	460
Maximum Stress (MPa)	88.220001
Plane Stress/Strain Constraint Factor	2.5
Young's Modulus	219367
Yielding Stress (MPa)	441.299988
alpha1	1.125
alpha2	0.93
beta1	7.000E-07
beta2	0.0005
Kth Ratio	9.5

Output: Fatigue Crack Growth Vs. dk



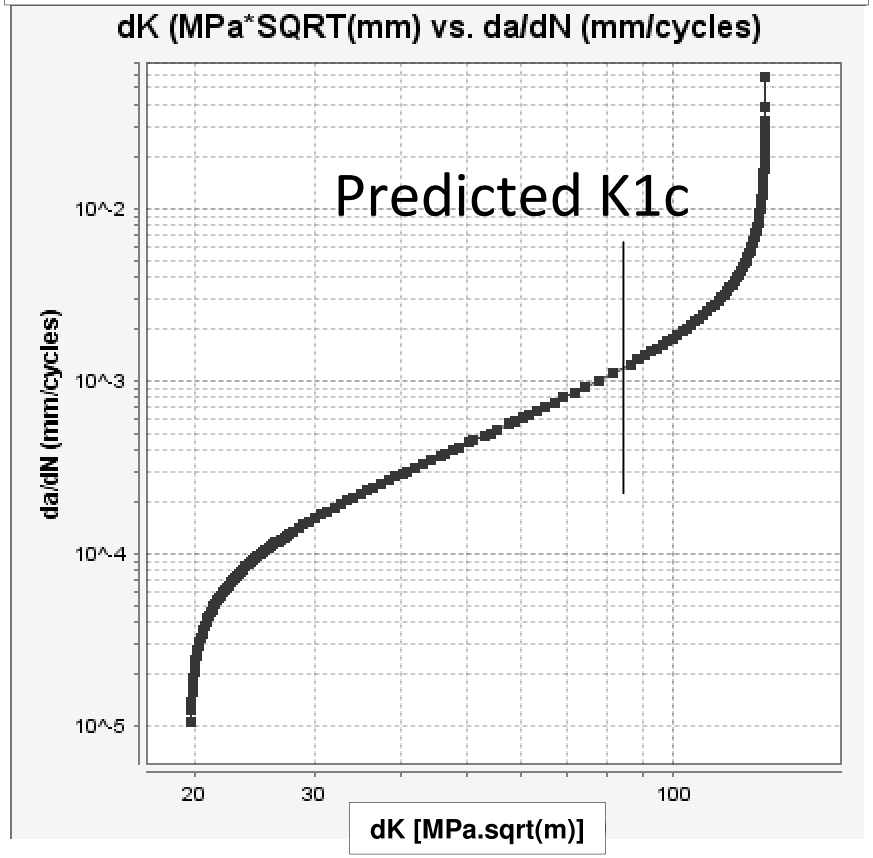
- Fracture Toughness value was taken from the test and K_{IC} estimated from FTD code
- beta1, beta2 values were adjusted slightly to match the test curve (rotation of FCG curve)
- Kth Ratio was adjusted slightly to match the dK_{th} value
- Imperial Test Specimen stopped before possible net-section yielding (indicated by blue line)
- Software FCG curve shows net-section yielding region (right side of blue line)
- FCG Curve and Imperial Test are in good agreement

PART 2: Fatigue Crack Growth (Steel S690QL)

Input

- S690QL
  - Description: Steel
  - Material Properties
    - P Constant = 5.000E-01
    - Q Constant = 5.000E-01
    - Kc = 1.516E+02 MPa*sqrt(mm)
    - KIc = 8.325E+01 MPa*sqrt(mm)
    - Stress Ratio = 1.000E-01
    - Plate Width = 4.600E+02 mm
    - Maximum Stress = 8.822E+01 MPa
    - Alpha Constant = 2.500E+00
    - Young's Modulus = 2.092E+05
    - Yielding Stress = 8.212E+02
    - alpha1 = 1.125E+00
    - alpha2 = 9.300E-01
    - beta1 = 3.700E-06
    - beta2 = 3.000E-04
    - Kth Ratio = 3.950E+00
    - Plate Thickness = 6.000E+00 mm

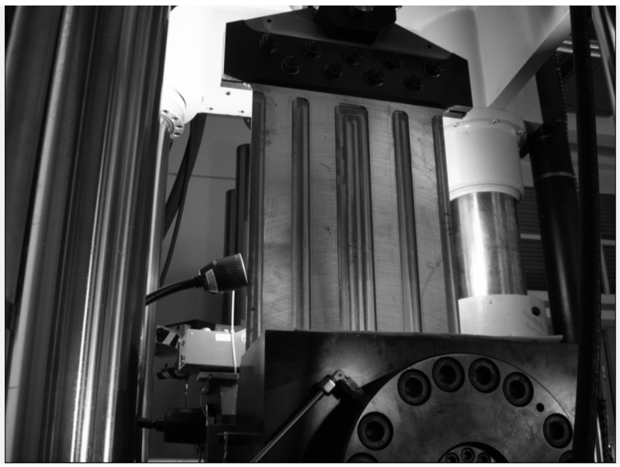
Output: Fatigue Crack Growth Vs. dk



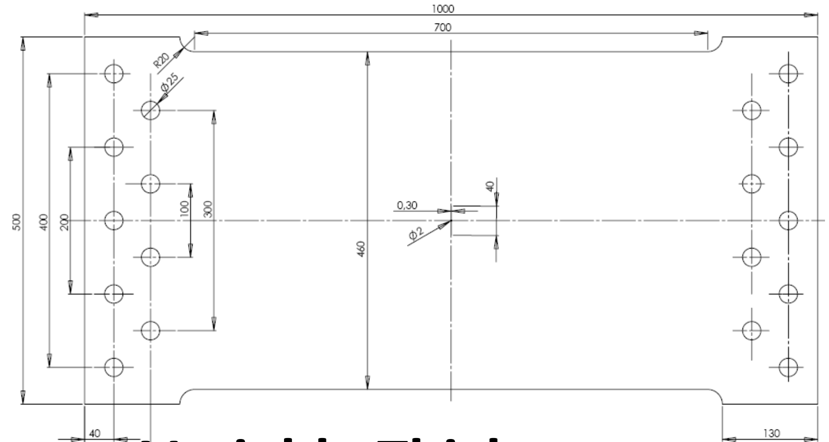
- Fracture Toughness (K_{IC} and K_C) values were estimated from FTD code
- beta1, beta2,Kth Ratio values were adjusted slightly

Constant & Variable Thickness Specimens (Fatigue)

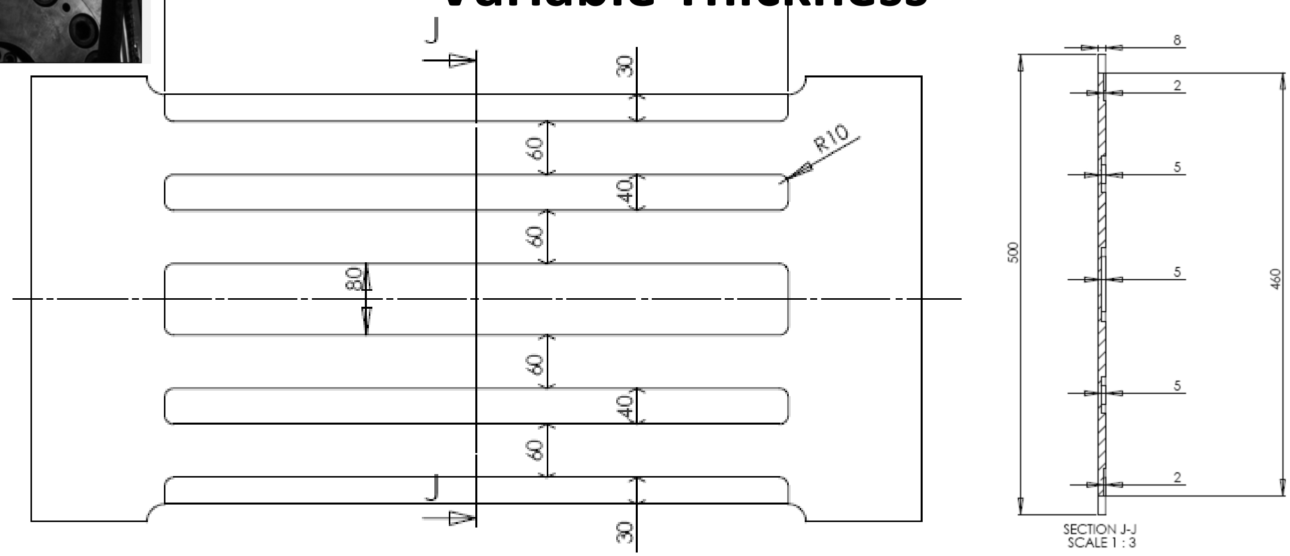
Various Crenellated M(T)200 specimen of AISI 304 steel



Constant Thickness



Variable Thickness

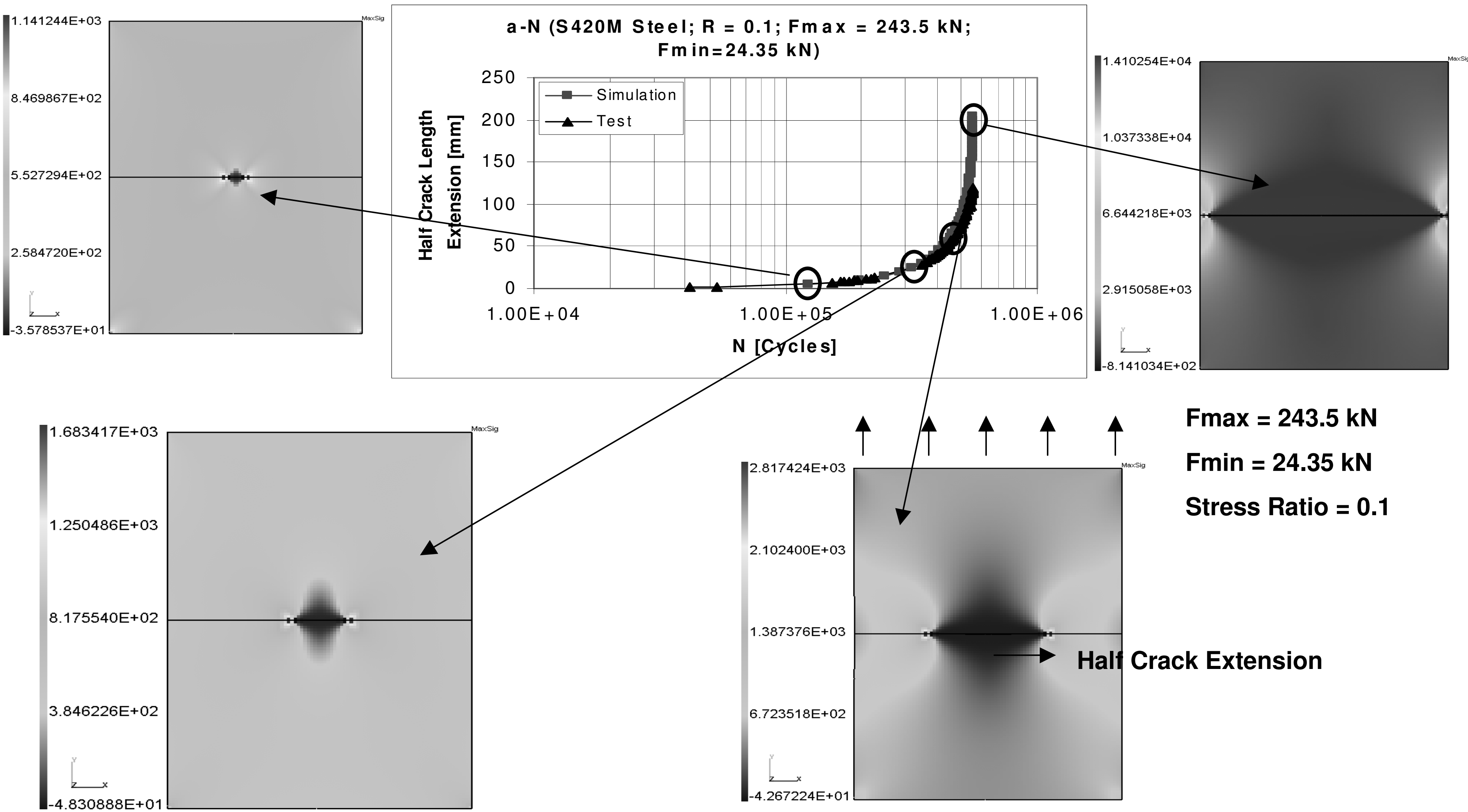


Ref: "S.E. Eren, "**Advancing the Damage Tolerance of Laser Beam Welded Steels using the Crenellation Technique**,", Ph.D. Thesis, Imperial College London, 2012",

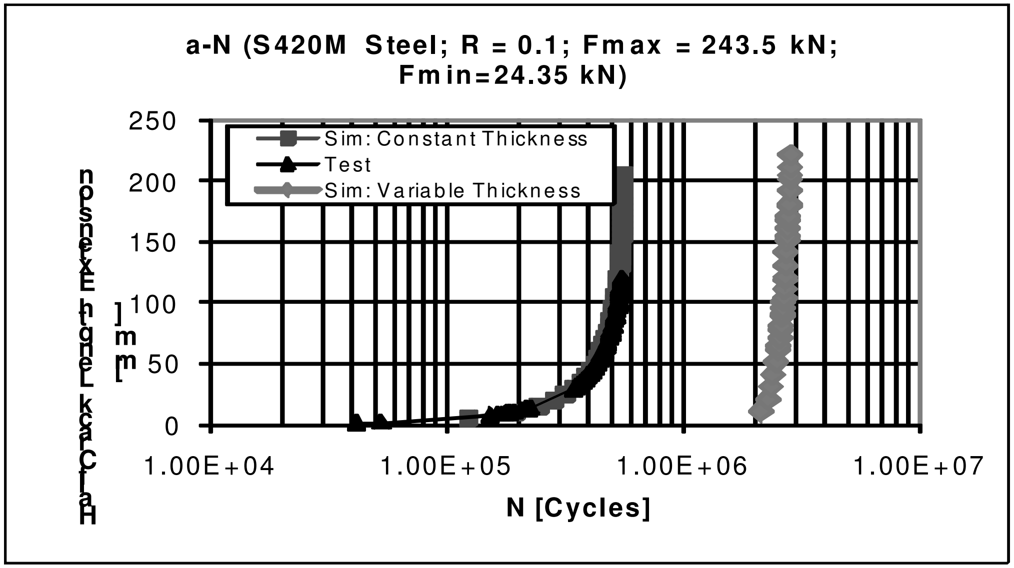
PART 3: Fatigue Crack Growth (Constant Thickness)

(Steel S420M)

Used 12880 shell (S4R) element for full model & Virtual Crack Closure Technique combined with fatigue analysis and reading the fatigue crack growth curve from previous slide



PART 3: Fatigue Crack Growth, Variable Thickness [S420M]



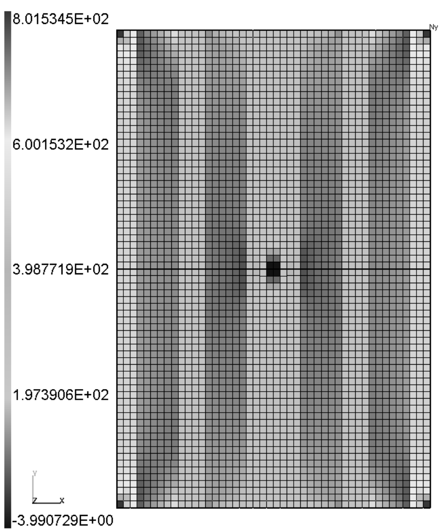
Fmax = 243.5 kN

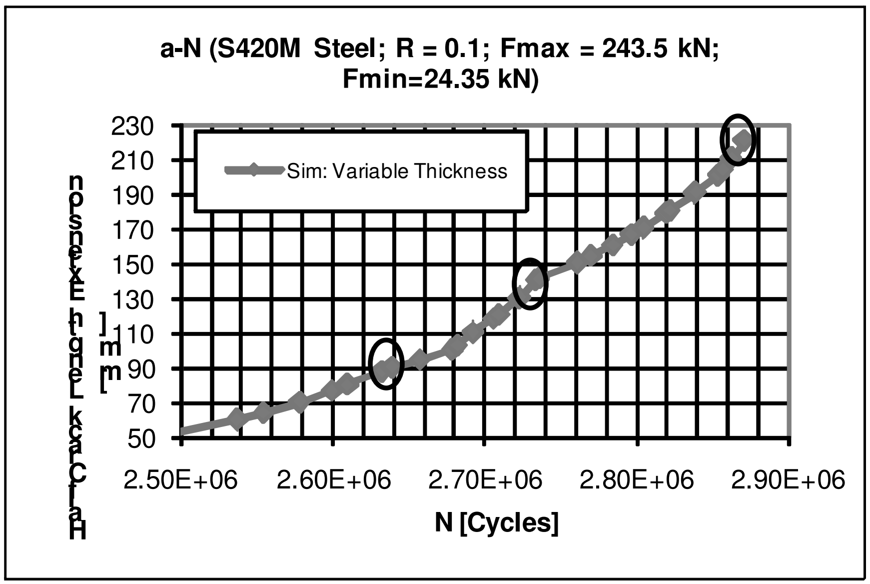
Fmin = 24.35 kN

Stress Ratio = 0.1

Used 12880 shell (S4R) element for full model & Virtual Crack Closure Technique combined with fatigue analysis and reading the fatigue crack growth curve from previous slide

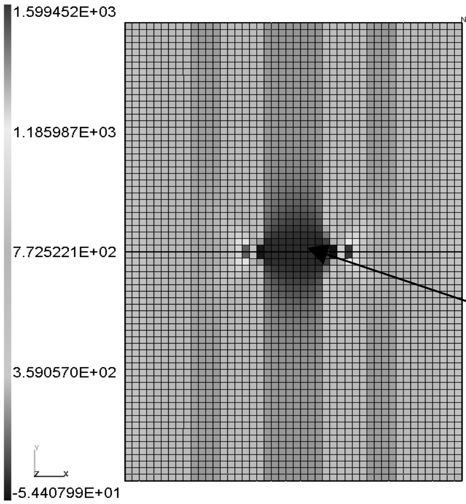
2.13E6 Cycles

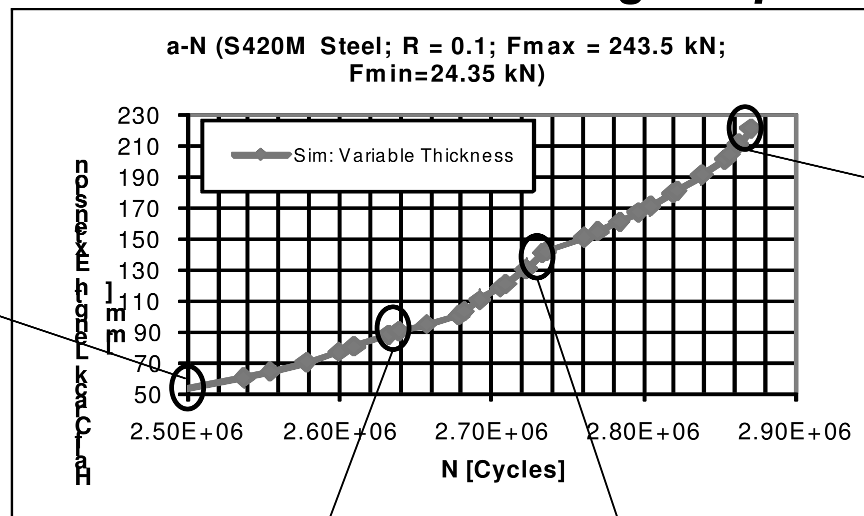


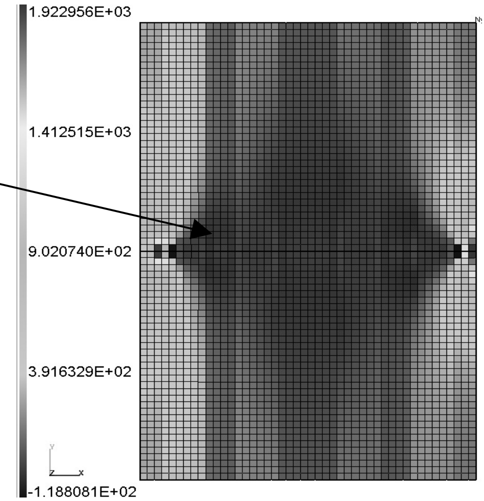


PART 3: Fatigue Crack Growth, Variable Thickness [S420M]

Crack Growth Peak are due to change in panel thickness





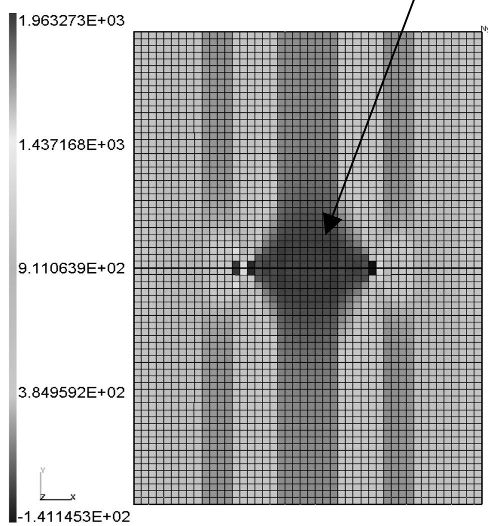


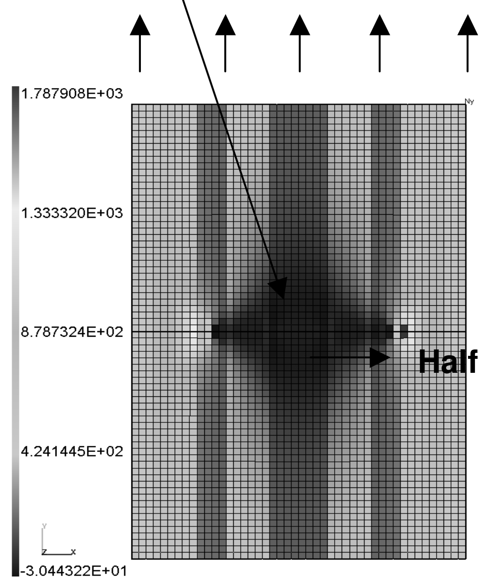
Fmax = 243.5 kN

Fmin = 24.35 kN

Stress Ratio = 0.1

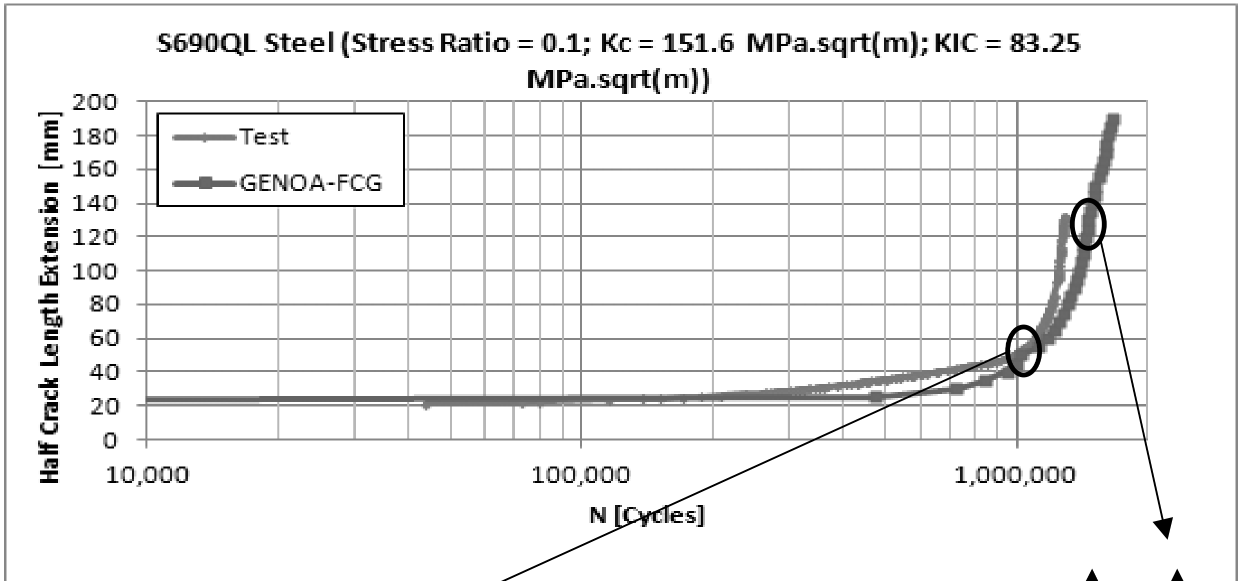
Used 3220 shell (S4) element for full model & Virtual Crack Closure Technique combined with fatigue analysis and reading the fatigue crack growth curve from previous slide

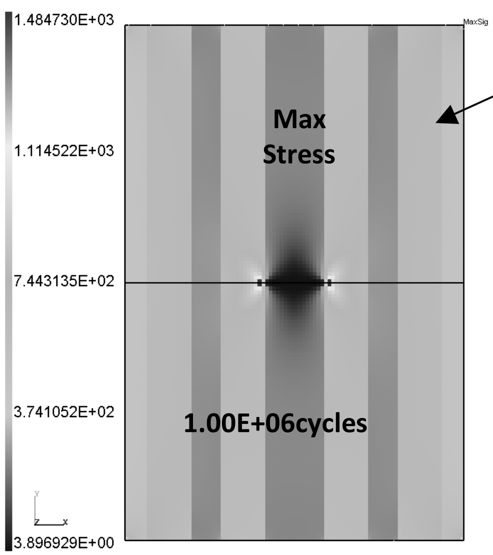




Half Crack Extension

PART 3: Fatigue Crack Growth, Variable Thickness [S690QL)



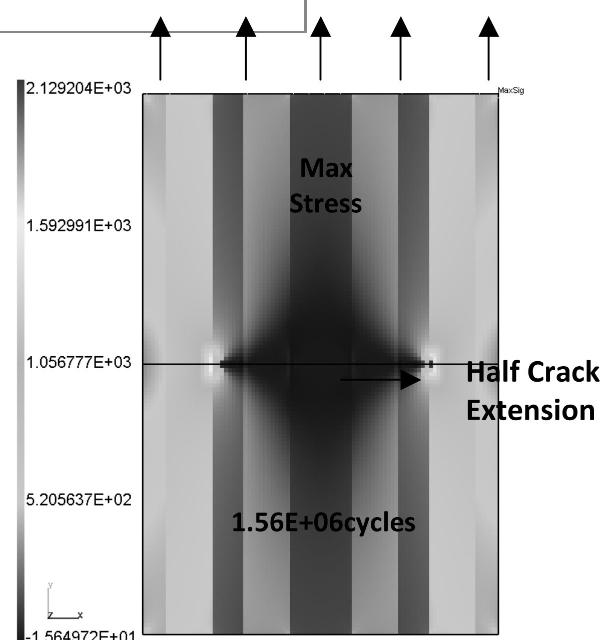


Variable Thickness Panel

Fmax = 243.5 kN

Fmin = 24.35 kN

Stress Ratio = 0.1



SUMMARY

- Life Assessment of metallic components can be performed Progressive Failure Analysis
- To precisely model the statically/cyclically loaded parts, GENOA recommends its unique 4-steps approach
  - **PART 1** : Fracture Toughness Determination (FTD); requires full material SS curve
  - **PART II** : Fatigue Crack Growth (FCG) Behavior (da/dN versus ΔK)
  - **PART III**: Progressive Failure Analysis (PFA) in conjunction with Virtual Crack Closure technique (VCCT) for linearly elastic materials and Discrete Cohesive Zone Modeling (DCZM) for parts made of softer material
- Each above mention PART Steel (S420M, and S690QL) were validated at RT
- Improvement of Fatigue Crack Growth in Crenellated Vs. Constant Thickness Steel Panels
- These predictive methods are anticipated to reduced fatigue testing and expenses at the coupon and component scales