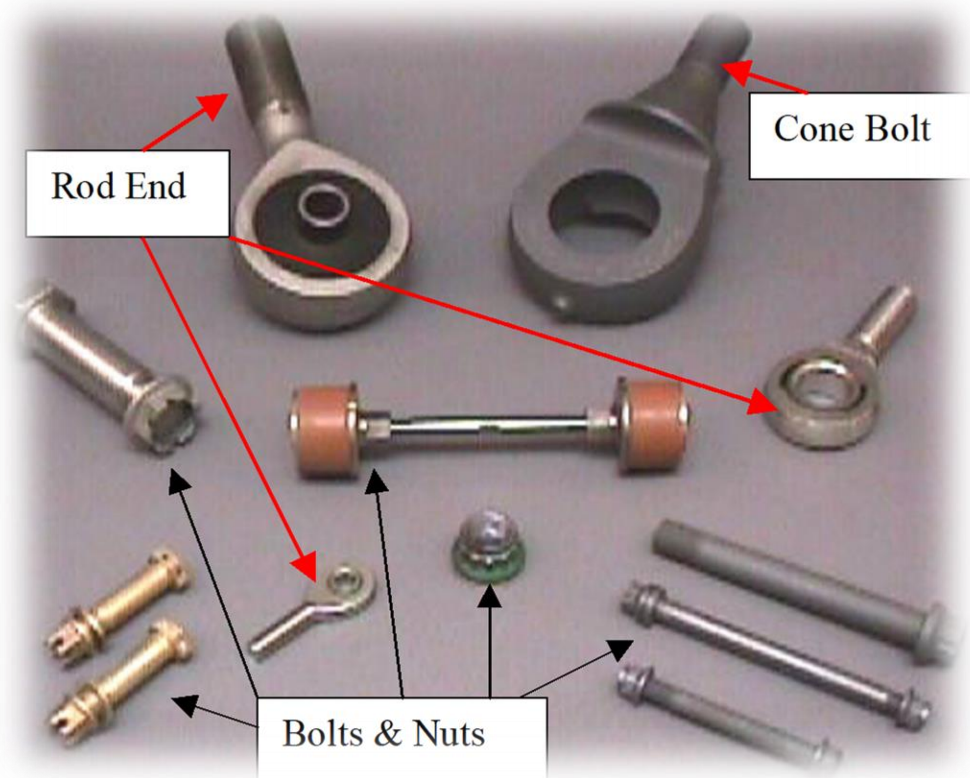
How Many Bolts Hold the Aircraft Engine On?



Kirk William Olsen, P.E., Ph.D.

SAE FD&E Spring 2021 Meeting

May 11, 2021

Throwback Aerospace Fastener Example

OUTLINE

1. **Data on Typical/Standard Fasteners**

2. **Installation Concerns (T vs P)**

3. **Typical Analyses:**

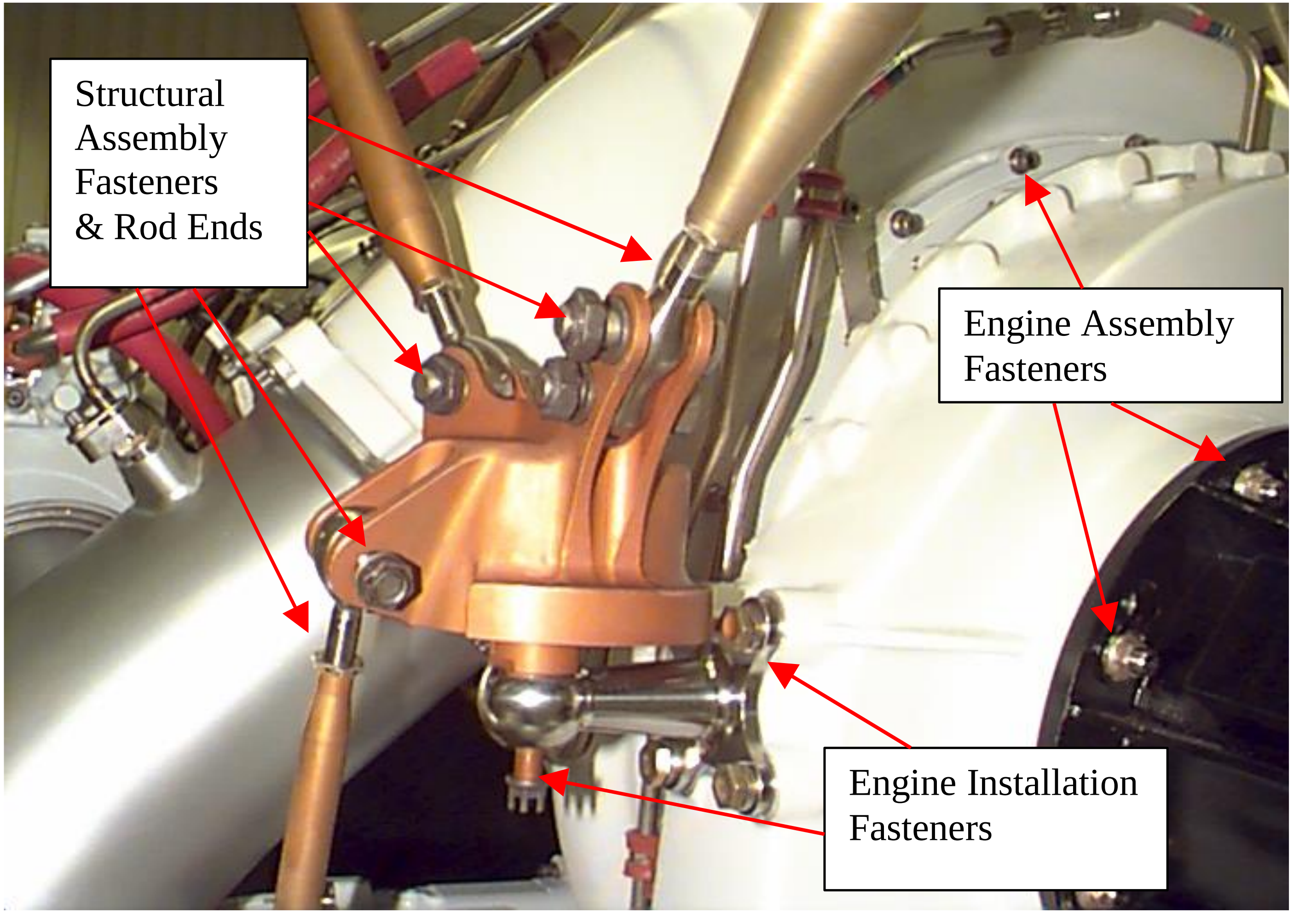
   Tension vs Shear, Static & Cyclic

4. **Crack Growth in Threads**

5. **Bonus Material: FAA Rules for Bolts**

How are Bolts Analyzed/Tested/Use?

(Aerospace: Post Heat Treat Cold Rolled Threads)



- **Simple Static Strength; Tensile & Shear**
- **Cyclic Strength; Fatigue and Crack Growth**

Standard Fasteners & Design Data

- **Hex A286 (Shear or Tension Use) – Ex NAS6700**
  - **Static Ultimate Strength BUT Shear Removed.**
  - **Spec Min 160 KSI but 140 KSI MMPDS S-Basis Data**

CUSTODIAN	REVISION
NATIONAL AEROSPACE STANDARDS COMMITTEE	**9**
TITLE (9) **BOLT, TENSION, HEX HEAD, CLOSE TOLERANCE, A286 CRES, LONG THREAD, REDUCED MAJOR THREAD DIA., SELF-LOCKING AND NONLOCKING, 160 KSI Ftu**	CLASSIFICATION PART STANDARD **NAS6703 THRU 6720** SHEET 1 OF 8

MATERIAL:	CRES - A286 (UNS S66286) CONFORMING TO THE CHEMISTRY OF AMS5731, AMS5732, AMS5737 OR AMS5853. LOCKING ELEMENT – NYLON OR EQUIVALENT PER MIL-DTL-18240 AND QPL-18240.
HEAT TREAT:	DEVELOP BASIC MATERIAL PROPERTIES AS FOLLOWS, WITH CONTROLS PER ~~AMS-H-6875 OR~~ AMS2759: /19/ 160 – 190 KSI Ftu

PROCUREMENT SPECIFICATION: NAS4003, EXCEPT AS NOTED. COLD WORK OF HEAD TO SHANK FILLET RADIUS AND FATIGUE TESTING ARE NOT REQUIRED FOR NAS6703 BOLTS. LOCKING ELEMENT FOR SELF-LOCKING BOLTS: PER NASM15981 AND MIL-DTL-18240, LOCKING ELEMENT TYPE, INCLUDING PATCH TYPE, IS OPTIONAL WHEN "L" CODE IS SPECIFIED. PATCH TYPE LOCKING ELEMENT (WITH NO METAL REMOVED) IS REQUIRED WHEN "P" CODE IS SPECIFIED. LOCKING ELEMENT MUST BE SUPPLIED BY A QUALIFIED SOURCE LISTED IN QPL-18240 OR APPROVED FOR LISTING IN QPL-18240. SHIPPING NOTICE SHOULD IDENTIFY SUPPLIER OF BOLT AND LOCKING ELEMENT SEPARATELY.

Standard Fasteners & Design Data

Spline Inconel 718 (Tension or Shear Use) – Ex MS14181

- **Spec Min 220ksi but 185ksi MMPDS A-Basis (220 S-Basis)**

PROCUREMENT SPECIFICATION	TITLE	CLASSIFICATION PART STANDARD
NAS4008	BOLT, TENSION, NICKEL ALLOY 718, 220 KSI Ftu, EXTERNAL WRENCHING, SPLINE DRIVE, FLANGED HEAD	NASM14181 SHEET 1 OF 6

TABLE I – DIMENSIONS AND STRENGTH VALUES (CONTINUED)

DIA DASH NO.	(U)	BEARING AREA (MEAN DIA) SQ. IN.	TENSILE STRENGTH (LBF) ROOM TEMPERATURE MAX.	TENSILE STRENGTH (LBF) ROOM TEMPERATURE MIN.	TENSILE STRENGTH (LBF) AT 800 °F MIN. /13/	DOUBLE SHEAR STRENGTH LBF MIN.	STRESS RUPTURE AT 800 °F (LBF) /13/	TOLERANCE X	TOLERANCE Z /16/
03	.039	.0517	5,640	4,770	3,810	7,100	2,670	.004	.004
04	.045	.0914	10,080	8,540	6,830	12,300	4,780	.005	
05	.052	.1442	15,960	13,500	10,800	19,200	7,560	.006	
06		.2106	24,700	20,900	16,720	27,650	11,700	.008	
07	.063	.2896	33,480	28,300	22,640	37,600	15,840	.009	.006
08		.3786	44,640	37,800	30,240	49,100	21,160	.010	
09	.089	.4808	56,570	47,900	38,320	62,150	26,820	.011	
10		.5945	70,820	59,900	47,920	76,700	33,540	.012	
12		.7512	100,800	86,900	69,500	109,857	48,700	.015	
14		1.1673	137,000	119,000	95,000	149,640	66,600	.018	.009
16	.100	1.5465	179,000	155,000	124,000	195,565	86,800	.020	

MATERIAL: NICKEL ALLOY 718 WITH CHEMISTRY OF AMS5662 (UNS N07718), AMS5663 (UNS N07718) OR AMS5962 (UNS N07718).

HEAT TREAT: MATERIAL MUST BE PROCESSED TO YIELD 220 KSI MINIMUM ULTIMATE TENSILE STRENGTH WITH THE PYROMETRY REQUIREMENTS OF AMS2750.

Business Opportunity

How can a company, university, or collaboration produce A basis standard fastener data for publication w/SAE, ASTM, MMPDS, ESDU?

TABLE I – DIMENSIONS AND STRENGTH VALUES (CONTINUED)

DIA DASH NO.	(U)	BEARING AREA (MEAN DIA) SQ. IN.	TENSILE STRENGTH (LBF)			DOUBLE SHEAR STRENGTH LBF MIN.	STRESS RUPTURE AT 800 °F (LBF) /13/
			ROOM TEMPERATURE		AT 800 °F MIN. /13/		
			MAX.	MIN.			
03	.039	.0517	5,640	4,770	3,810	7,100	2,670
04	.045	.0914	10,080	8,540	6,830	12,300	4,780
05	.052	.1442	15,960	13,500	10,800	19,200	7,560
06		.2106	24,700	20,900	16,720	27,650	11,700
07	.063	.2896	33,480	28,300	22,640	37,600	15,840
08		.3786	44,640	37,800	30,240	49,100	21,160
09	.089	.4808	56,570	47,900	38,320	62,150	26,820
10		.5945	70,820	59,900	47,920	76,700	33,540
12		.7512	100,800	86,900	69,500	109,857	48,700
14		1.1673	137,000	119,000	95,000	149,640	66,600
16	.100	1.5465	179,000	155,000	124,000	195,565	86,800

What’s in Your Library?

- **Bickford, John H., “..The Design and Behavior of Bolted Joints..” (Any Edition).**
- **Bruhn, E.F., “Analysis and Design of Flight Vehicle Structures”, Jacobs Publishing, 1973 (out of print).**
- **FAA, “Federal Aviation Regulations (FAR)”, 14 CFR 25 or 23, Public Domain.**
- **MMPDS-01 (Mil-HDBK-5), Public Domain (-15).**
- **ASTM STPs 1236, 1391, & 1487, “Structural Integrity of Fasteners” (all three).**
- **SAE???**

Hints: AbeBooks.com for used copies of older books

HC Pacific for Fasteners (http://hcpacific.com/web/products/)

Torque vs Preload: $T_{in} = (KD)P + T_p$

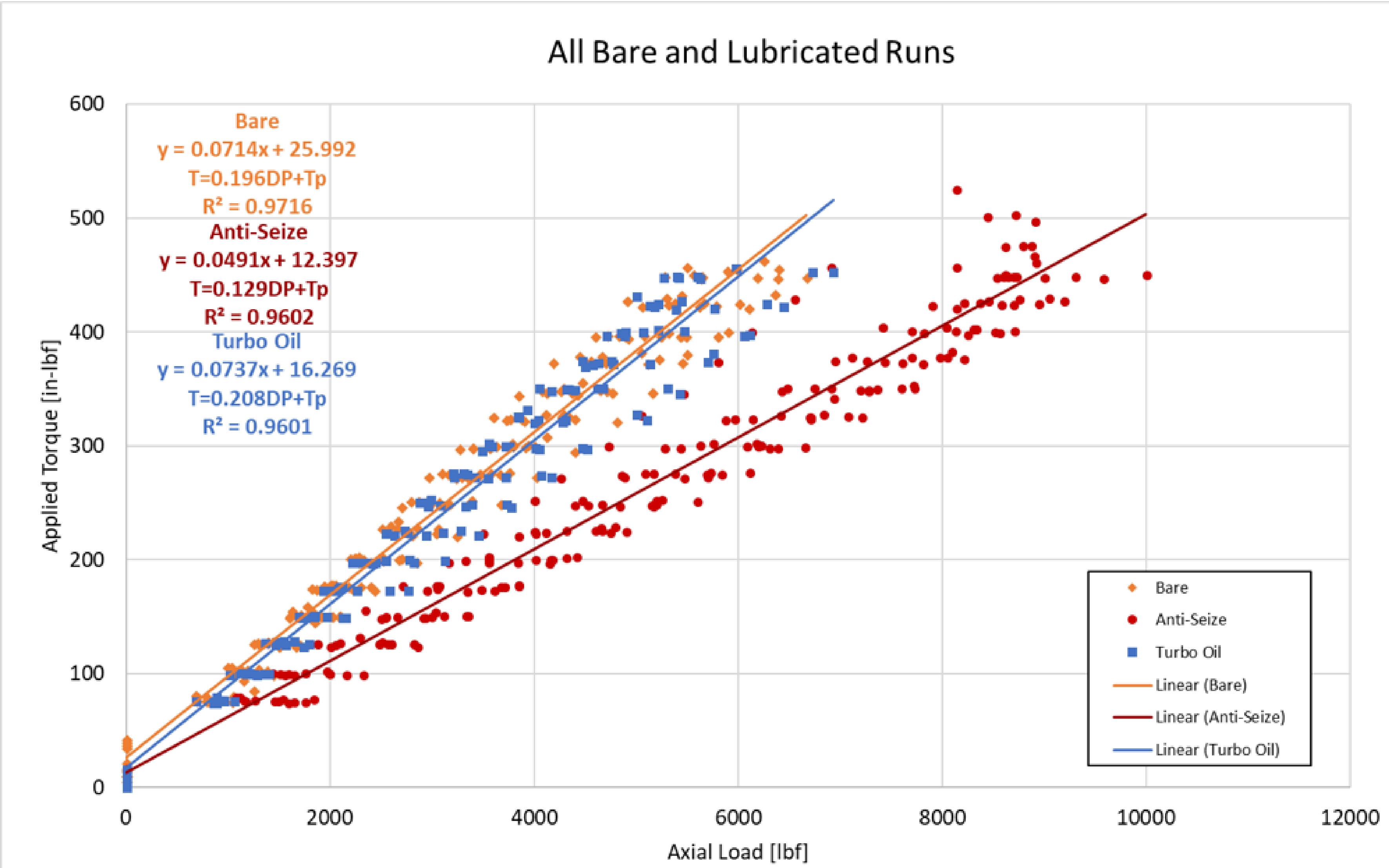


Figure 59: Bolt (NAS6706DU24) and Castellated Nut (MS21225-6) All Tested Lubes, Runs 1-6

Simple Static Strength; Tensile

Tension Strength; Thread Area for Net Section

- **Conservative Area ≈ Minor Diameter of Thread**
- **Truer Tensile Area ≈ Pitch Diameter of Thread**
- **Check Net Section Yield and Failure; K_t is not very useful**

Simple Static Strength; Tensile

- **Highest Preload is "Good" for Gapping & Fatigue**

  $F_p \approx 0.7 * F_{ty} * A$

- **Preload is REALLY Pre-Strain**

  Once Joint Gaps (Bolt Yields) "Preload" is Lost.

****I will leave Joint Analyses for Others.. Jeff A. Chambers of NASA, "TM 106943", Dec '95**

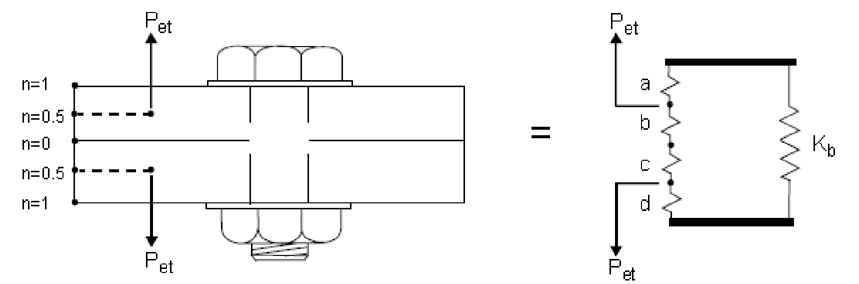


Figure 4.—Joint and spring analogy.

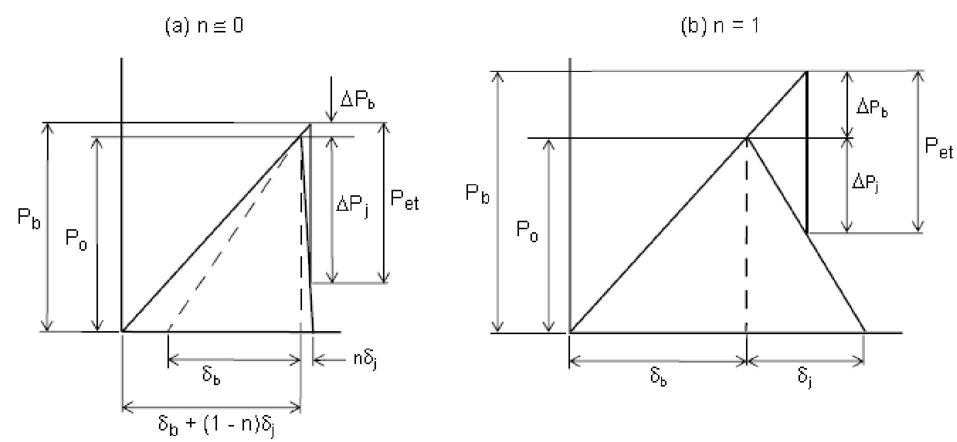


Figure 5.—Effects of loading plane.

Simple Static Shear Strength; "Preload" & Shear Interaction Equations (Bruhn) too Conservative.

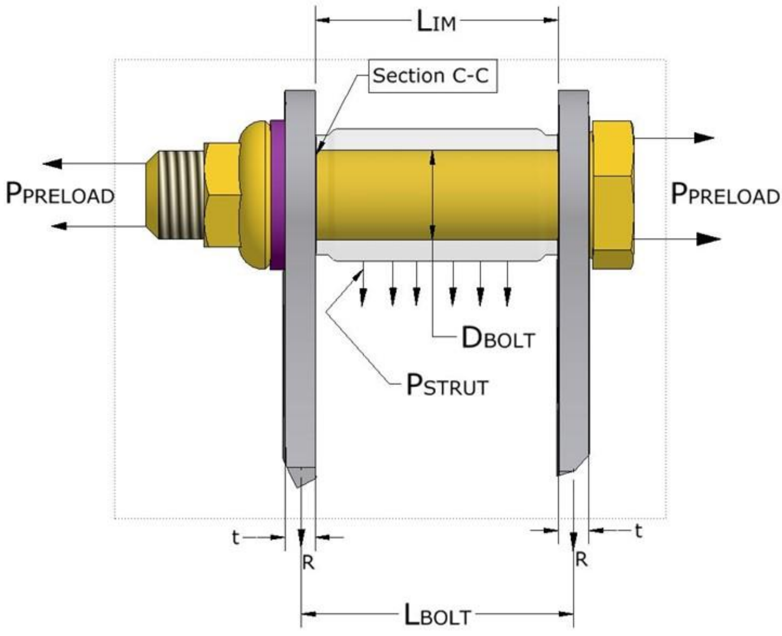
C3.13 Strength Under Combined Bending Flexural Shear and Axial Compression.

The subject of the ultimate strength design under combined loads is treated in detail in a later chapter.

A conservative interaction equation for combined bending, shear and axial load is,

$$(R_a + R_b)^2 + R_s^2 = 1$$

$$\text{or M.S.} = \frac{1}{\sqrt{(R_a + R_b)^2 + R_s^2}} - 1$$



Recall Long Beam Bending Stress Theory Assumes L/D > 10
Shear Dominates/Affects L/D < 5

Simple Static Shear Strength; Shear w/Preload

Olson, Sean M., ASTM, STP #1236, Structural Integrity of Fasteners: The Effect of a Tensile Load on the Ultimate Shear Capacity of a Fastener Shank, Editor Pir M. Toor, May 1995.

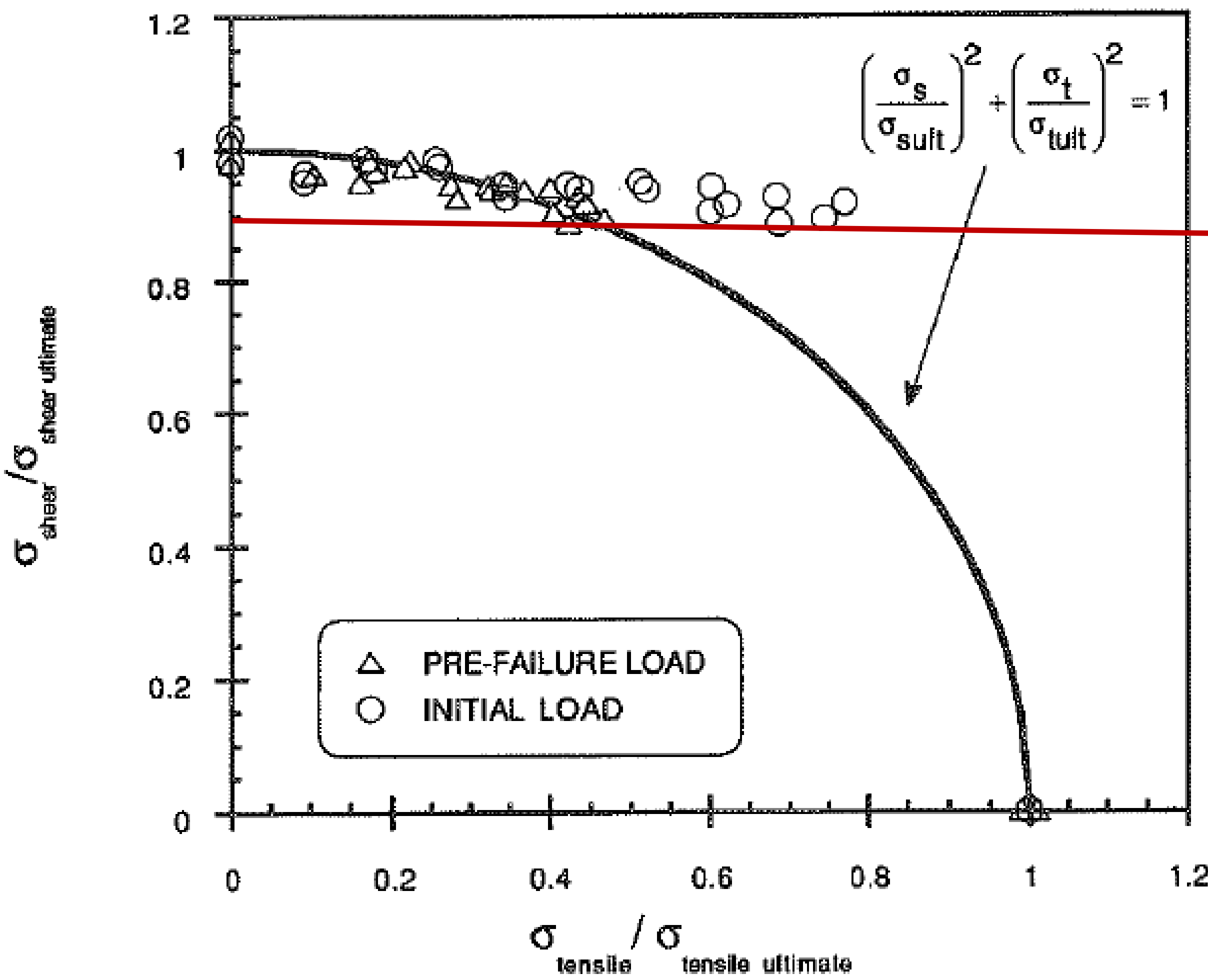


FIG. 9—*Ultimate shear stress versus nonconstant tensile stress for titanium.*

10% Reduction Suggested

Classic Fatigue Strength

- Fatigue Strength in Tension, Rarely in Shear
- Fastener Acceptance Limits of Some Use
- Base Material Data Hard to Apply (Marin Factors)
- K_f is key:
  - Rolled vs Cut Threads
  - Nut vs Turnbuckle Thread Loading

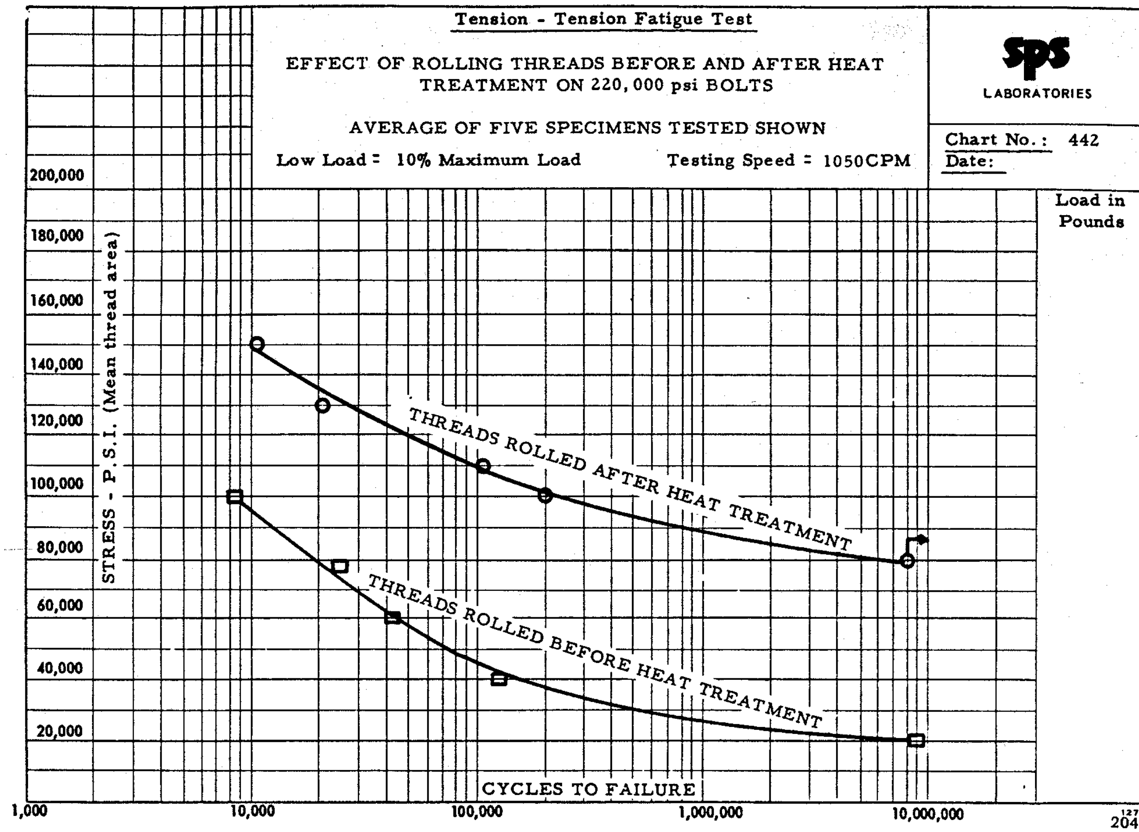
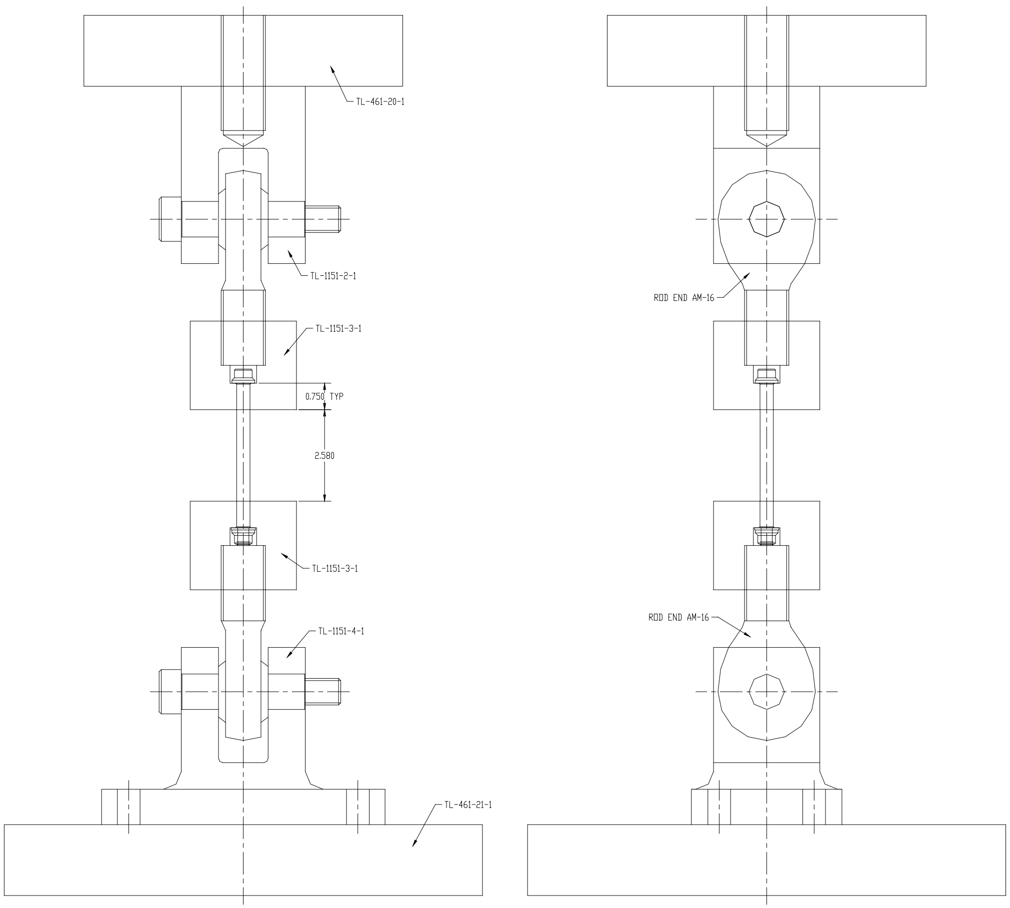


Fig. V-10

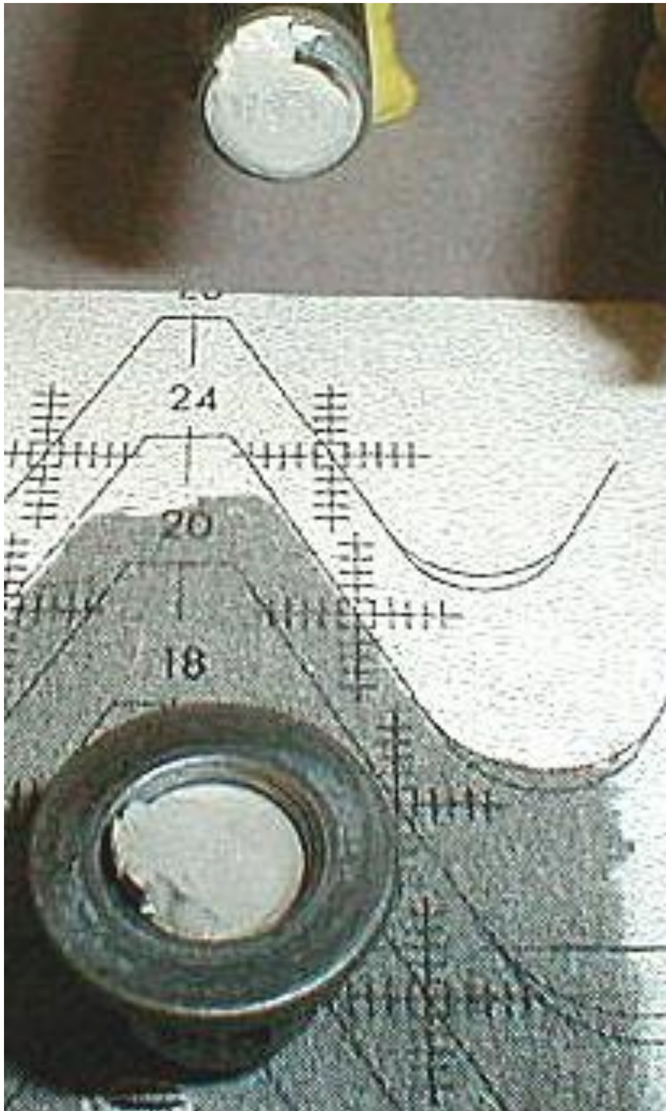
2256B

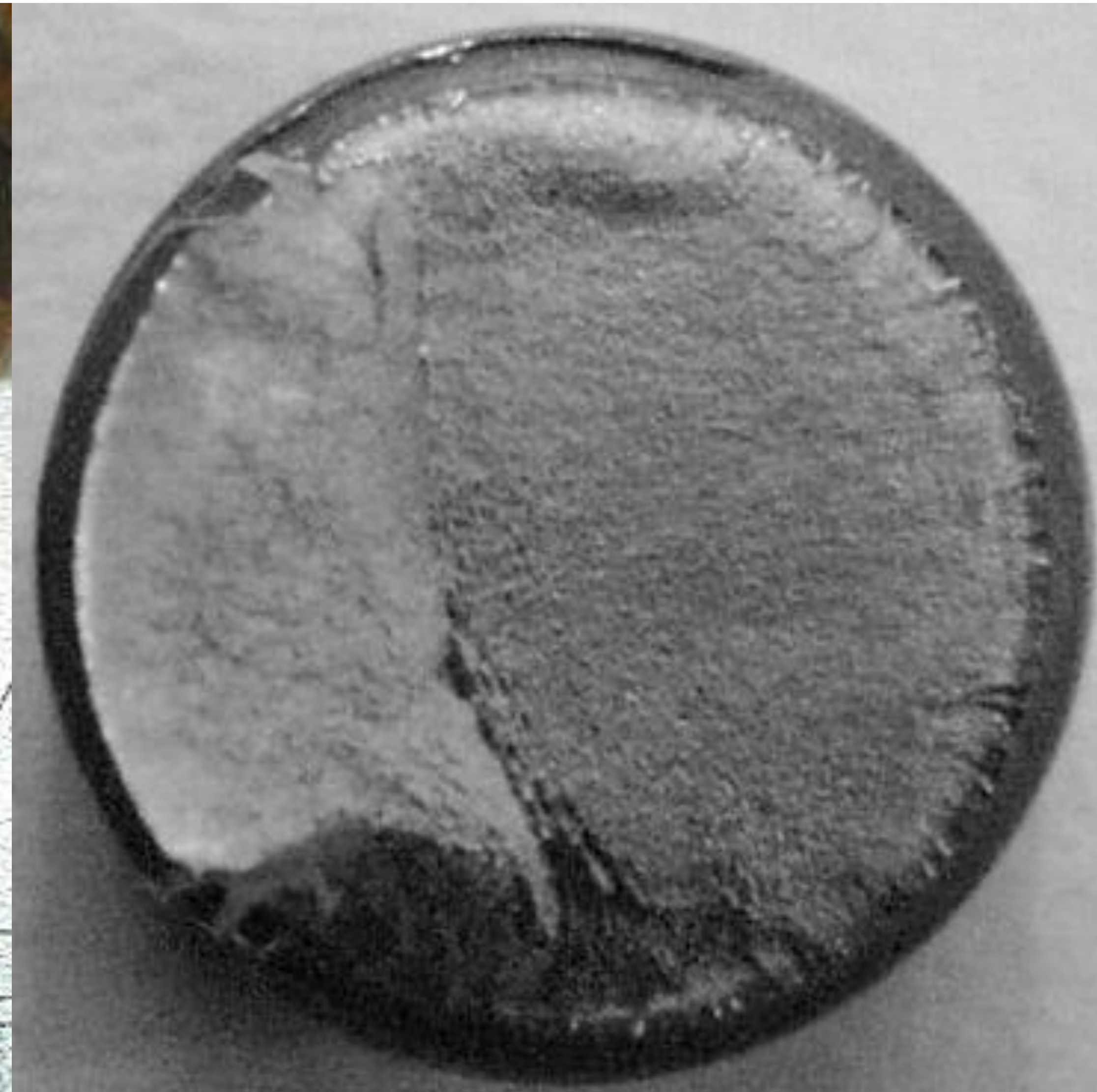
Test Lab, Machines, & Set Up

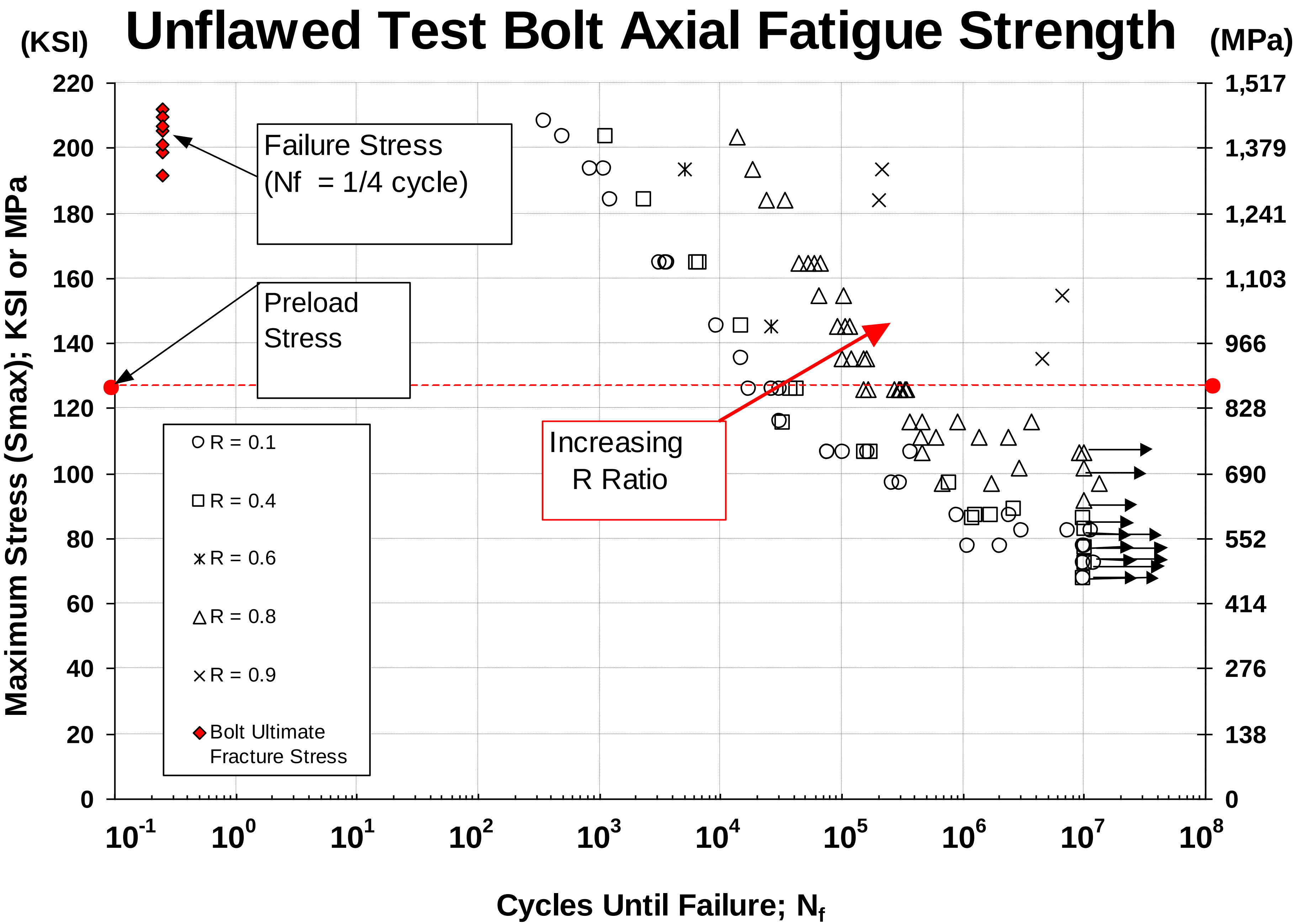


- **Std. Lab Air (N.I.S.T.)**
- **Instron 245 kN [55 Kip] or Custom 66.7 kN [15 Kip] Servohydraulic Test Machines**
- **Calibrated Load Cells**
- **Axial Fatigue Test**
  (≈ 5-9% Shank Bending)
  (Spherical Rod Ends)
- **Bolt Preload is Test Machine Controlled**

Fatigue Fractured Bolt



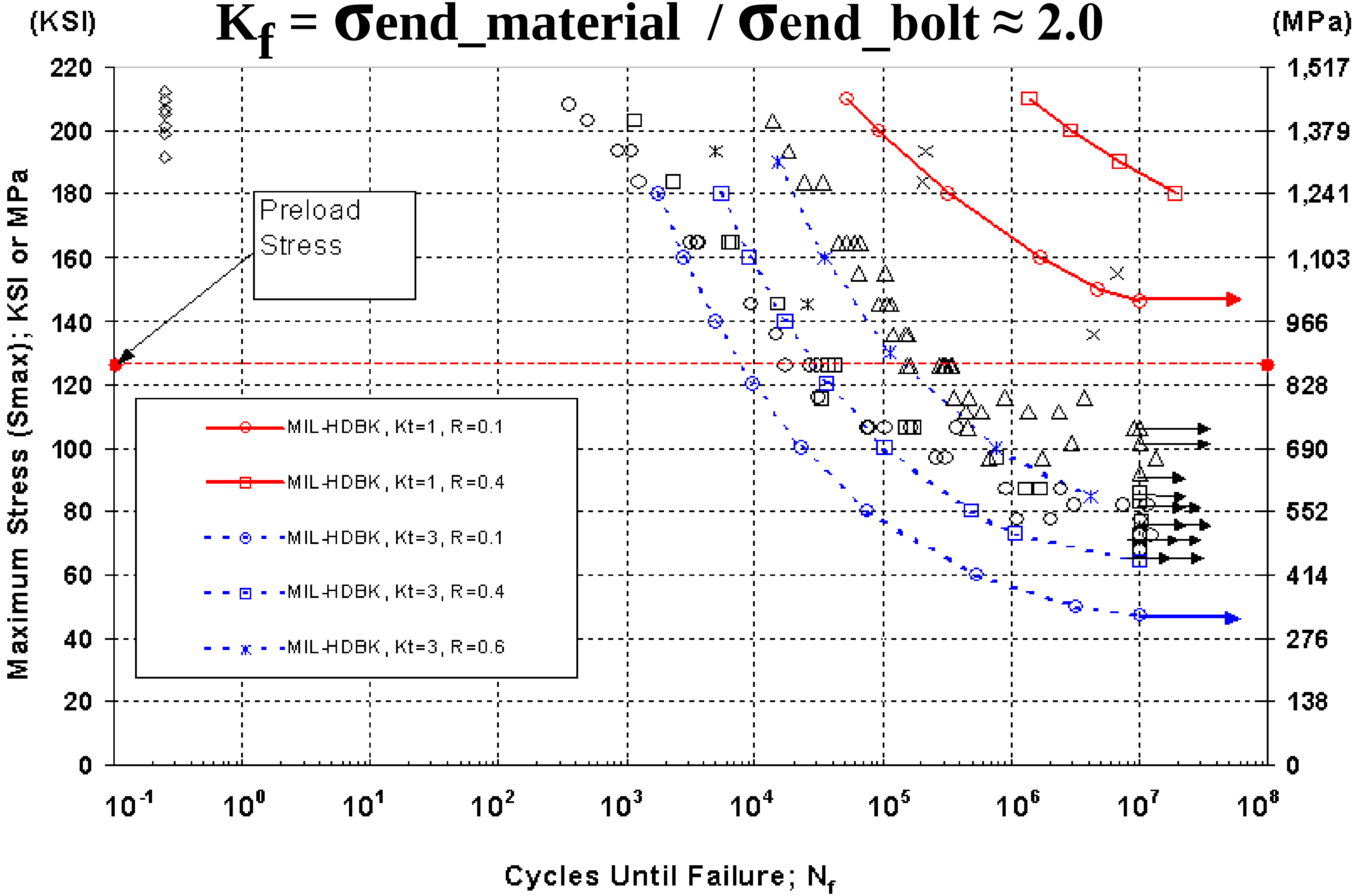




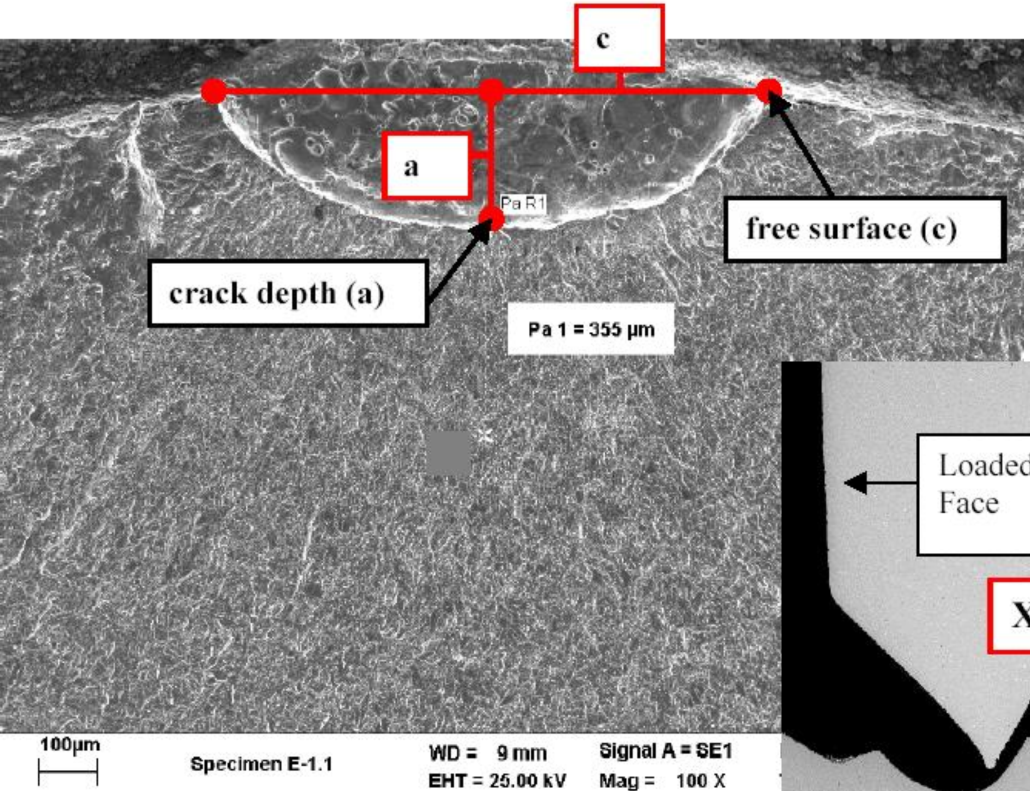
(KSI)
Unflawed Test Bolt Axial Fatigue Strength
(MPa)
Failure Stress
(Nf = 1/4 cycle)
Preload
Stress
Increasing
R Ratio
R = 0.1
R = 0.4
R = 0.6
R = 0.8
R = 0.9
Bolt Ultimate
Fracture Stress
Maximum Stress (Smax); KSI or MPa
Cycles Until Failure; N_f
220
200
180
160
140
120
100
80
60
40
20
0
1,517
1,379
1,241
1,103
966
828
690
552
414
276
138
0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}

Bolt Fatigue Strength w/Material Fatigue Strength

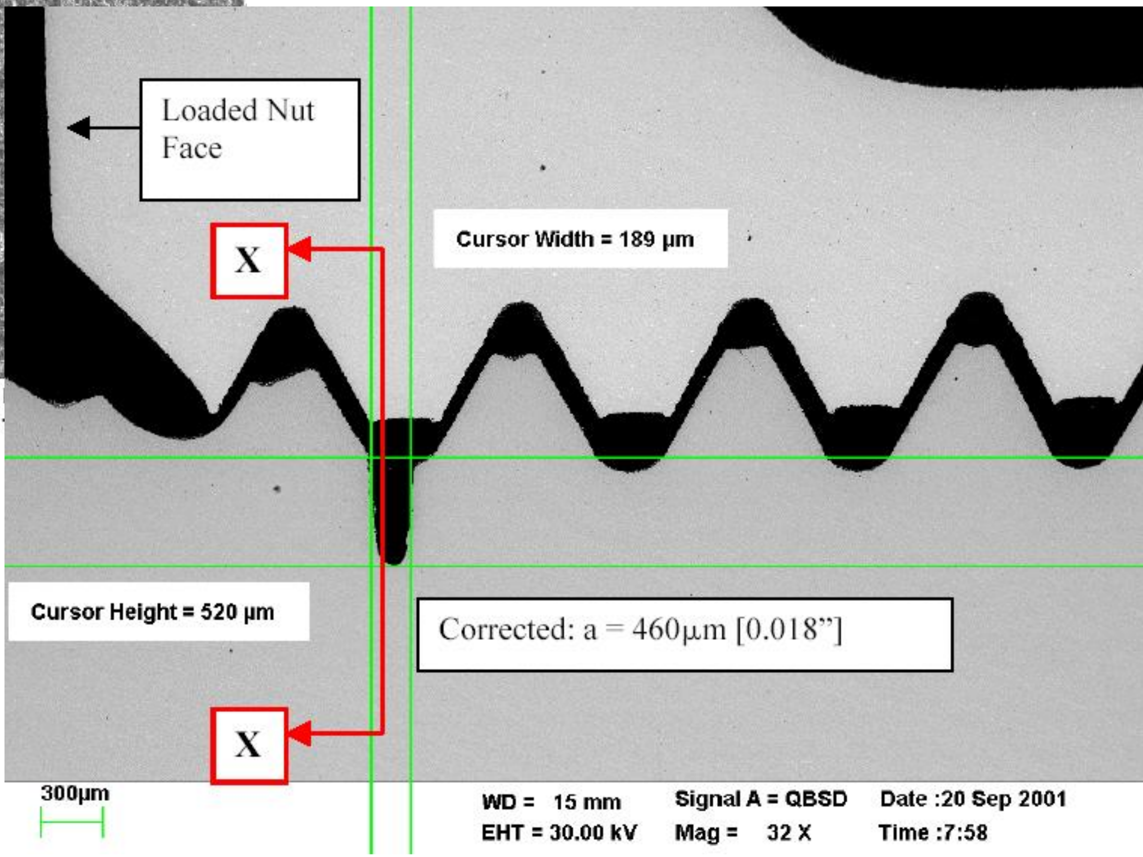
$$K_f = \sigma end\_material \;/\; \sigma end\_bolt \approx 2.0$$



EDM Flaw in Bolt Thread Root

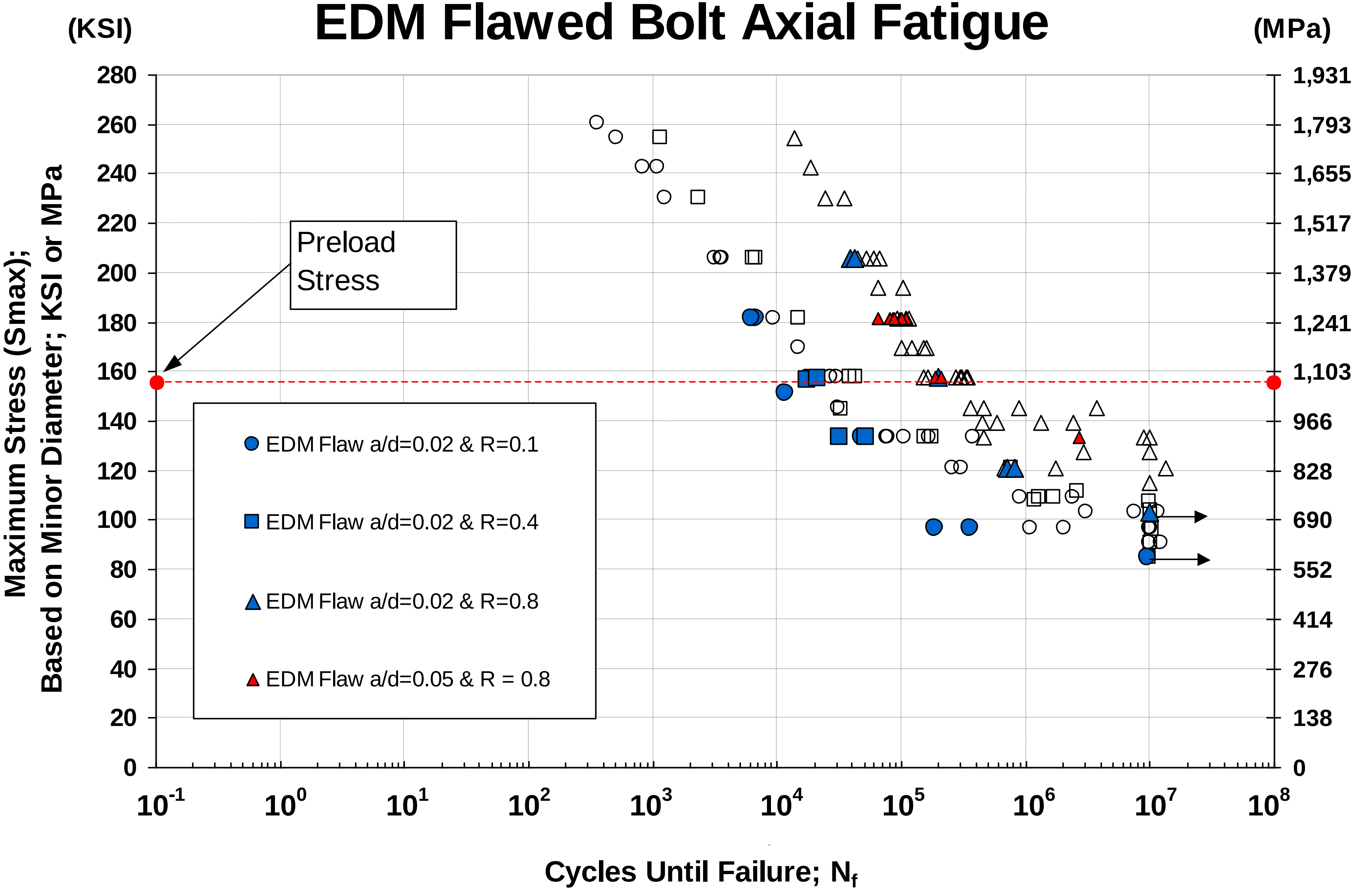


- 14 Initial EDM Flaws at a = 0.76-1.27 mm [0.03-0.05”]
- 20 Research EDM Flaws at a = 0.38 mm [0.015”]

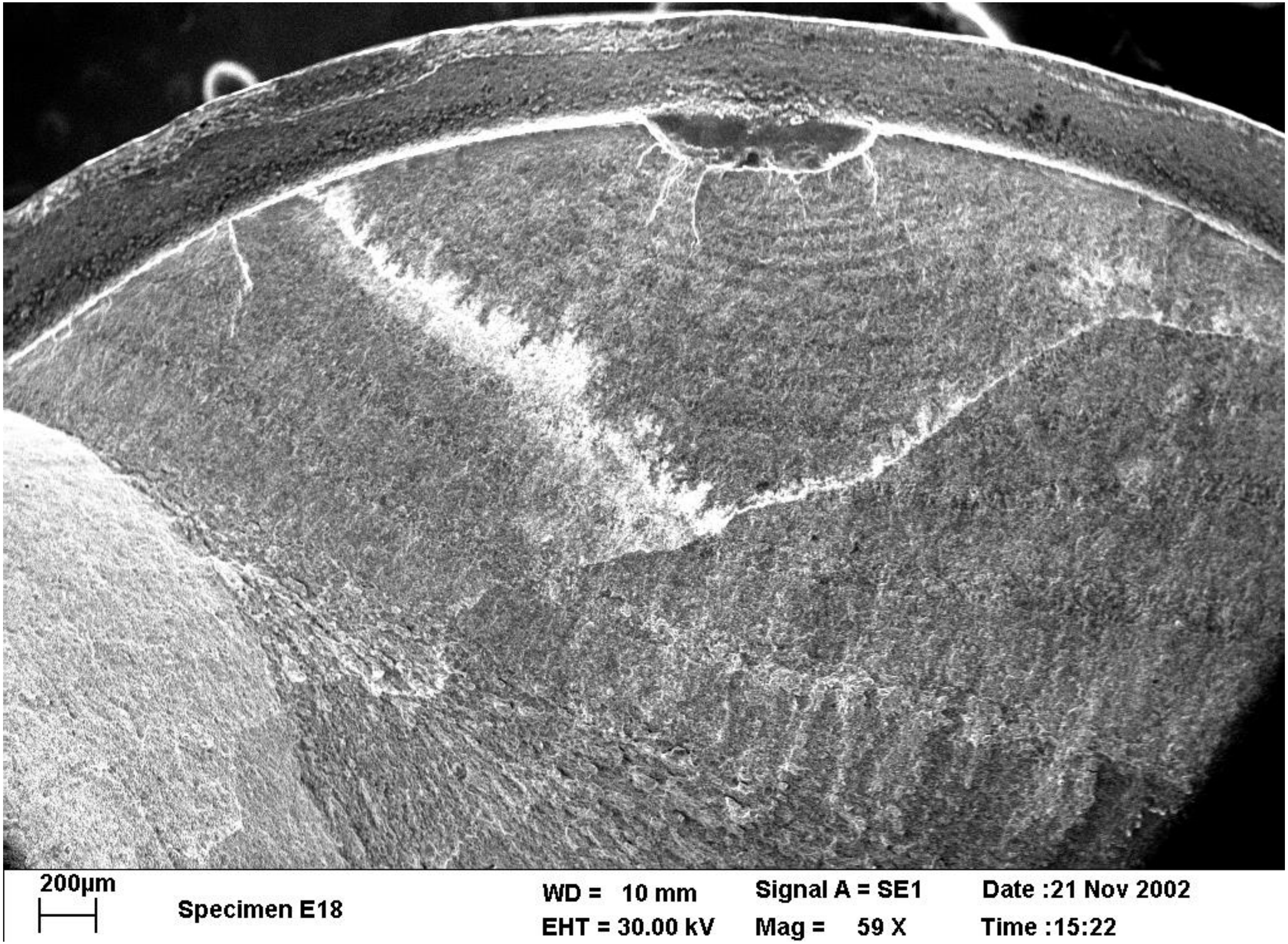


- All Flaw Depths
  < Residual Stress Depth

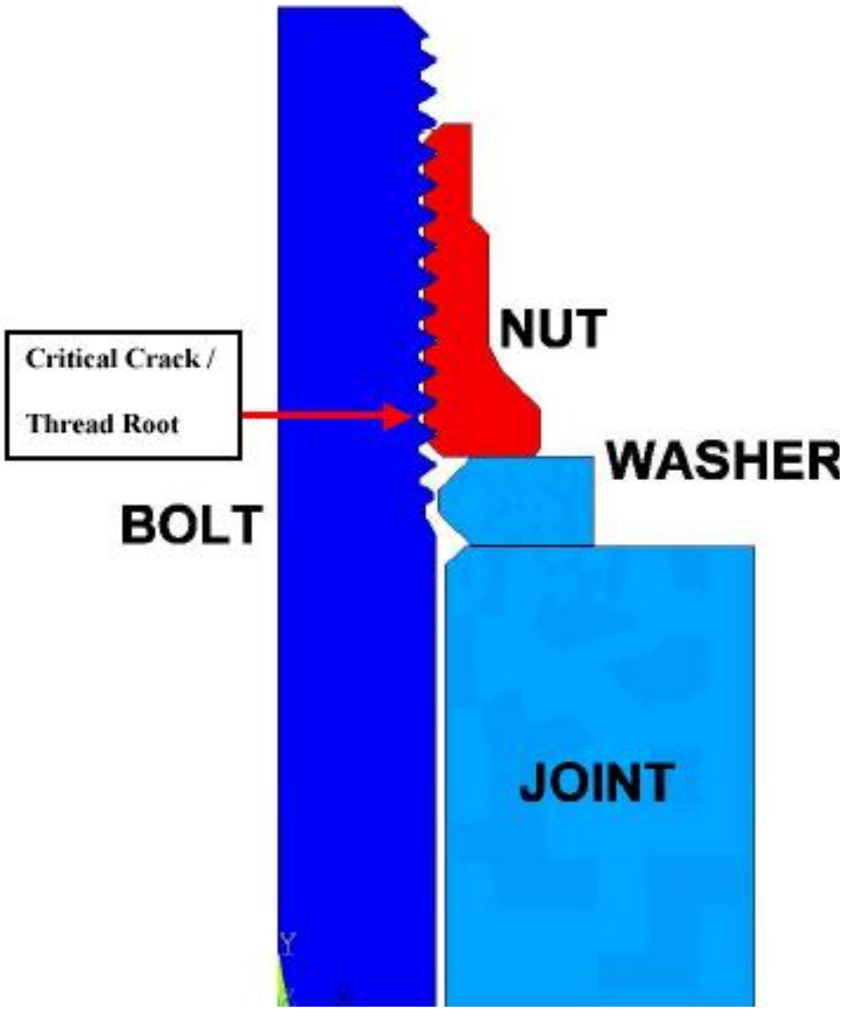
EDM Flawed Bolt Axial Fatigue



Marker Bands on EDM Flawed Bolt



Need for Y(a) and How its Used



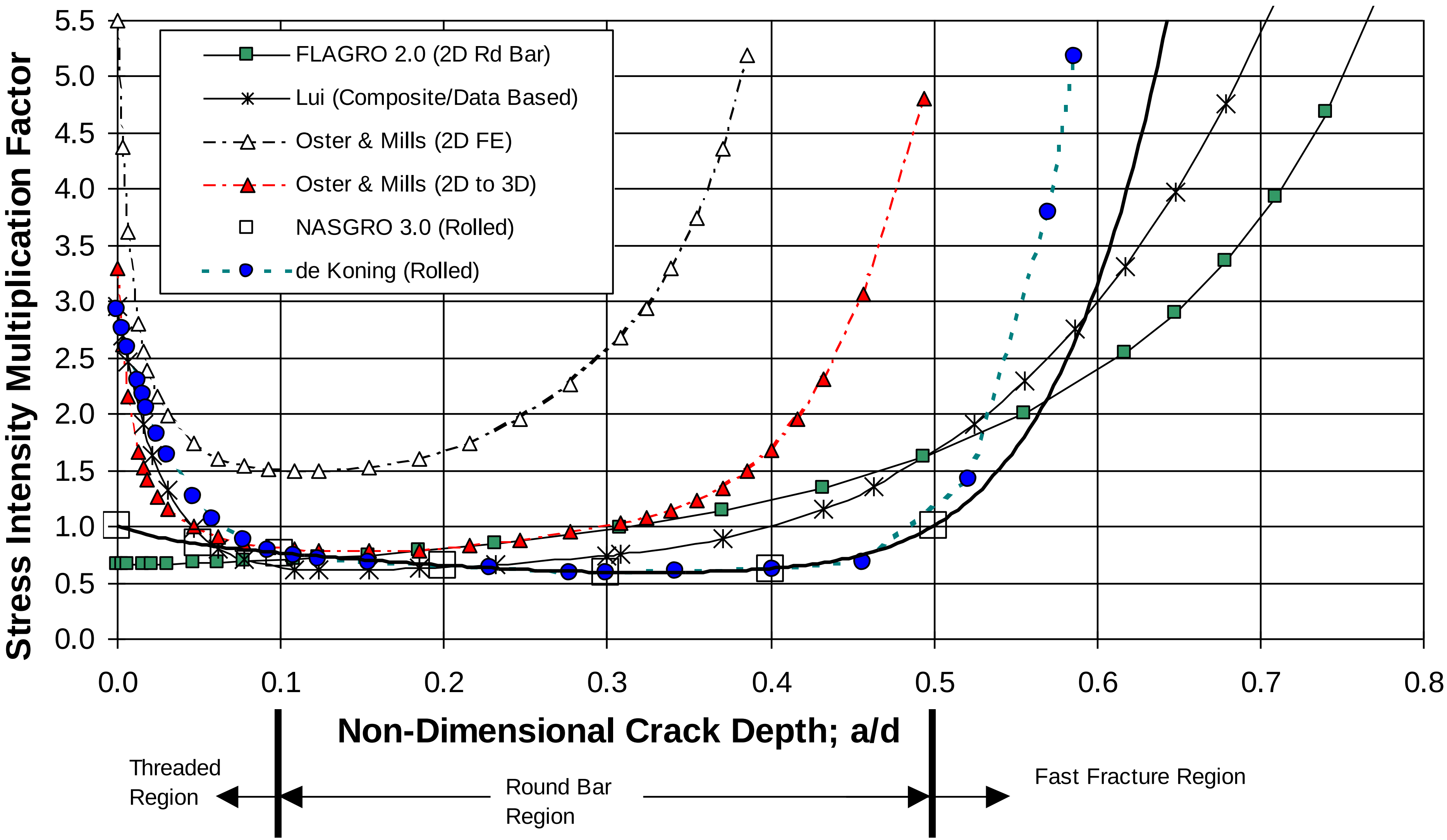
$$\frac{da}{dN} = C\left[\frac{\Delta K}{(1-R)^{(1-m)}}\right]^n$$

$$\Delta K(a) = \Delta\sigma Y(a)\sqrt{\pi a}$$

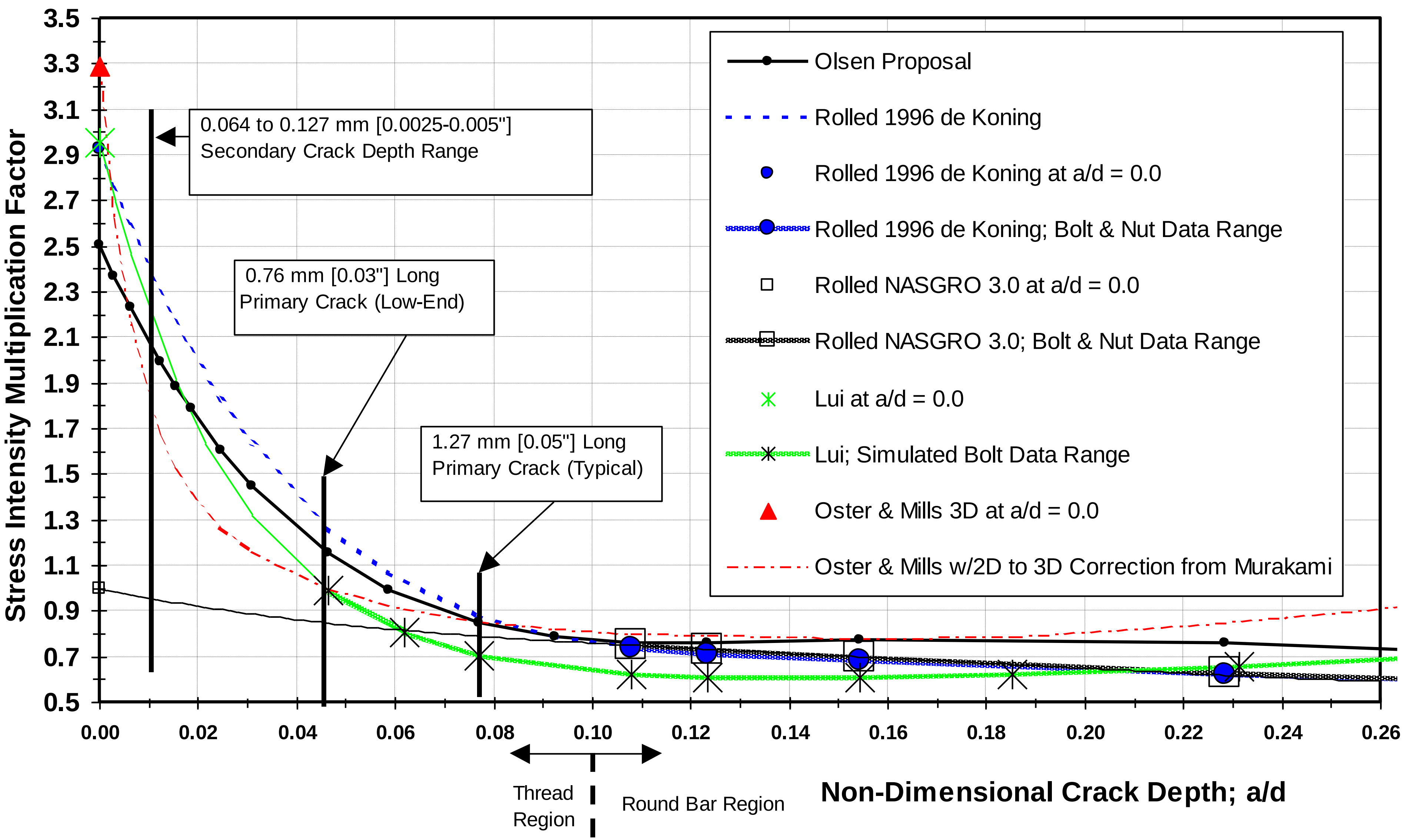
** Y(a) is primary unknown for characterized materials

Current Y(a/d) Prediction Methods

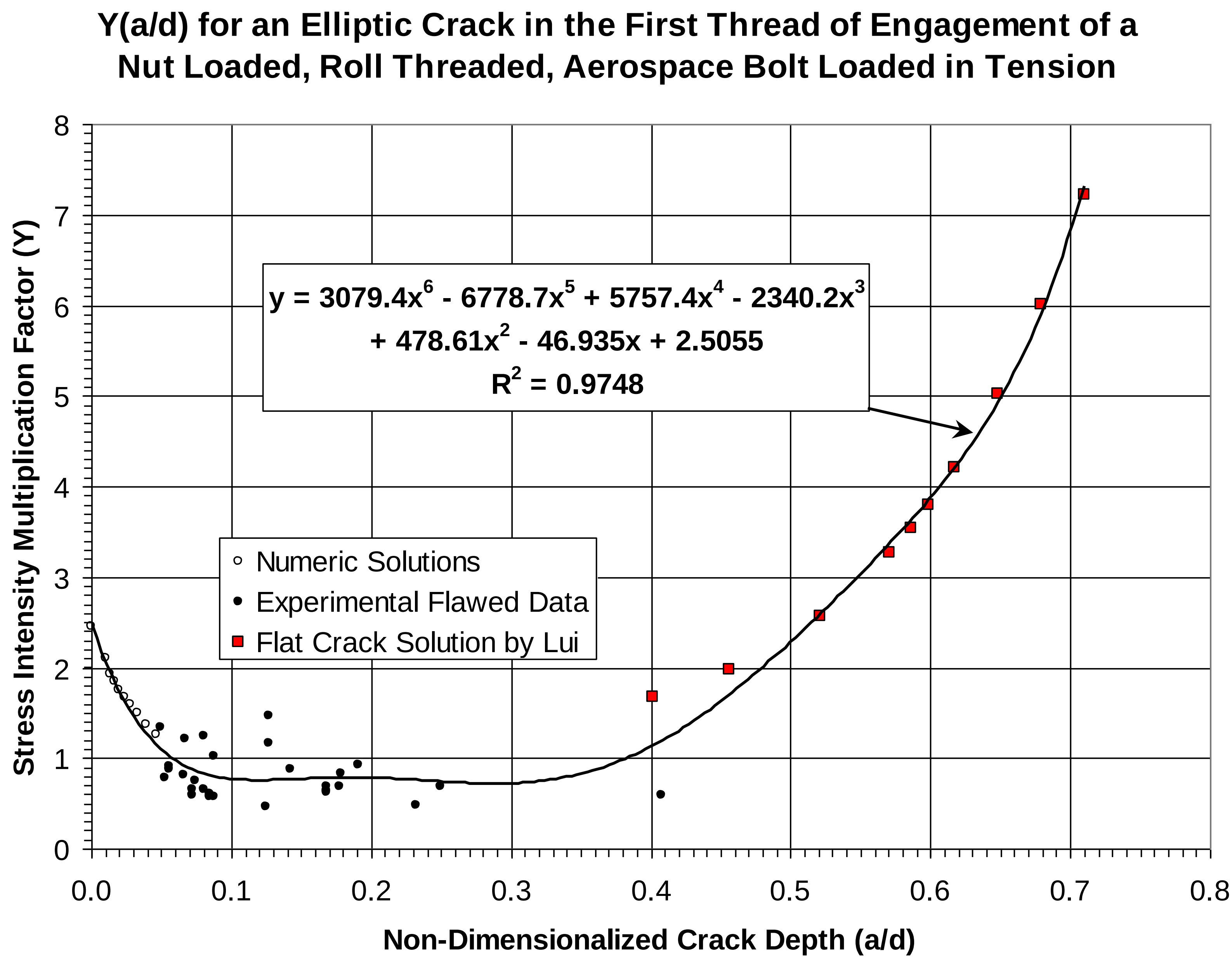
Stress Intensity Multiplication Factor vs Crack Depth



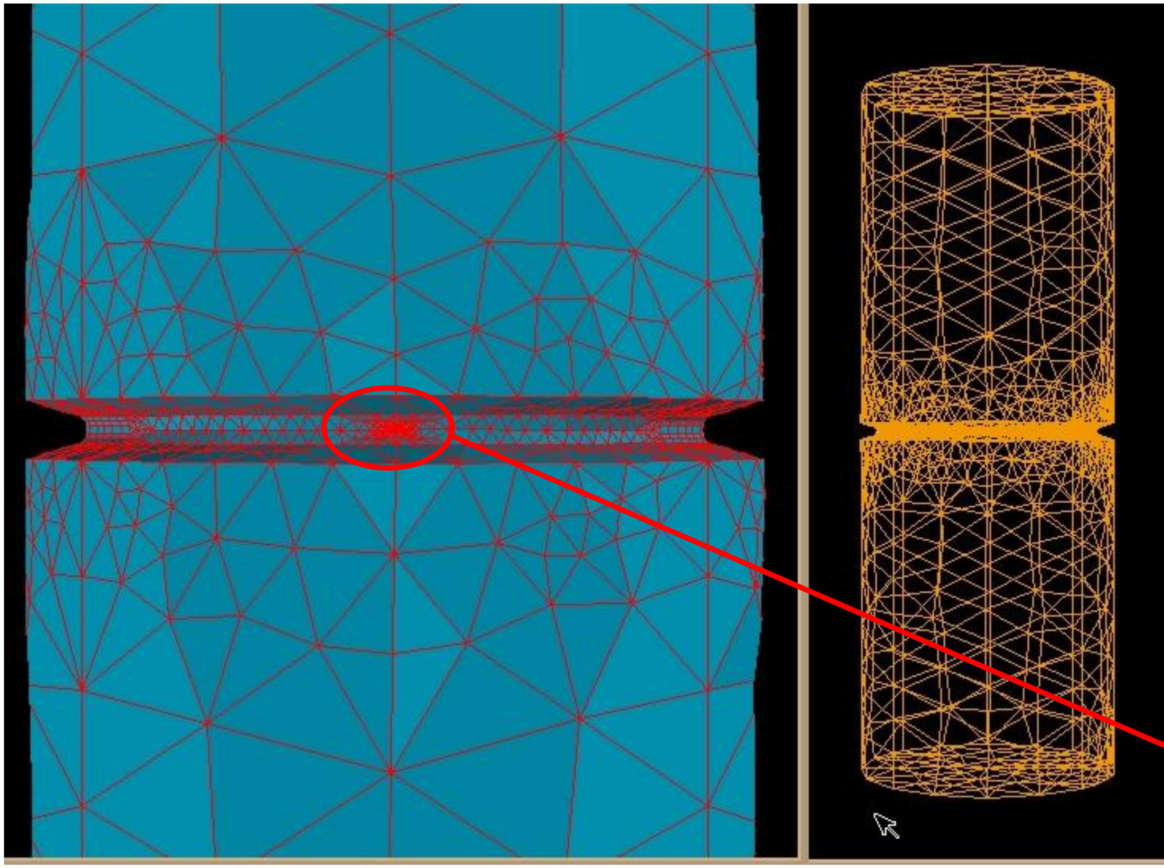
Current Y(a/d) Prediction Methods

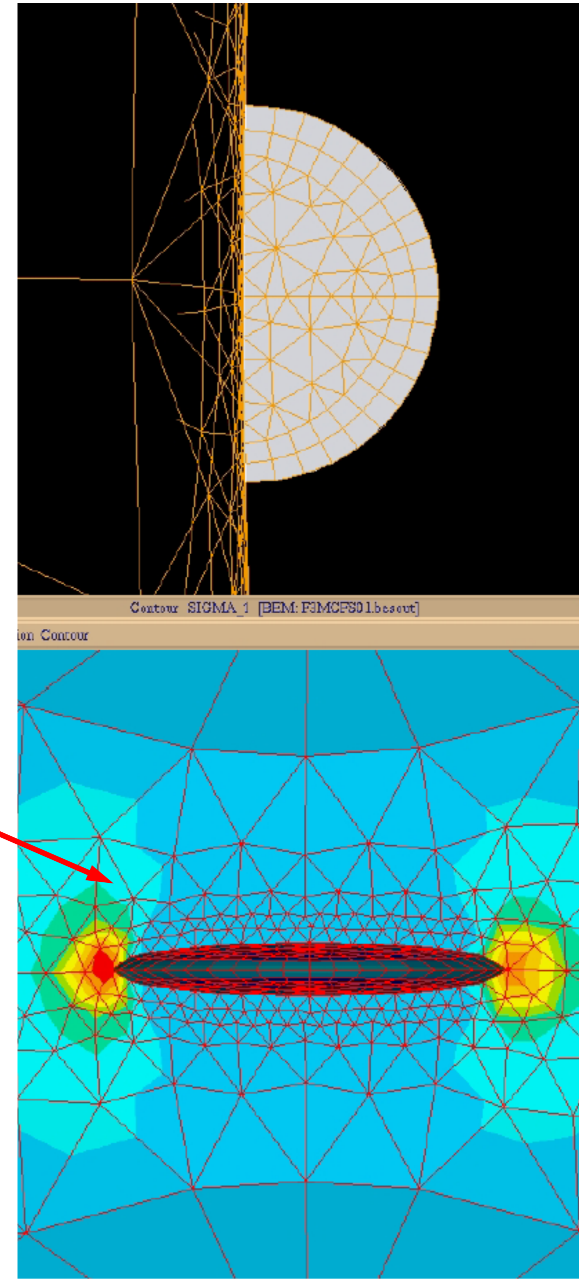


Y(a/d) for an Elliptical Crack



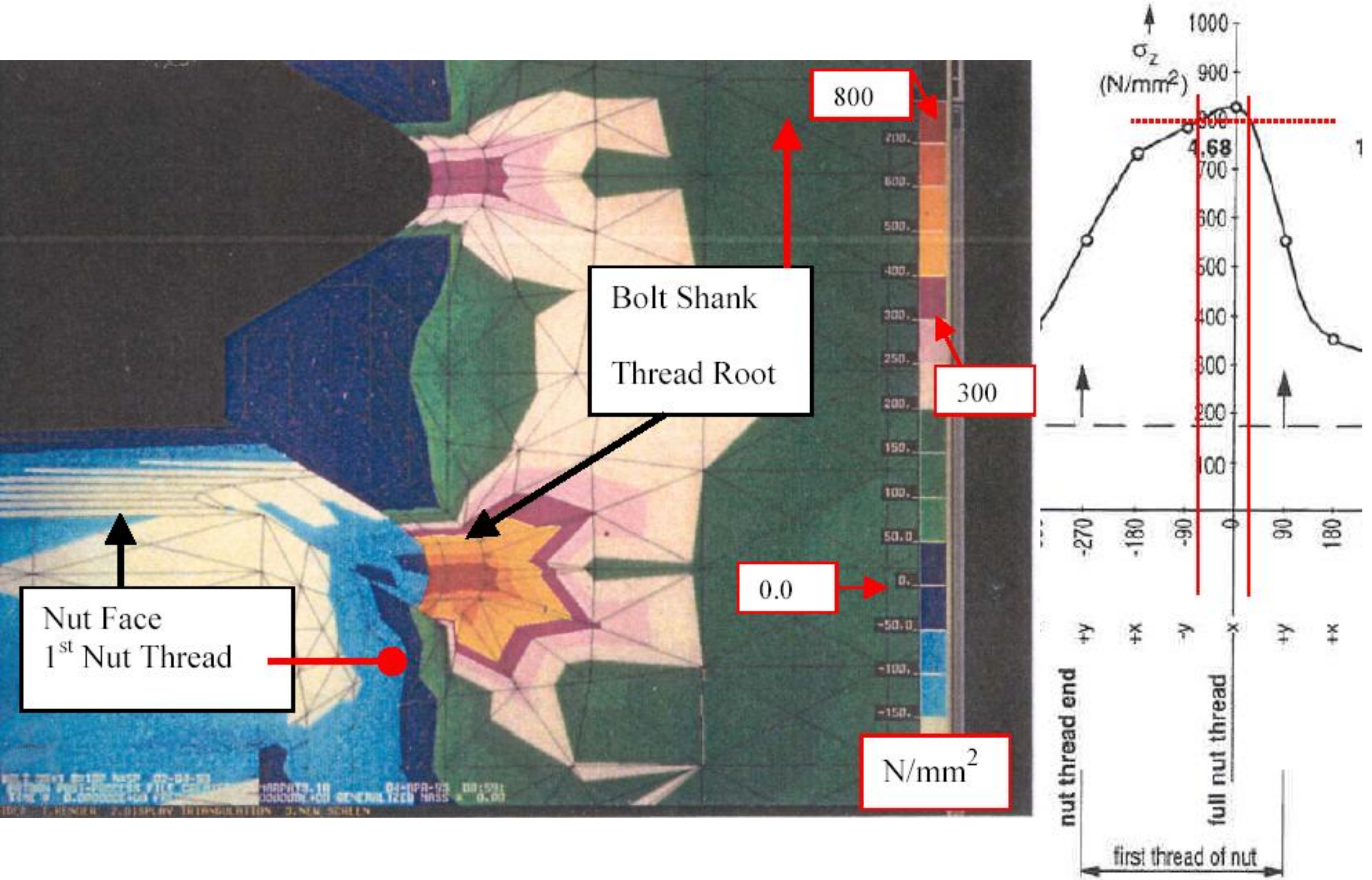
BE Model & Installed Crack



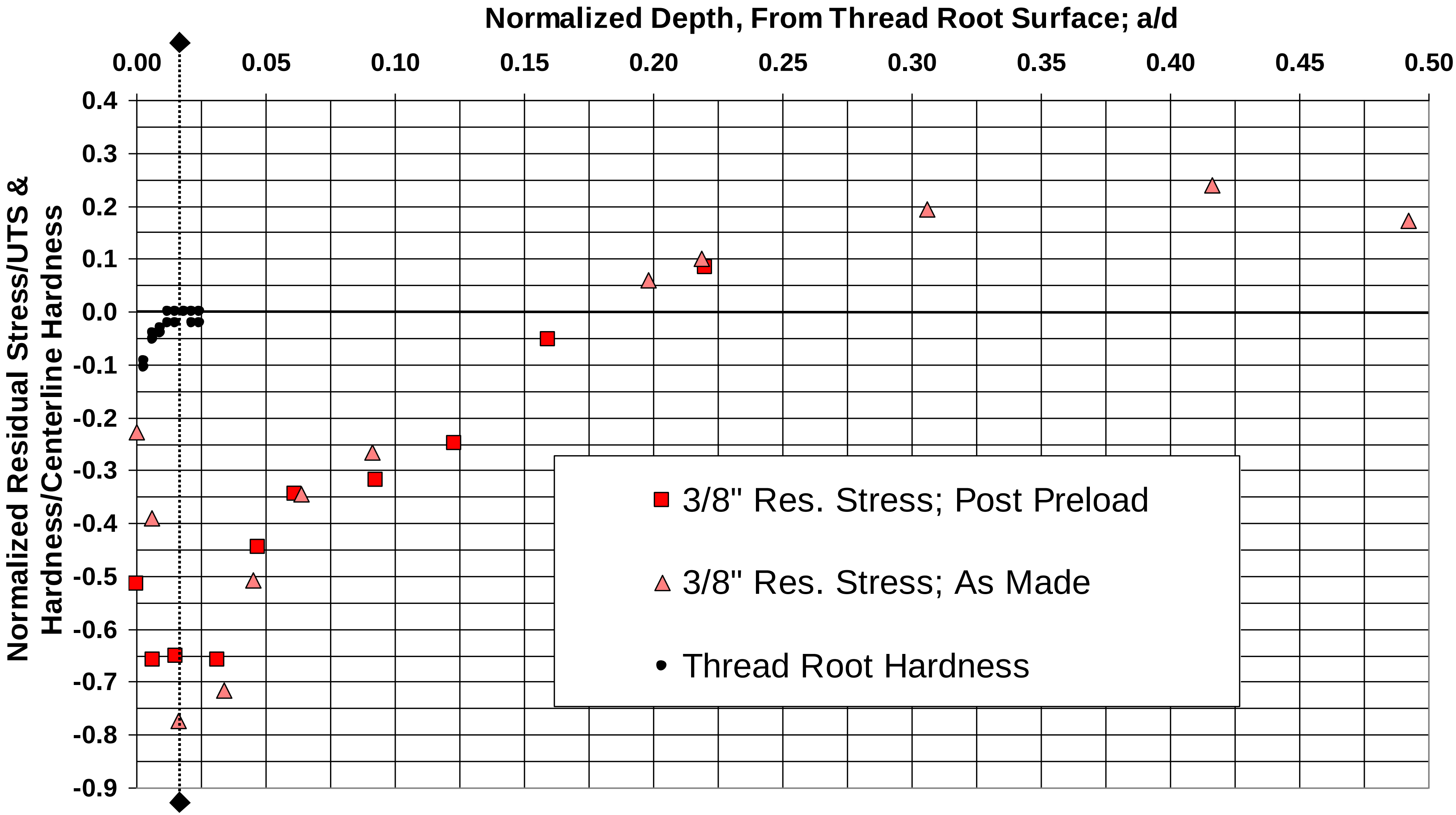


- **Test Bolt Dimensions & Material**
- **Notched Right Cylinder**
- **a/d = 0.009 (a = 0.076 mm [0.003”])**
- **Crack Face Loading (Superposition)**

3D FEA Stress Field for Superposition



Axial Residual Stress & Hardness



Conclusions

1. **Find ALL Possible Data or Create it**
2. **Test for Full & Repetitive Preload Response**
3. **Analyze & Test Each Joint (Logically)**
4. **There are NEW Methods in Public Domain**
5. **We NEED better Data & Methods**
6. **Bonus: Know the Certification Rules**

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Fixed Wing Engineering
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Ph.D. Dissertation: "Fatigue crack growth analyses and experimental verification of aerospace threaded fasteners," Case Western Reserve University, August 2004.

ASTM, STP #1487, *Structural Integrity of Fastener, Vol. 3*, Fatigue crack growth analyses of aerospace threaded fasteners; Part I: State-of-bolt crack growth analyses methods.
ASTM, STP #1487, *Structural Integrity of Fastener, Vol. 3*, Fatigue crack growth analyses of aerospace threaded fasteners; Part II: Material/stress state and bolt strength.
ASTM, STP #1487, *Structural Integrity of Fastener, Vol. 3*, Fatigue crack growth analyses of aerospace threaded fasteners; Part III: Experimental crack growth behavior.
ASTM, STP #1487, *Structural Integrity of Fastener, Vol. 3*, Fatigue crack growth analyses of aerospace threaded fasteners; Part IV: Numeric analyses and synthesis of all results.

Page 30 *Kirk W. Olsen © 2021*

FAA CFR Part 25
“The Rules” for Bolts

FAA 14 CFR Part 25.607 Fasteners (The Rules)

§ 25.607 Fasteners.

(a) Each ***removable*** bolt, screw, nut, pin, or other removable fastener must ***incorporate two separate locking devices if*** —

(1) Its loss could preclude continued flight and landing within the design limitations of the airplane using normal pilot skill and strength; or

(2) Its loss could result in reduction in pitch, yaw, or roll control capability or response below that required by Subpart B of this chapter.

(b) The fasteners ***specified in paragraph (a)*** of this section and their locking devices ***may not be adversely affected*** by the environmental conditions associated with the particular installation.

(c) No self-locking nut may be used on any ***bolt subject to rotation*** in operation ***unless a nonfriction locking device is used in addition*** to the self-locking device.

[Amdt. 25–23, 35 FR 5674, Apr. 8, 1970]

25.607 Removable Fasteners Summary

CFR 25.607 Thread Locking Minimums

Joint Types:	**Rotational**	**Not Rotational**
Critical	Physical & Friction	Any Two
Not Critcal	Only Physical	Any One

Note: 25.607 does not require bolt-in-bolt

Schmidt's Law #12

"The bolts are always the weak link in any design."

FAA Part 25.603 Materials

§ 25.603 Materials.

The ***suitability and durability of materials*** used for parts, the failure of which could adversely ***affect safety***, ***must*** —

(a) ***Be established*** on the basis of ***experience or tests***;

(b) ***Conform to approved specifications*** (such as industry or military specifications, or Technical Standard Orders) that ***ensure their having the strength*** and other properties assumed in the design data; and

(c) Take into ***account the effects of environmental*** conditions, such as temperature and humidity, expected in service.

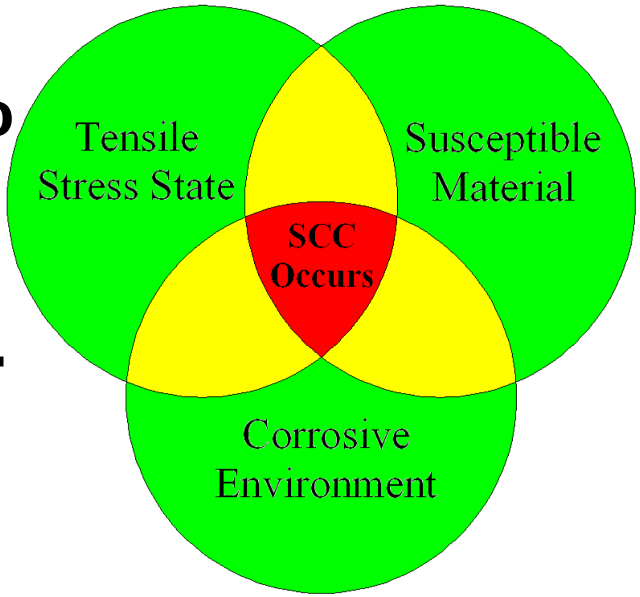
[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25–38, 41 FR 55466, Dec. 20 1976; Amdt. 25–46, 43 FR 50595, Oct. 30, 1978]

25.603 Materials – Discussion

Always check for Advisory Circulars:
http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgAdvisoryCircular.nsf/MainFrame?OpenFrameSet
This process is rather tedious, but must be done, not all are as simple as looking for 25.603.

The only AC I found for 603 was: AC20-127 from 1987: SAE H11 Bolts should not be used due to SCC. If you come across their use you should read this AC and likely you'll need to change any hardware made of SAE H11 material.

Note: Bolts & Nuts, due to their threads and tensile preloads, are primary worries for SCC concerns.



25.603 Good Materials for Heat?
Peak normal use? Coincident fire & ultimate?

FAA Part 25.609 Protection of Structure

§ 25.609   Protection of structure.

Each part of the structure must—

(a) Be ***suitably protected against deterioration*** or loss of strength in service ***due to any cause***, including—

(1) Weathering;

(2) Corrosion; and

(3) Abrasion; and

(b) Have provisions for ***ventilation and drainage*** where necessary for protection.

Note: I could find no ACs which applied to 25.609

25.613 Material Strength Properties and Design Values

§ 25.613 Material strength properties and material design values.

(a) Material strength properties must be based on enough tests of material meeting approved specifications to establish design values on a statistical basis.

(b) Material design values must be chosen to minimize the probability of structural failures due to material variability. Except as provided in paragraphs (e) and (f) of this section, compliance must be shown by selecting material design values which assure material strength with the following probability:

(1) Where applied loads are eventually distributed through a single member within an assembly, the failure of which would result in loss of structural integrity of the component, 99 percent probability with 95 percent confidence.

(2) For redundant structure, in which the failure of individual elements would result in applied loads being safely distributed to other load carrying members, 90 percent probability with 95 percent confidence.

(c) The effects of environmental conditions, such as temperature and moisture, on material design values used in an essential component or structure must be considered where these effects are significant within the airplane operating envelope.

(d) [Reserved]

(e) Greater material design values may be used if a "premium selection" of the material is made in which a specimen of each individual item is tested before use to determine that the actual strength properties of that particular item will equal or exceed those used in design.

(f) Other material design values may be used if approved by the Administrator.

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25–46, 43 FR 50595, Oct. 30, 1978; Amdt. 25–72, 55 FR 29776, July 20, 1990; Amdt. 25–112, 68 FR 46431, Aug. 5, 2003]

From 25.613 to AC 25.613-1 to MMPDS

(1) Where applied loads are eventually distributed through a single member within an assembly, the failure of which would result in loss of structural integrity of the component, 99 percent probability with 95 percent confidence.

•The A and B properties published in MMPDS (MIL-HDBK-5) or ESDU 00932 are acceptable, as are the statistical methods specified in the applicable chapters/sections of those handbooks. Other methods of developing material design values may be acceptable to the FAA.

A Basis (99%) for Single Load Path Structure

or B Basis (95%) for Redundant Structure

***A-Basis*.—**The lower of either a statistically calculated number, or the specification minimum (S-basis). The statistically calculated number indicates that at least 99 percent of the population of values is expected to equal or exceed the A basis mechanical design property, with a confidence of 95 percent.

***B-Basis*.—**At least 90 percent of the population of values is expected to equal or exceed the B-basis mechanical property allowable, with a confidence of 95 percent.

***S-Basis*.—**The S-value is the minimum property value specified by the governing industry specification (as issued by standardization groups such as SAE Aerospace Materials Division, ASTM, etc.) or federal or military standards for the material. (See MIL-STD-970 for order of preference for specifications.) For certain products heat treated by the user (for example, steels hardened and tempered to a designated *Ftu*), the Svalue may reflect a specified quality-control requirement. **Statistical assurance associated with this value is not known.**

AC for 25.613 Material Strength Properties and Design Values

- AC No: 25.613-1
- Material Strength Properties. Material properties that define the strength related characteristics which are ultimate and yield values for compression, tension, bearing, shear, etc.
Material Design Values. Material strength properties that have been established based on the requirements of § 25.613 (b), or by other means as defined in this AC. These values are generally statistically determined based on enough data that, when used for design, the probability of structural failure due to material variability will be minimized. Typical values for moduli are used.

- Statistically Based Design Values. Design values required by § 25.613 should be based on sufficient testing to assure a high degree of confidence in the values. In all cases, a statistical analysis of the test data should be performed. (90-95% CI 99% P).

- The A and B properties published in MMPDS (MIL-HDBK-5) or ESDU 00932 are acceptable, as are the statistical methods specified in the applicable chapters/sections of those handbooks. Other methods of developing material design values may be acceptable to the FAA.

- The test specimens used for material property certification testing should be made from material produced using production processes. Test specimen design, test methods, and testing should:

    - (a) Conform to (ASTM), (EN), (ISO), or other national standards acceptable to the FAA

    - (b) Conform to those chapters/sections of MMPDS, MIL-HDBK-17, ESDU 00932, or other handbooks.

    - (c) Be accomplished in accordance with an approved test plan which includes definition of test specimens and test methods. This provision would be used, for example, when the material design values are to be based on tests that include effects of specific geometry and design features as well as material.

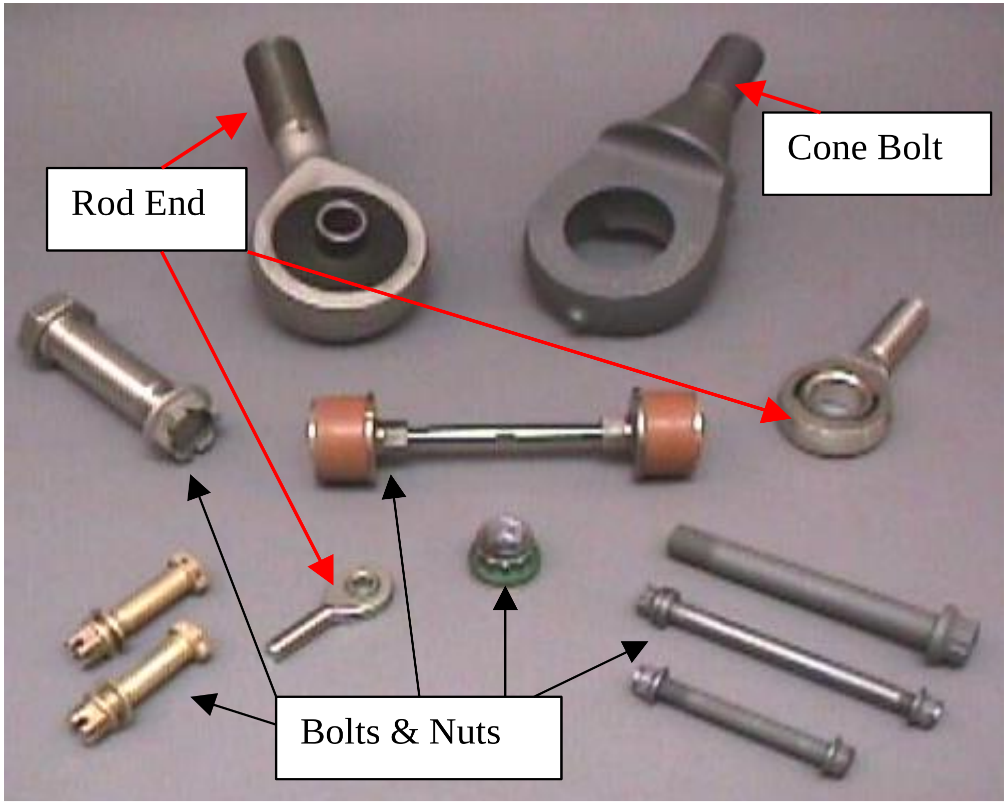
- The FAA may approve the use of other material test data after review of test specimen design, test methods, and test procedures that were used to generate the data.

- Consideration of Environmental Conditions. The material strength properties of a number of materials, such as non-metallic composites and adhesives, can be significantly affected by temperature as well as moisture absorption. For these materials, the effects of temperature and moisture should be accounted for in the determination and use of material design values.

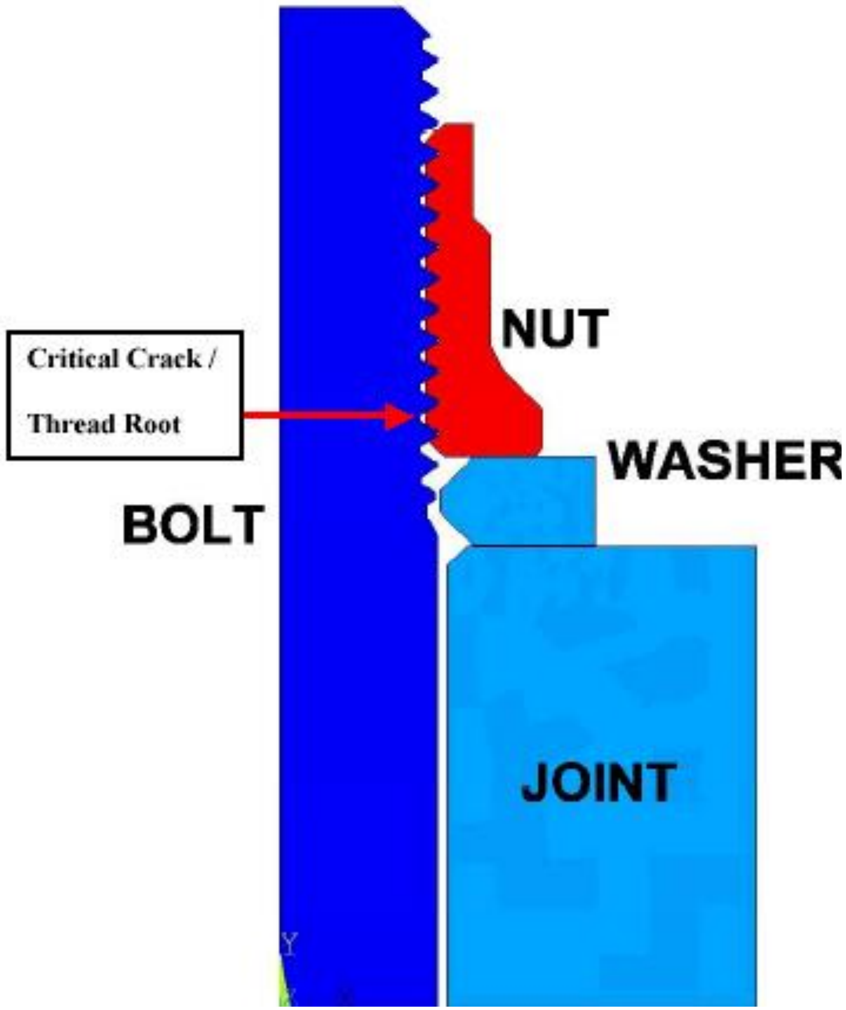
Bolt Crack Growth
Previous ASTM
& Ph. D. Published Work

Why? Roll-Threaded Bolt Fatigue Crack Growth Analyses are Required in Aerospace Design

- **100,000+ Fasteners/Aircraft**
- **Flight Safety Critical**
- **Static, Fatigue & Damage Tolerant Analyses are FAA Mandated**



Need for Y(a) and How its Used



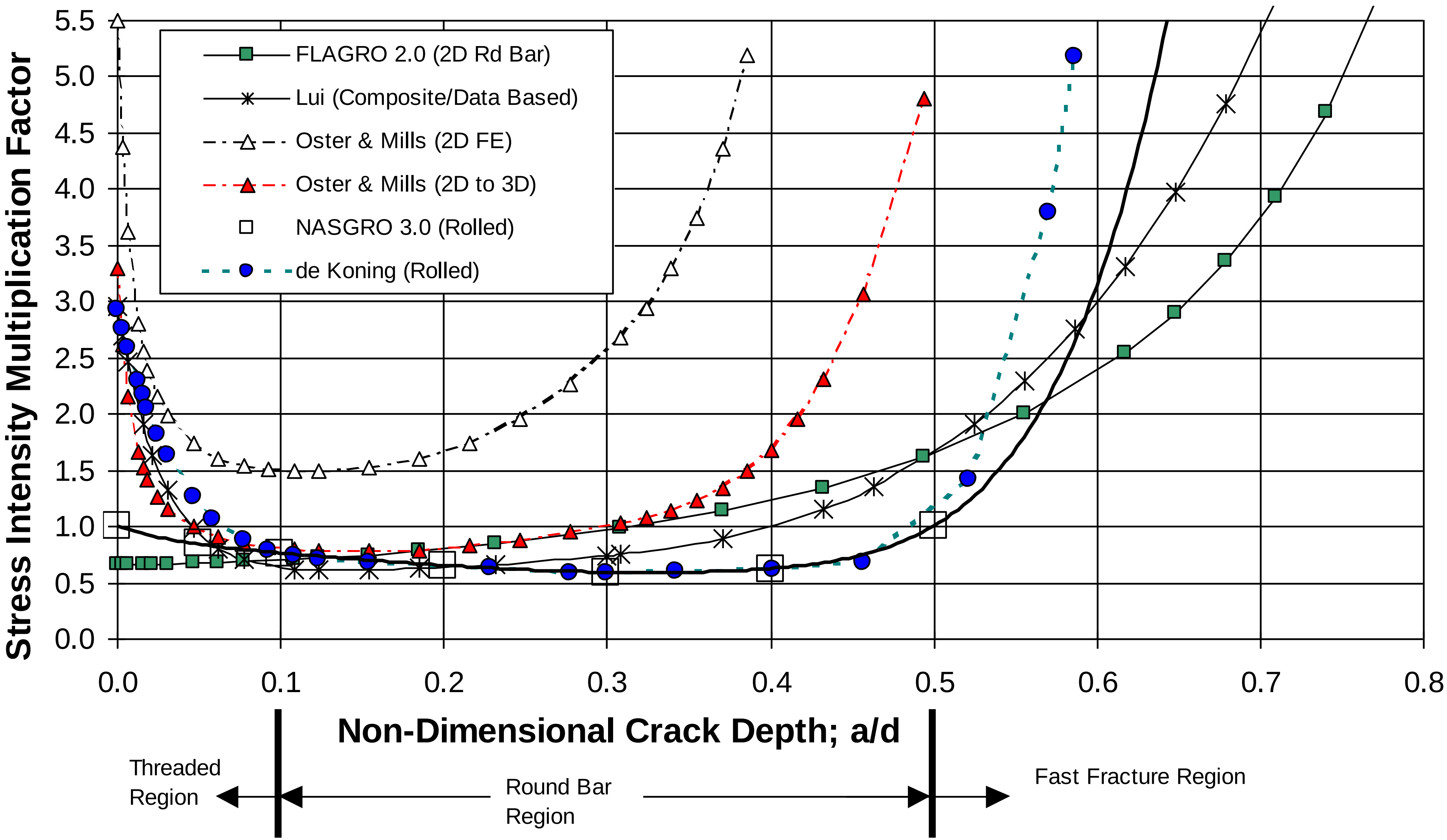
$$\frac{da}{dN} = C\left[\frac{\Delta K}{(1-R)^{(1-m)}}\right]^n$$

$$\Delta K(a) = \Delta\sigma Y(a)\sqrt{\pi a}$$

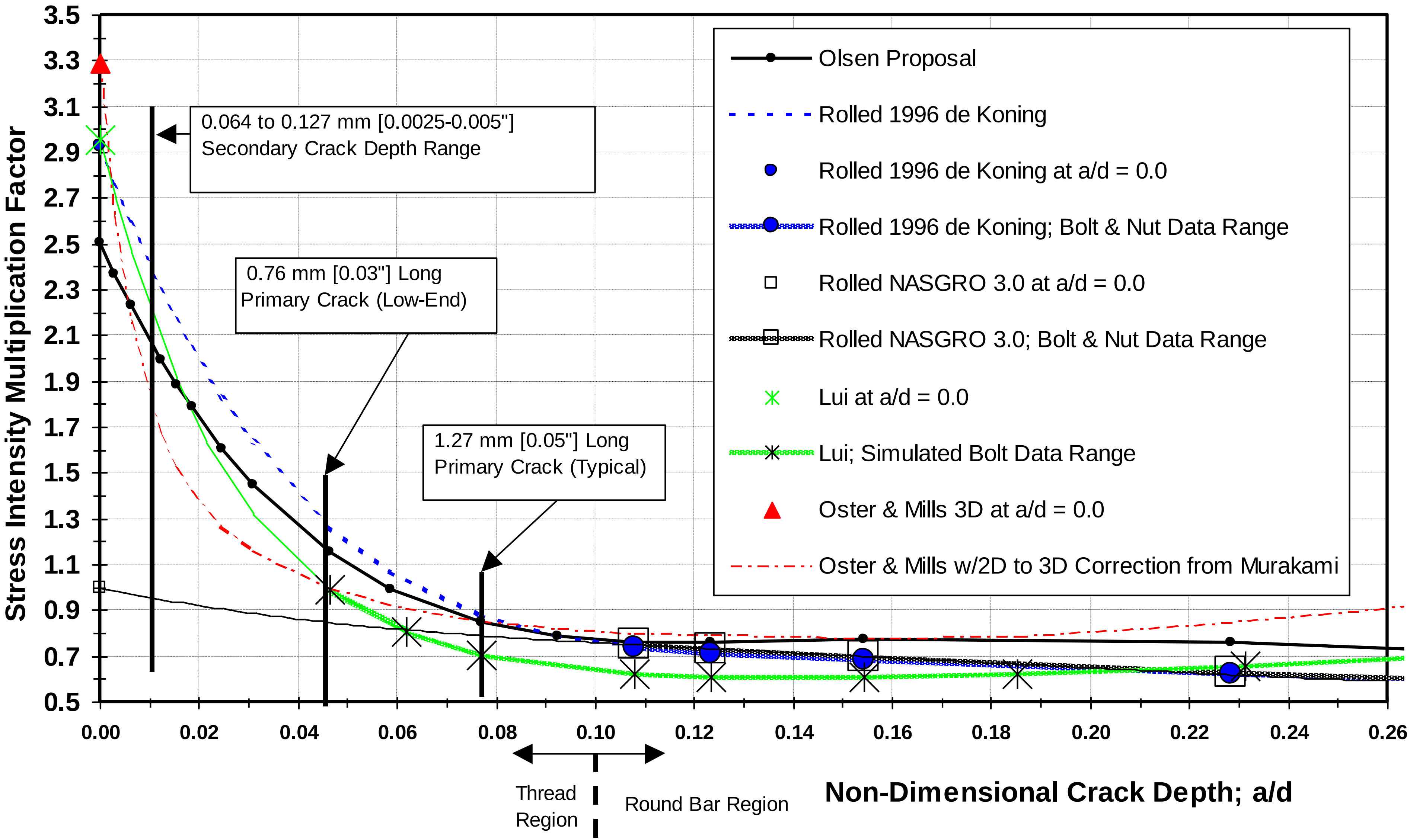
** Y(a) is primary unknown for characterized materials

Current Y(a/d) Prediction Methods

Stress Intensity Multiplication Factor vs Crack Depth



Current Y(a/d) Prediction Methods



Findings

1. For $a/d < 0.05$, $Y(a/d)$ solutions vary greatly
2. Little to no data at $a/d < 0.05$
3. Analytic and Numeric methods are based on significant assumptions – rough estimates
4. Crack Growth Life Effected by $Y(a/d)$ when

   $a/d < 0.05$ AND $0.05 < a/d < 0.3$

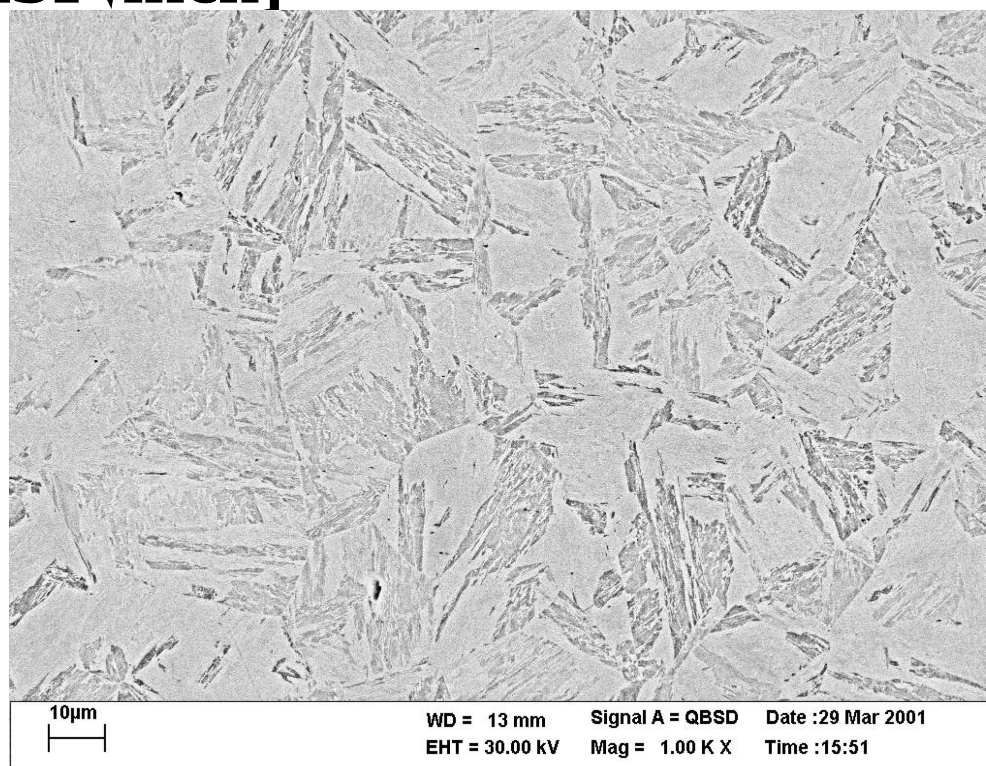
The Test Bolts, Nuts, & Washers

Nat'l Aerospace Std. Tension Bolts (NAS626-66)

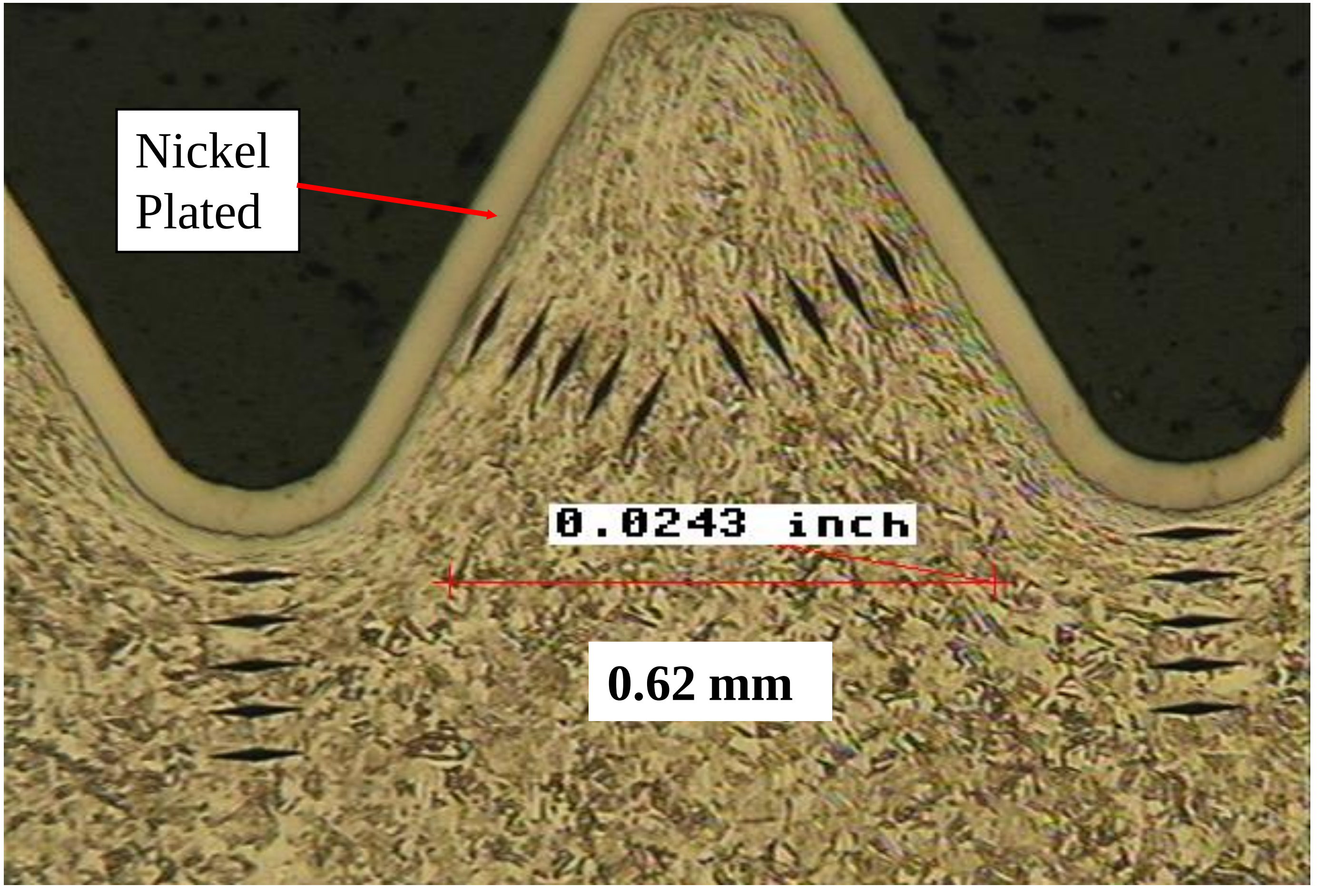
- **9.53 mm OD (3/8"-24 UNJF)**
- **120.5 mm [4.74"] Long**
- **Cold Rolled Threads**
- **MIL-S-8879 Controlled Root Radii (Smooth)**

Test Bolt Material

- **PH 13-8 Mo CRES (AMS5864)**
  Fe Base w/13% Cr, 8% Ni, 2% Mo, & 1% Al
- **Solution Heat Treated & Aged (MIL-H-6875)**
  - **$K_{IC} \doteq 110$ MPa$\sqrt{m}$ [KSI$\sqrt{inch}$]**
  - **1393 MPa Yield TS [202 KSI]**
  - **1414 MPa UTS [205 KSI]**
  - **16% Elongation**
  - **64% RA**



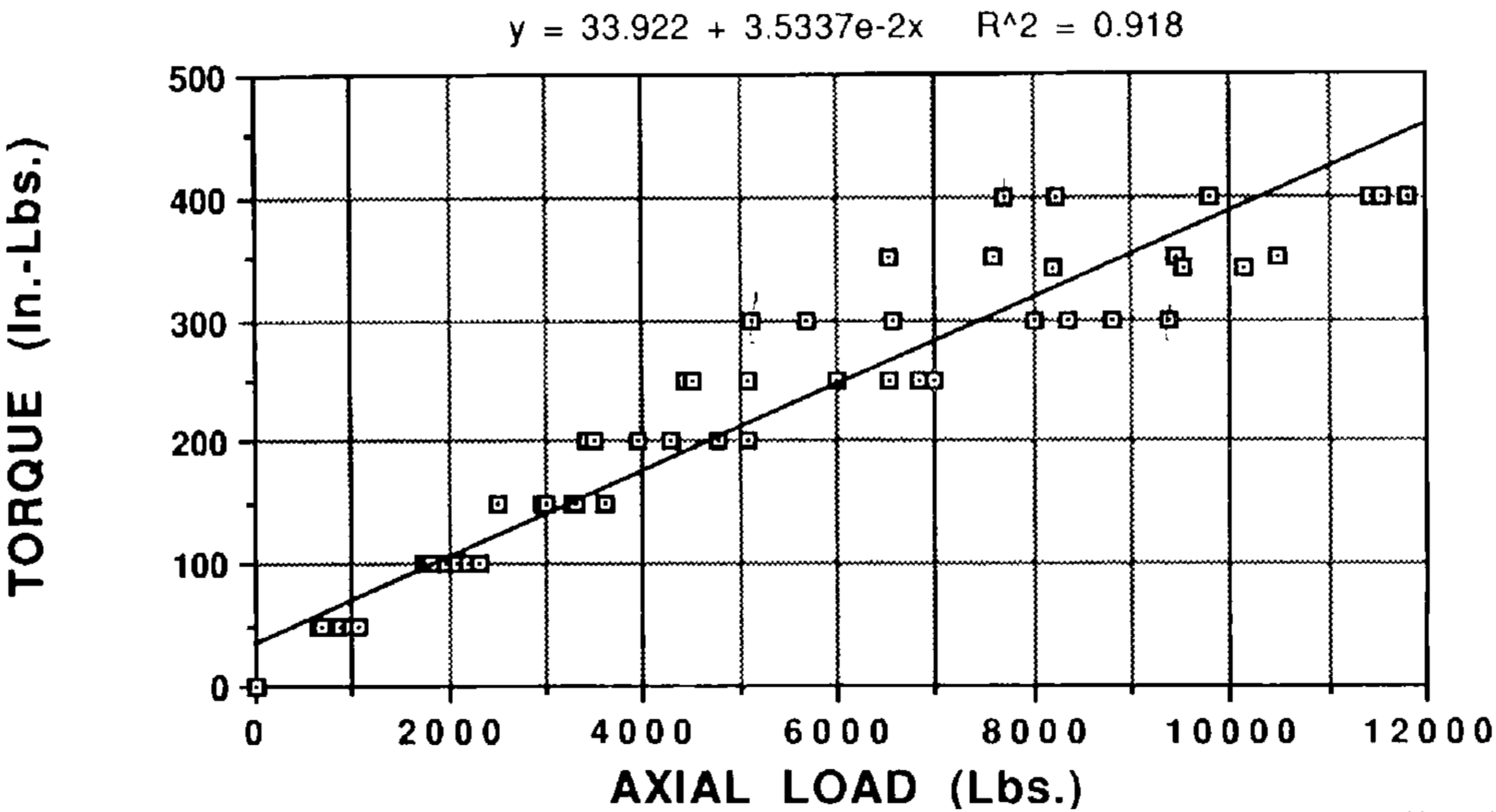
Cold Rolled Bolt Thread Grain



- **Depth of Aligned Grains < 0.07 mm [0.003”]**
- **#6.5 - 7.0 Grain Size (ASTM E112: ¼ mm = 10 Grains)**
- **Tempered Martensite (BCT Lattice w/Intragranular NiAl)**

Experimentally Simulated Bolt Preload

- **Observed: Excessive Preload Scatter from Torque**
- **Want: Ideal Preload ≡ 70% YS*Area of Bolt Shank**
- **Used: Simulated Preload of 56 kN [12.7 Kips]**



Test Rationale for All Bolts

- **Load Range (30 – 98 kN [7 - 22 Kip])**
  ⇒ Gives Data from $1/4 < N_f < 10^7+$ Cycles
- **$S_{max} \equiv$ Applied Load/Critical Area**
  - **Unflawed: Critical Area ≡ Bolt UTS/Material UTS**
  - **Flawed: Critical Area ≡ $\pi/4*(\phi_{Minor})^2$**
- **Load Control (S_{max}- N_f)**
- **Sinusoidal Wave Form**
- **Freq.: ¼ or 10 to 20 Hz. (as S_{max} ⇑, Freq. ⇓)**
- **Loading Ratio Range: $0.1 < R < 0.9$**

Bolt Test Protocol

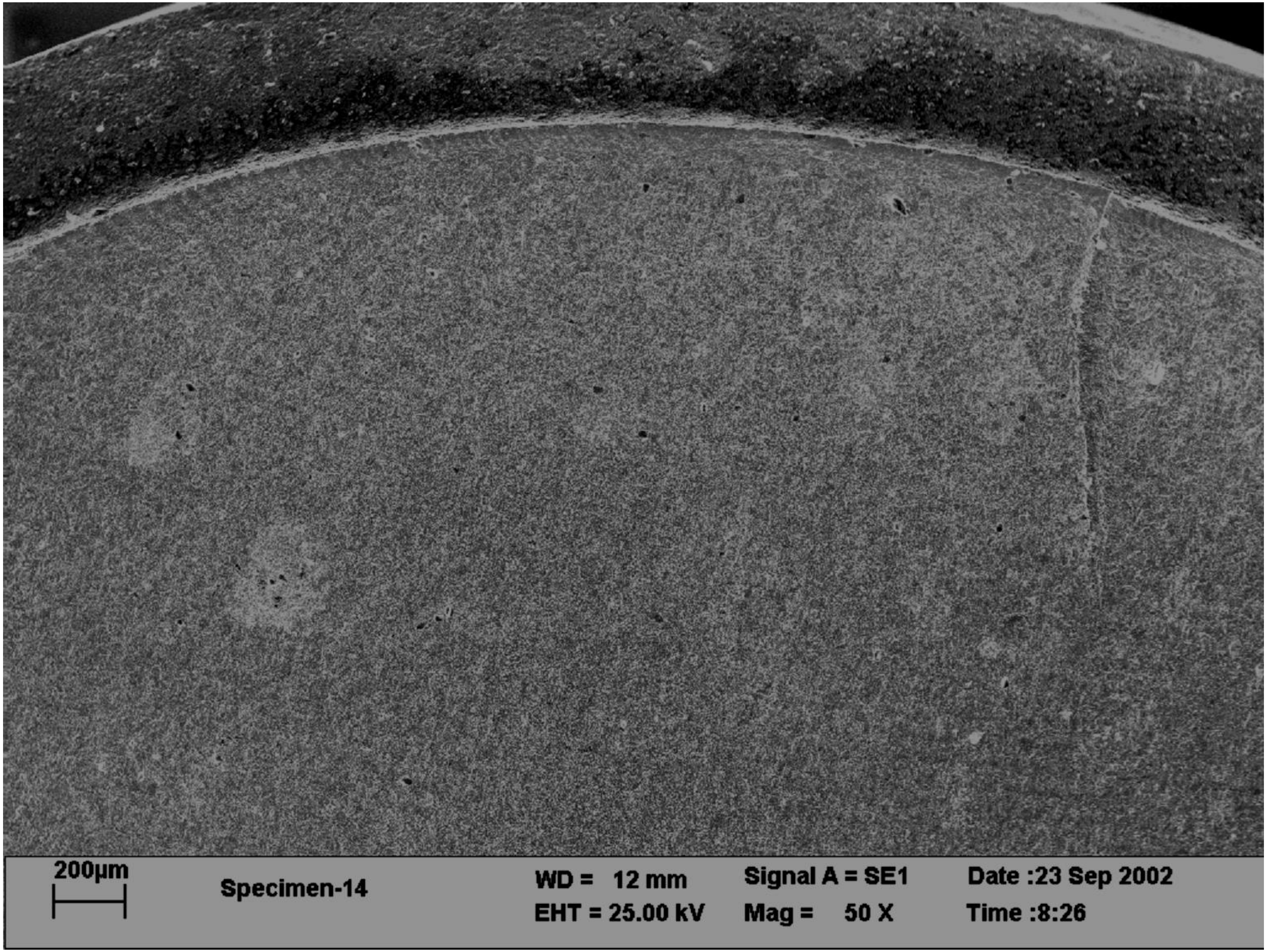
- **143 Aerospace Bolt and Nut Pairs Tested**
- **R = 0.8 (Represents Ideal Preload)**
- **R = 0.0 (A Bolt with No Preload)**

Loading Ratio (R)	Unflawed Test Bolts		EDM Flawed Test Bolts	
	Valid Data	Invalid Data	Valid Data	Invalid Data
0.1	34	1	7	1
0.4	20	3	4	1
0.6	2	0	0	0
0.8	42	2	16	5
0.9	4	1	0	0
Totals:	**102**	**7**	**27**	**7**

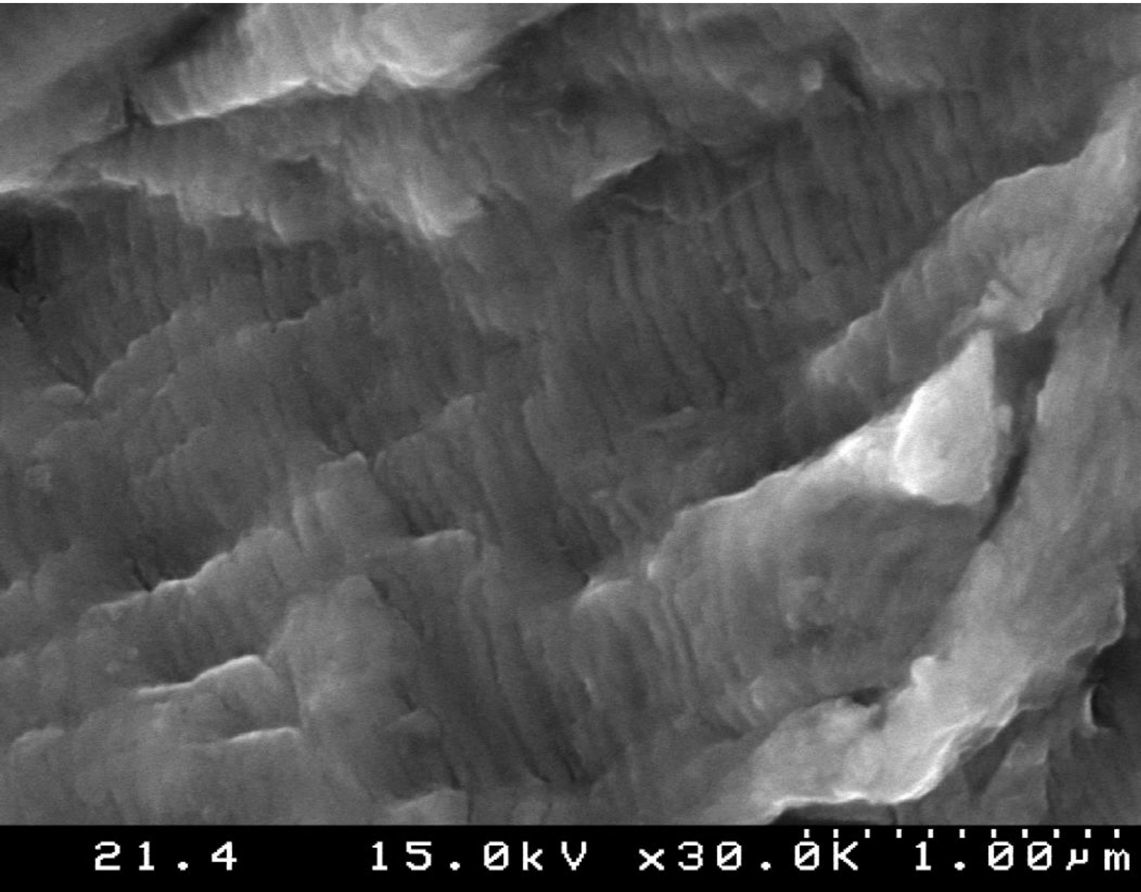
Unflawed & Flawed Bolt Test Results

- **Failure Initiates at First Full Thread of Engagement w/in the Bolt Threads Only**
- **Elliptical ⇨ Crescent Crack Front Shape**
  - **As S_{max} ⇑, a/c ⇓ (Tends Toward Crescent)**
  - **Shape Changes w/Growth (a ⇑, a/c ⇓)**
- **EDM Flaws Reduce S_{max} by 10% min.**
- **Life Reduction Worsens as S_{max} Decreases**

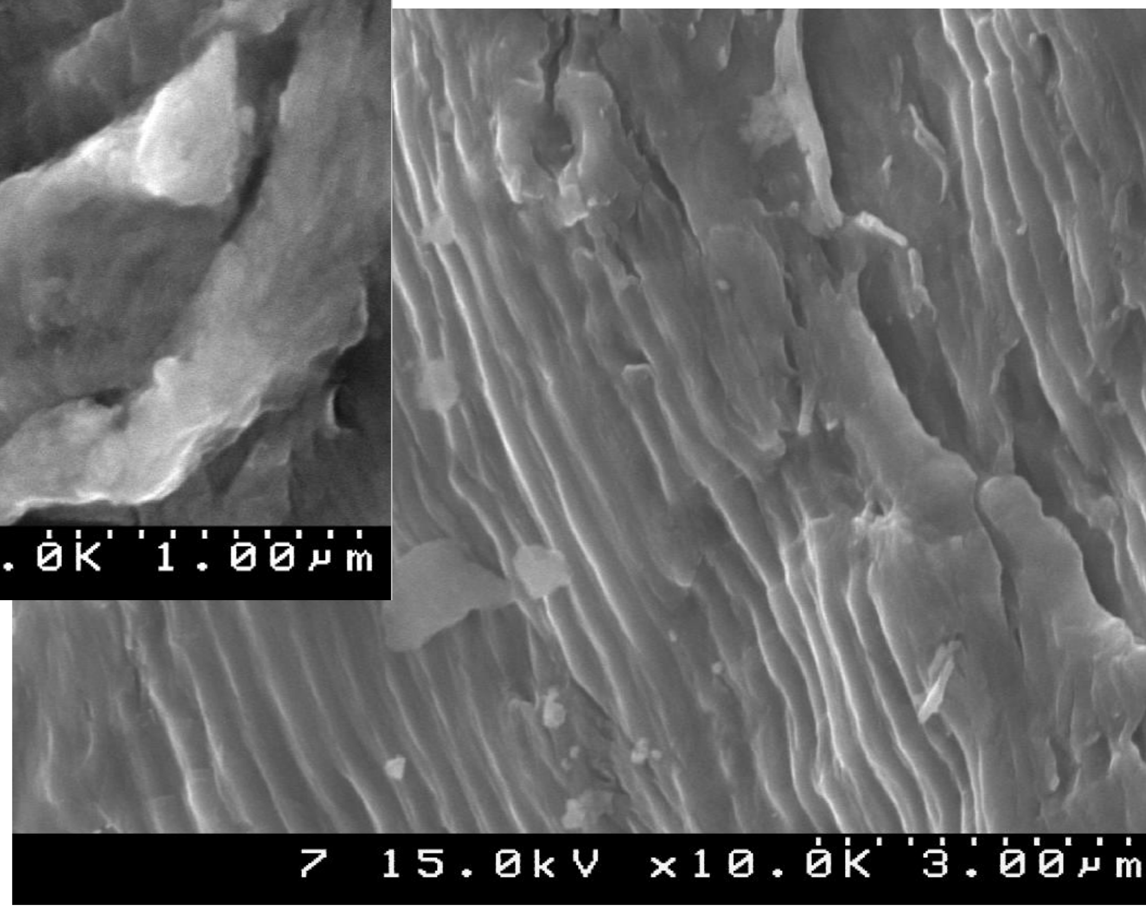
Marker Bands on Unflawed Bolt



Unflawed & Flawed Fracture Surface Striations

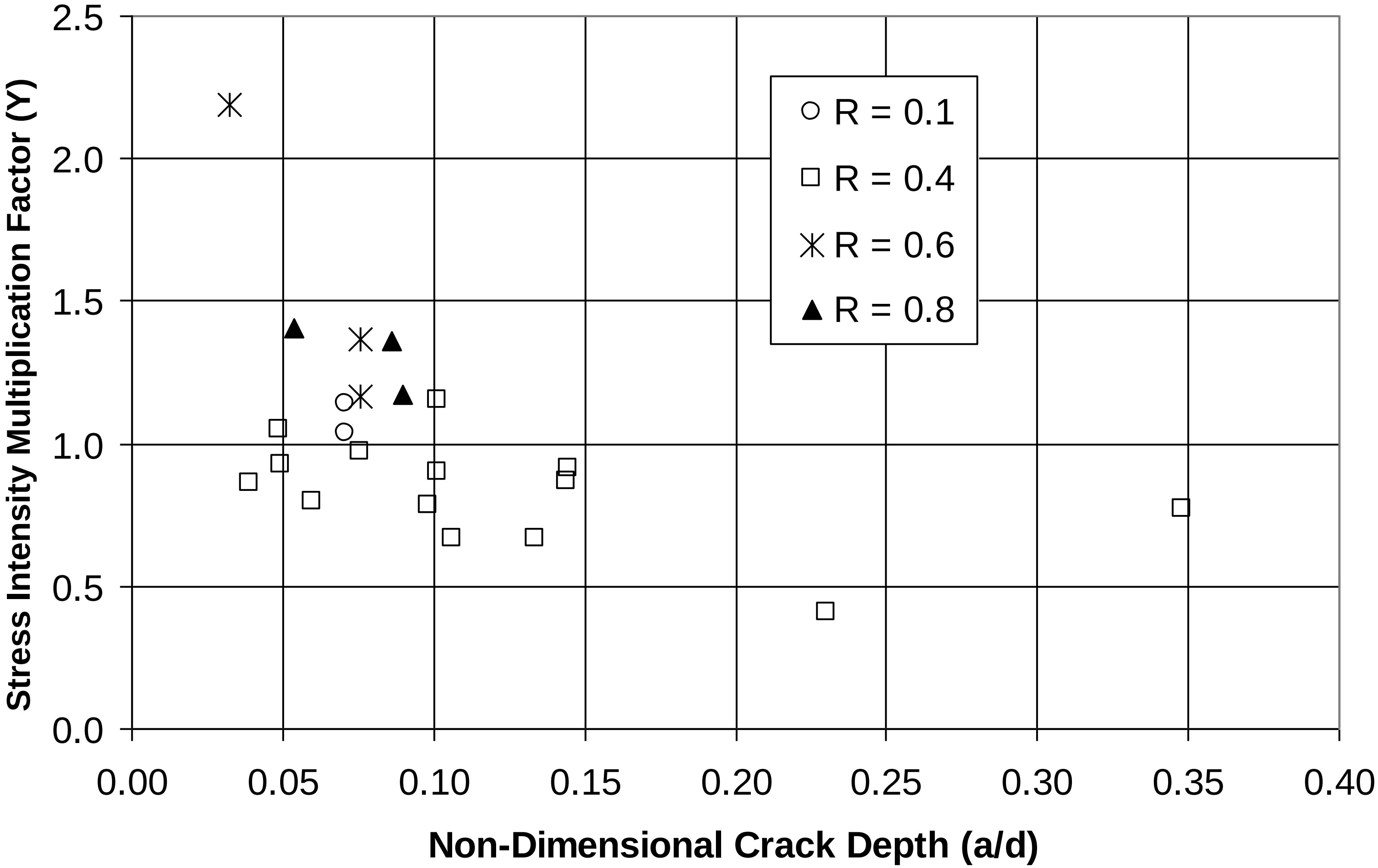


- **51 Striation Measurements**
- **5.6×10^{-5} to 7.9×10^{-4} mm**
  [2.2×10^{-6} to 3.1×10^{-5} ”]



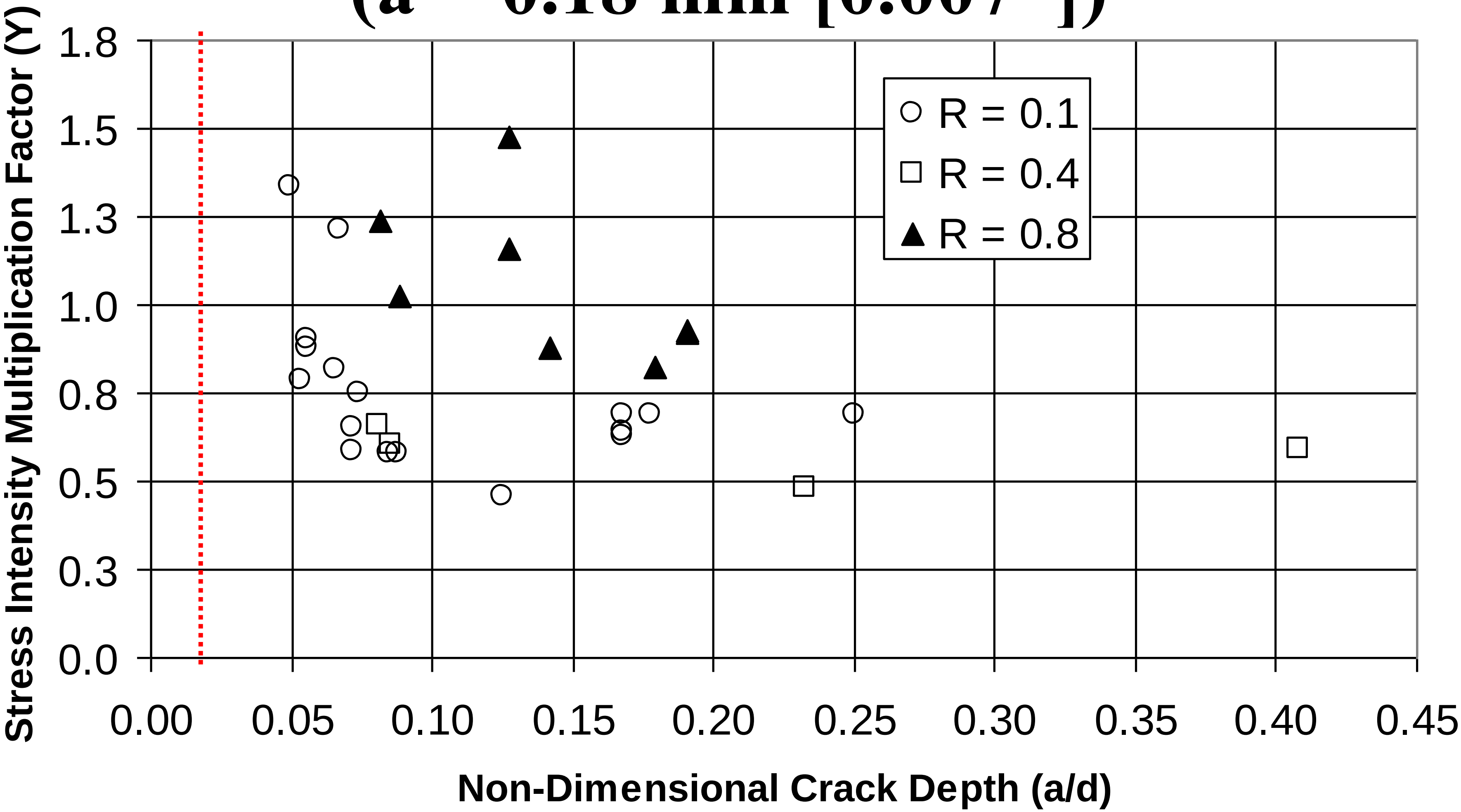
- **a/d ≥ 0.035 (0.29 mm [0.011”])**
  for unflawed bolts
- **a/d ≥ 0.051 (0.41 mm [0.016”])**
  for flawed bolts

Y versus a/d for Unflawed Bolts



- **Striations Spacing = da/dN**
- **ΔK via Material Data & Test Conditions**
- **Y from $\Delta K = Y \Delta\sigma \sqrt{\pi a}$**

Y versus a/d for EDM Flawed Bolts
(a = 0.18 mm [0.007”])



Fracture Surface Striations ⇛ K @ a ⇛ Y vs. a/d

Unflawed & Flawed Fracture Surface Examination for Striation Results

- **Typical Scatter in Y versus a/d Data**
- **Insufficient Test Data for a Complete Y(a/d) Solution**
- **Striations Were Found on 22 of 37 Test Bolts**
- **Data to a/d = 0.035 (Unflawed) and a/d = 0.05 (Flawed)**

  Prior Research was:

  a/d = 0.38 for Stainless Steel Aerospace Bolts

  a/d = 0.11 for Titanium Aerospace Bolts

  a/d = 0.046 for Notched Round Bars

Experimental Research Conclusions

- **Crack Front Shape is Initiation Dependent**

  (Discrete Surface Defect and No Defect)

- **Elliptical ⇨ Crescent Crack Fronts**

  (Assumed Circular (Non-Conservative))

- **Cannot Ignore Residual Stress from Roll Threads**

  (Up to 65% of -UTS; 50%+ to a/d<0.05)

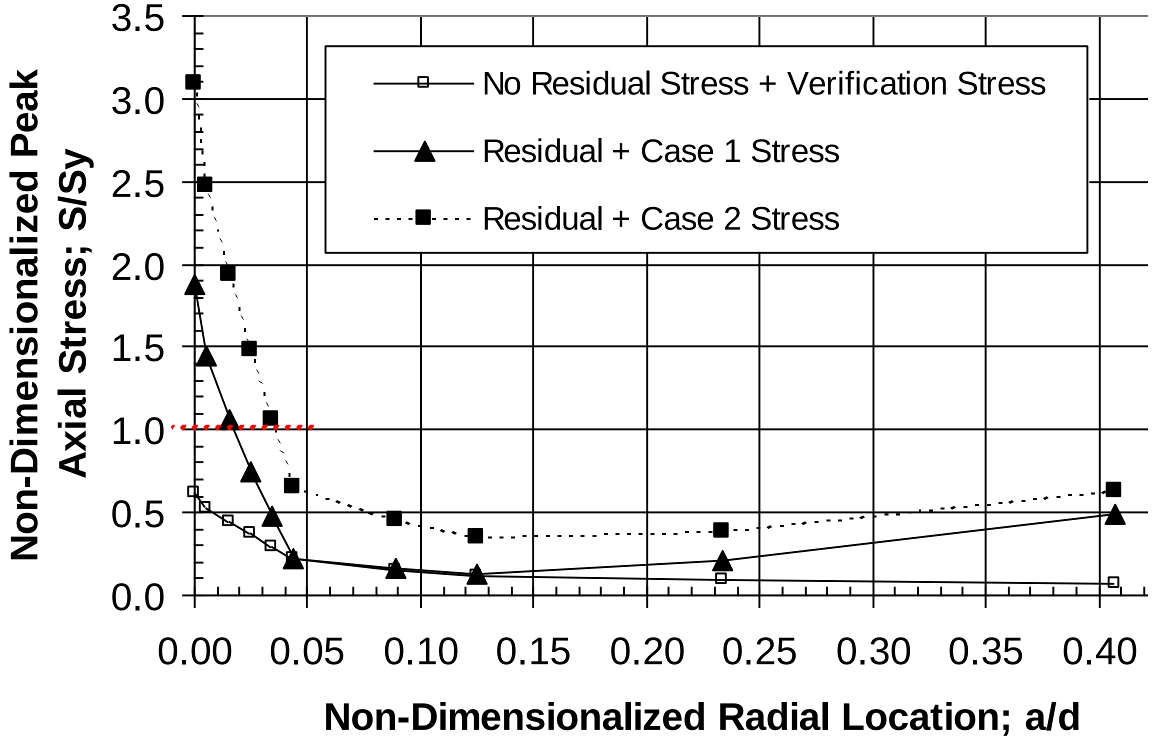
- **Rolled Threads are Damage Tolerant**

  (10%+ σ Reduction for EDM Flaws)

Verification & Load Cases

- **<u>Verification case</u>: 3D FEA σ_0 (175 MPa [25 KSI]) + No residual stress (σ_{Rc})**
  (de Koning, Lof, & Schra)
- **<u>Load case 1</u>: 3.9 x σ_0 (690 MPa [100 KSI]) + Experimentally measured σ_{Rc}**
  Flawed test bolt fatigue failures between $2x10^5 < N_f < 10^7$
- **<u>Load case 2</u>: 5.9 x σ_0 (1034 MPa [150 KSI] + Experimentally measured σ_{Rc}**
  Flawed test bolt fatigue failures between $3x10^4 < N_f < 8x10^5$
- **$S = a \cdot \sigma_0 + b \cdot \sigma_{Rc}$**

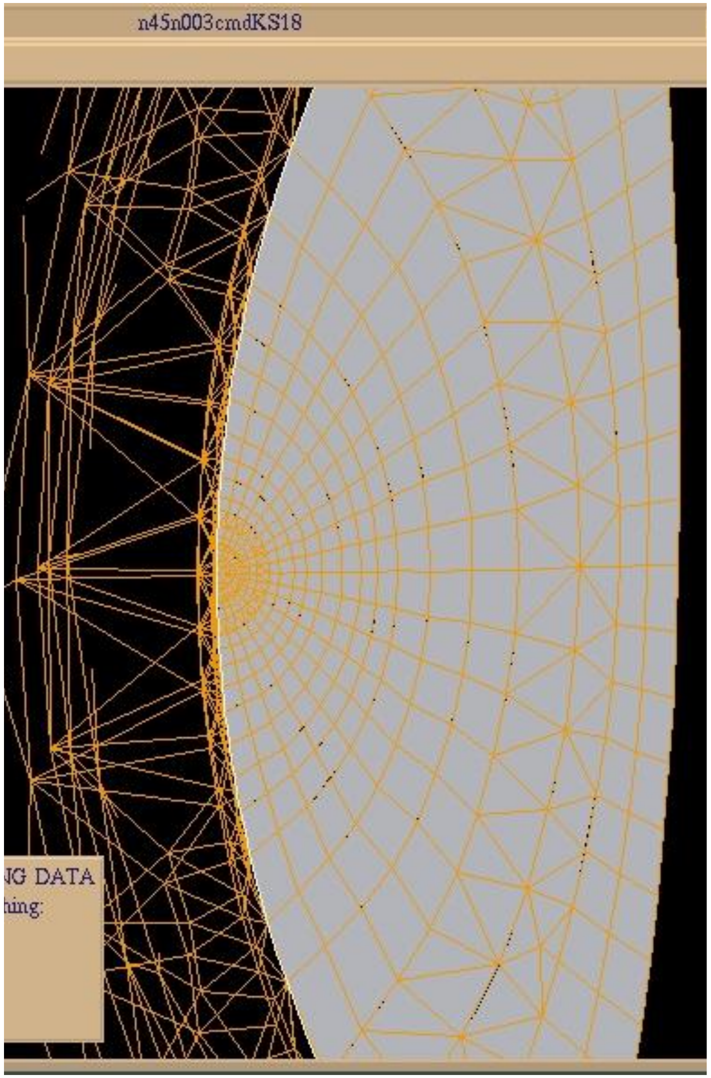
Case	a	b
Verification	1.00	0.00
Case 1	3.94	1.00
Case 2	5.91	1.00

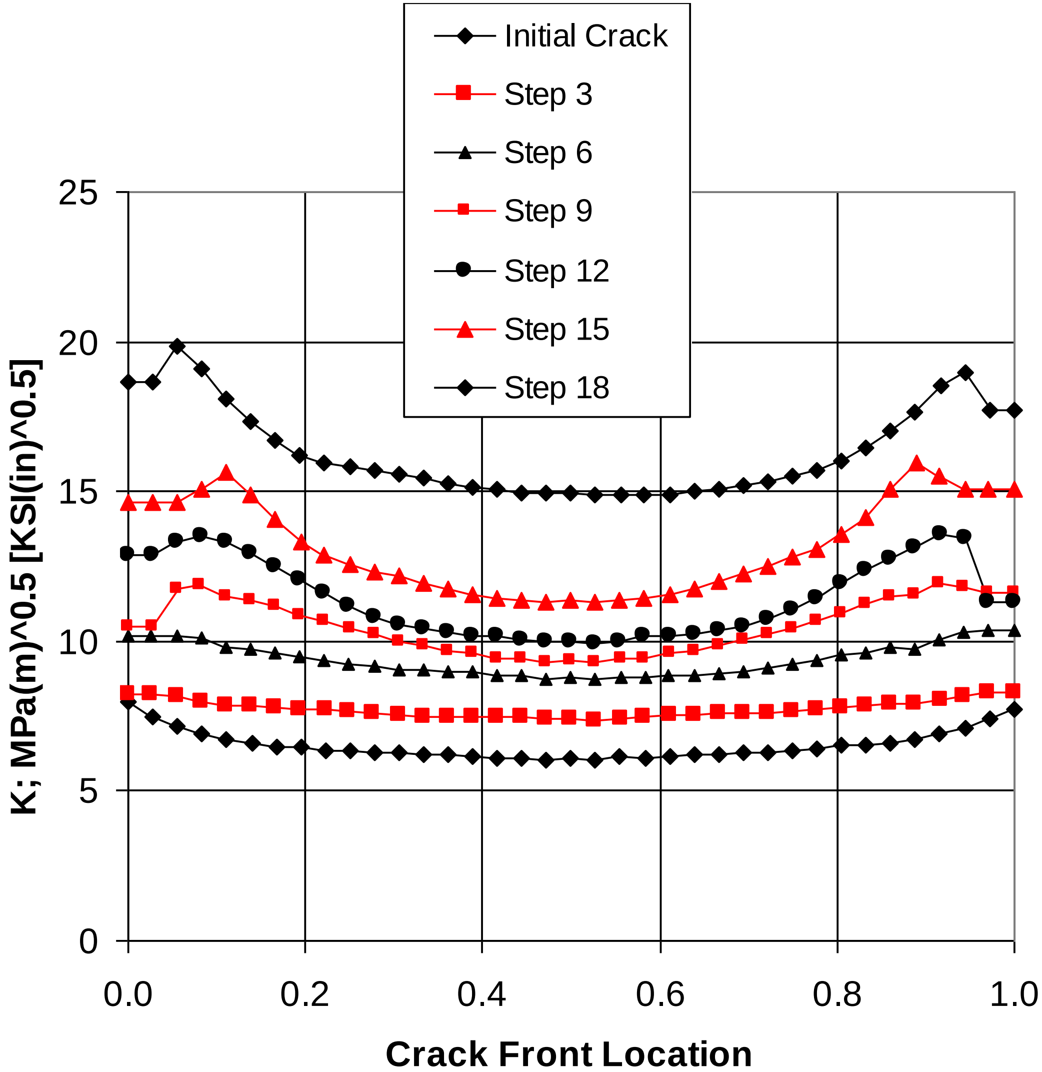


Analysis Assumptions

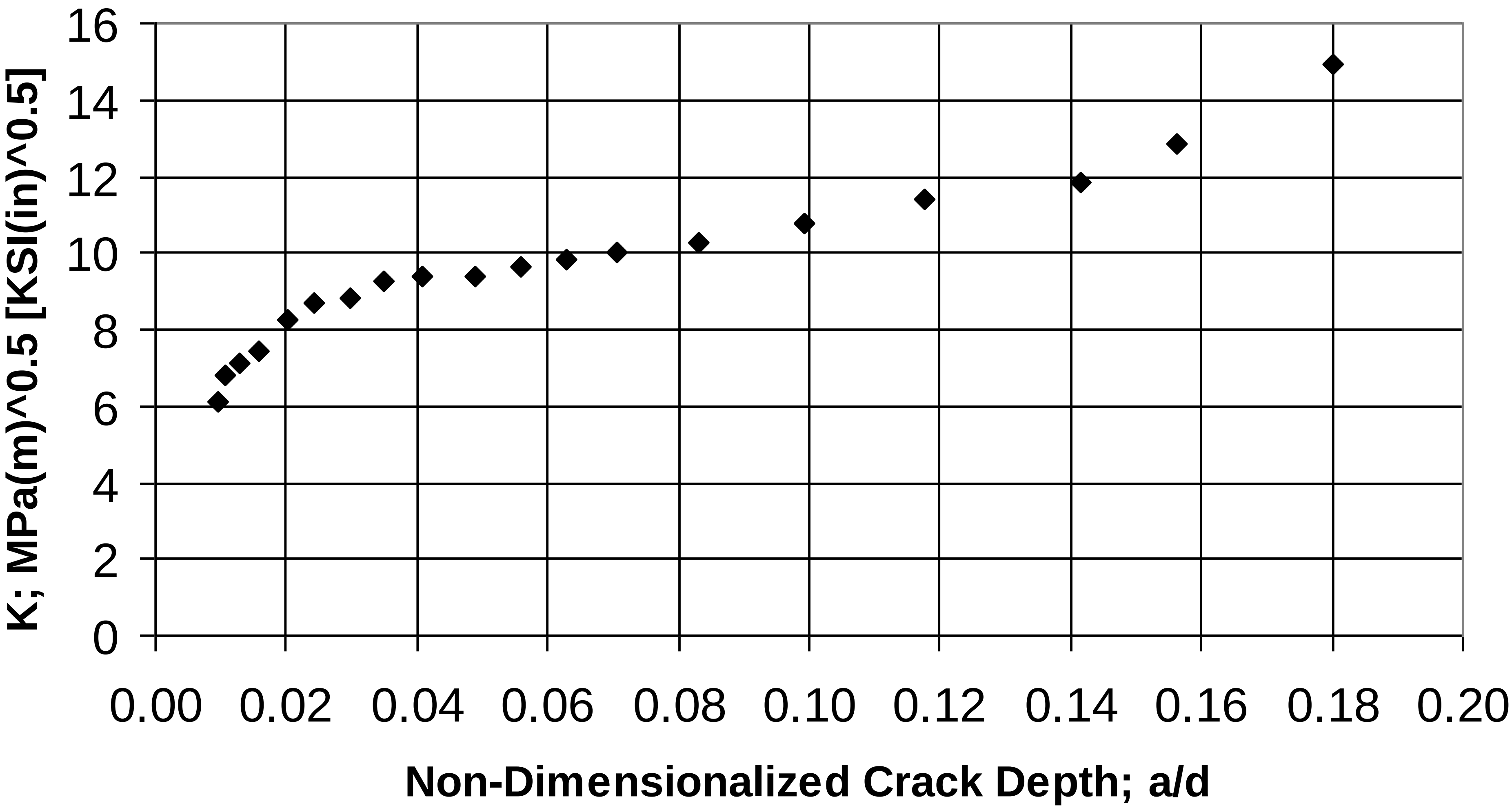
- LEFM & Plane Strain Material Behavior Applies
- Ignore Near Surface Plain Stress Behavior
- Conservatively Ignoring Local Plasticity
  (Both Surrounding Material & Crack Growth)
- Measured Residual Stresses do not Redistribute

Verification Crack Front History & K versus Crack Front Location

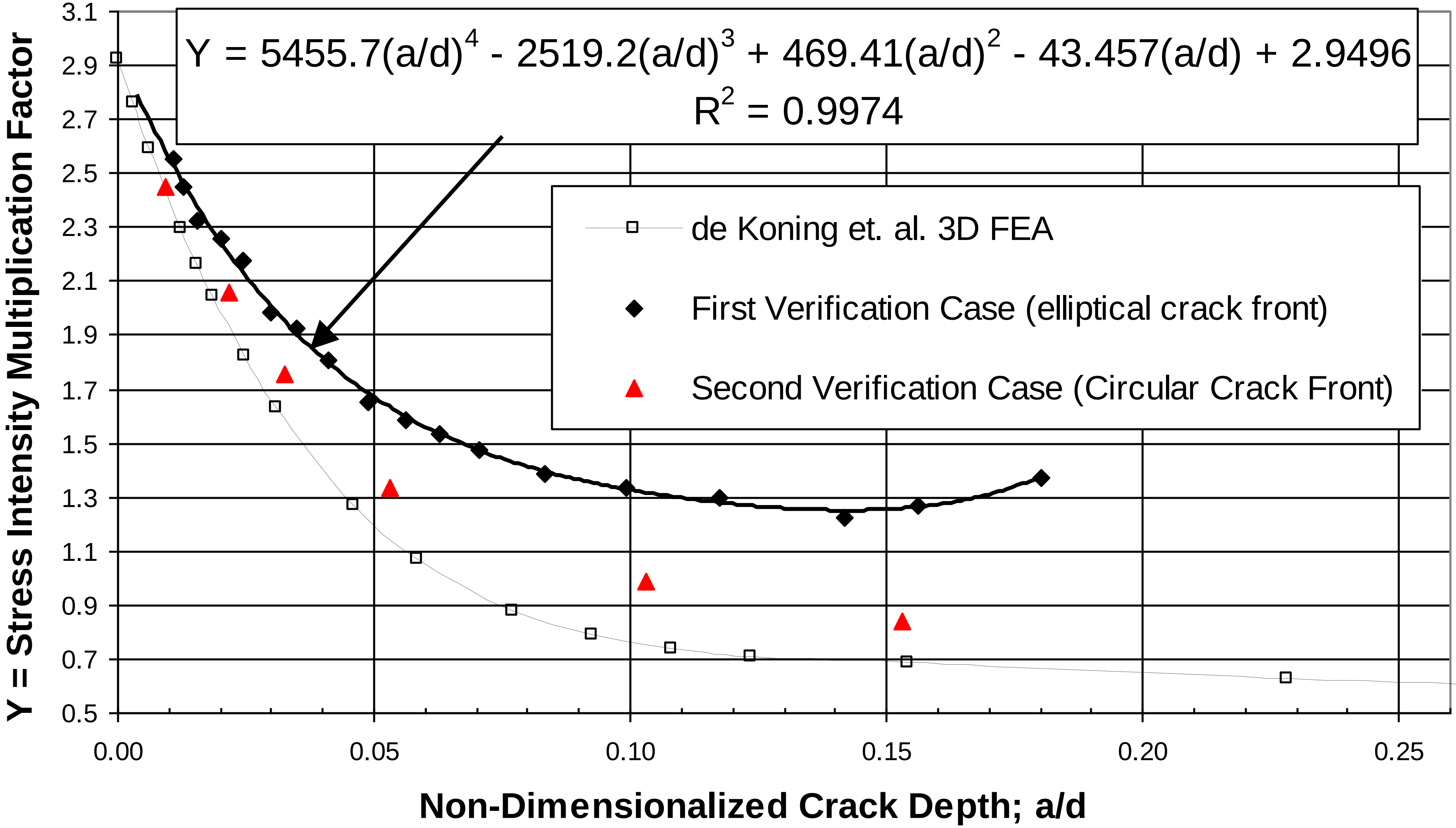




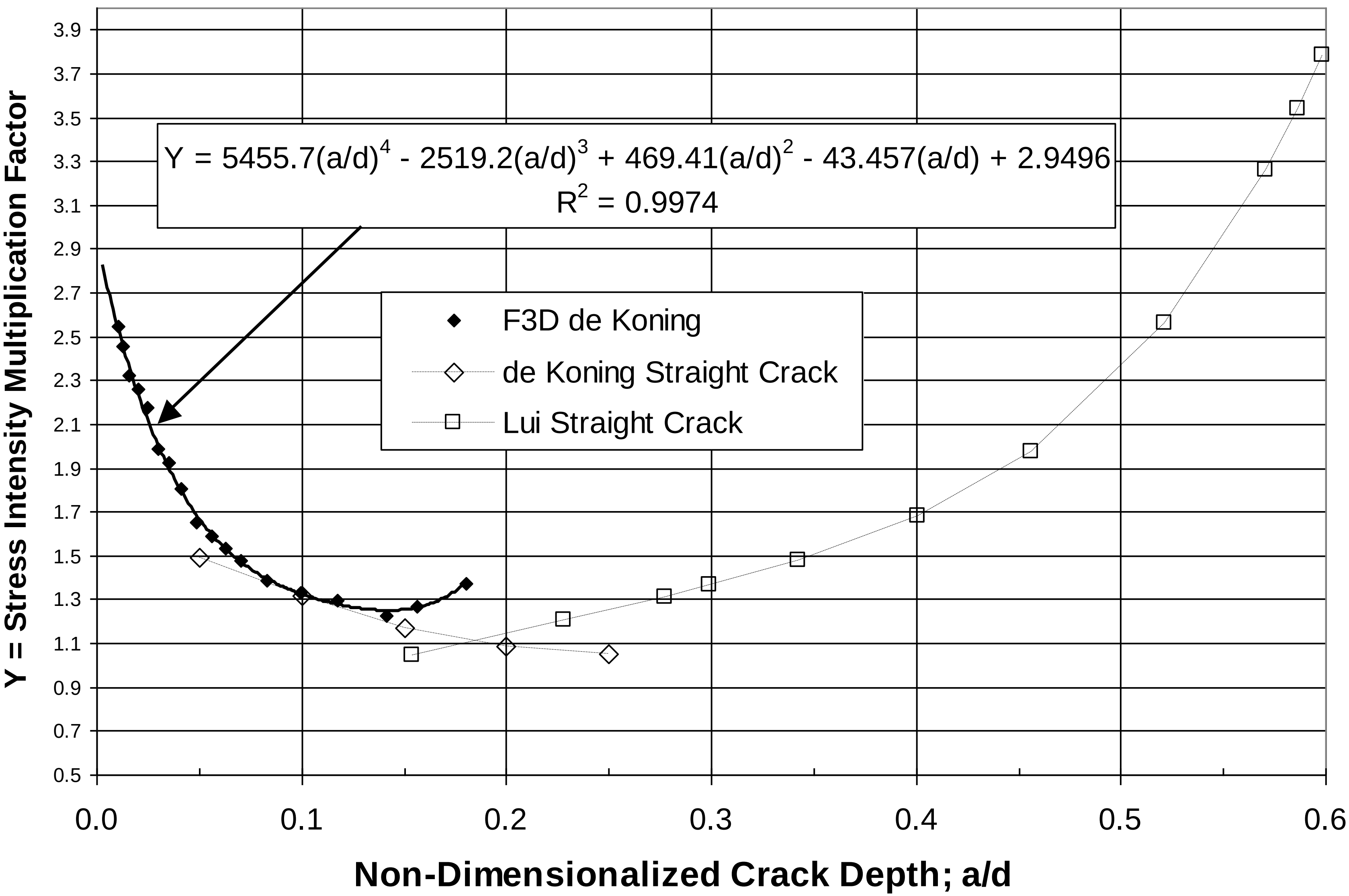
Verification K versus a/d Prediction



Verification Y(a/d) Prediction



Verification Prediction Comparison



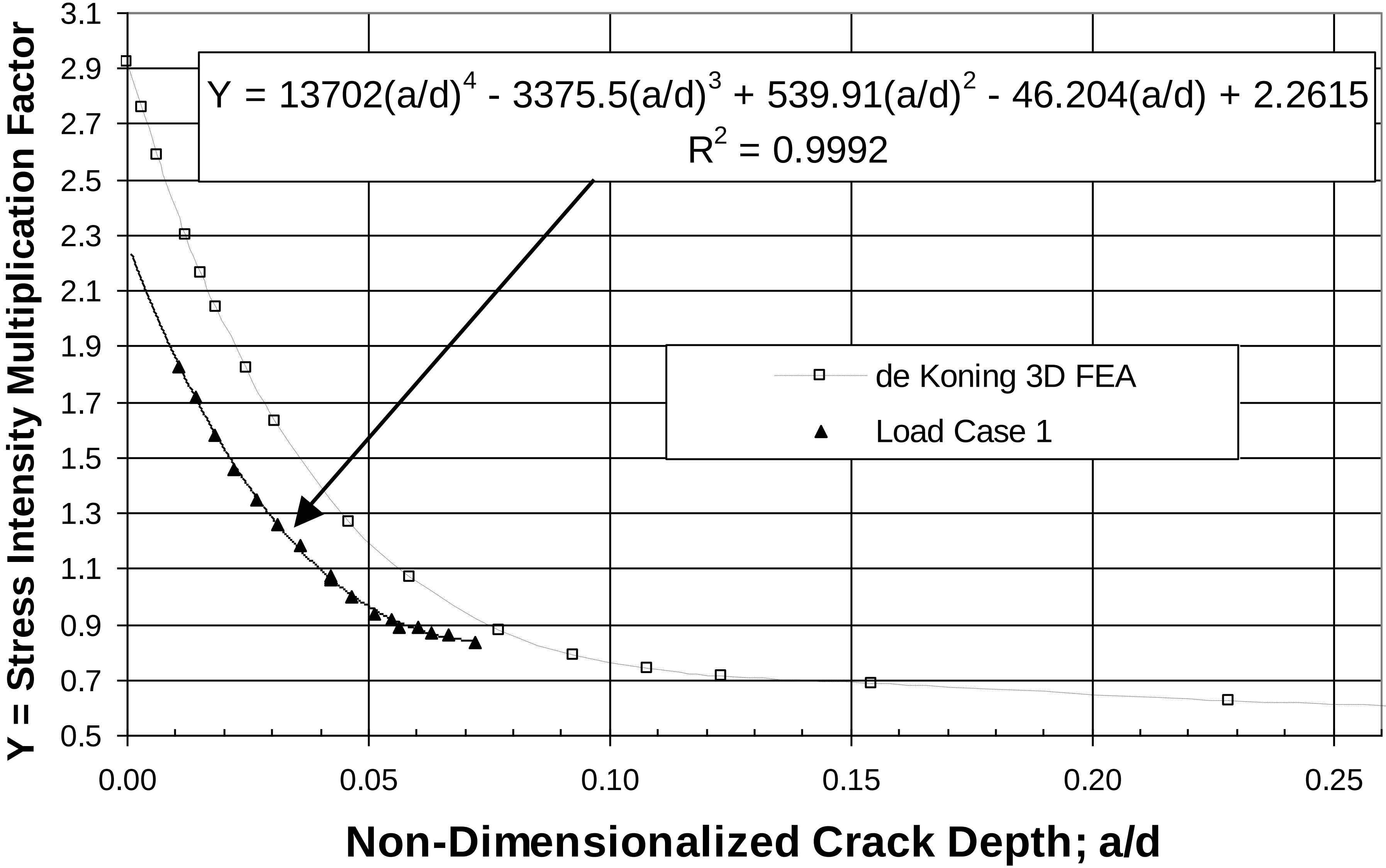
Verification Case Prediction Summary

- FRANC3D Model w/in 1% to 15%

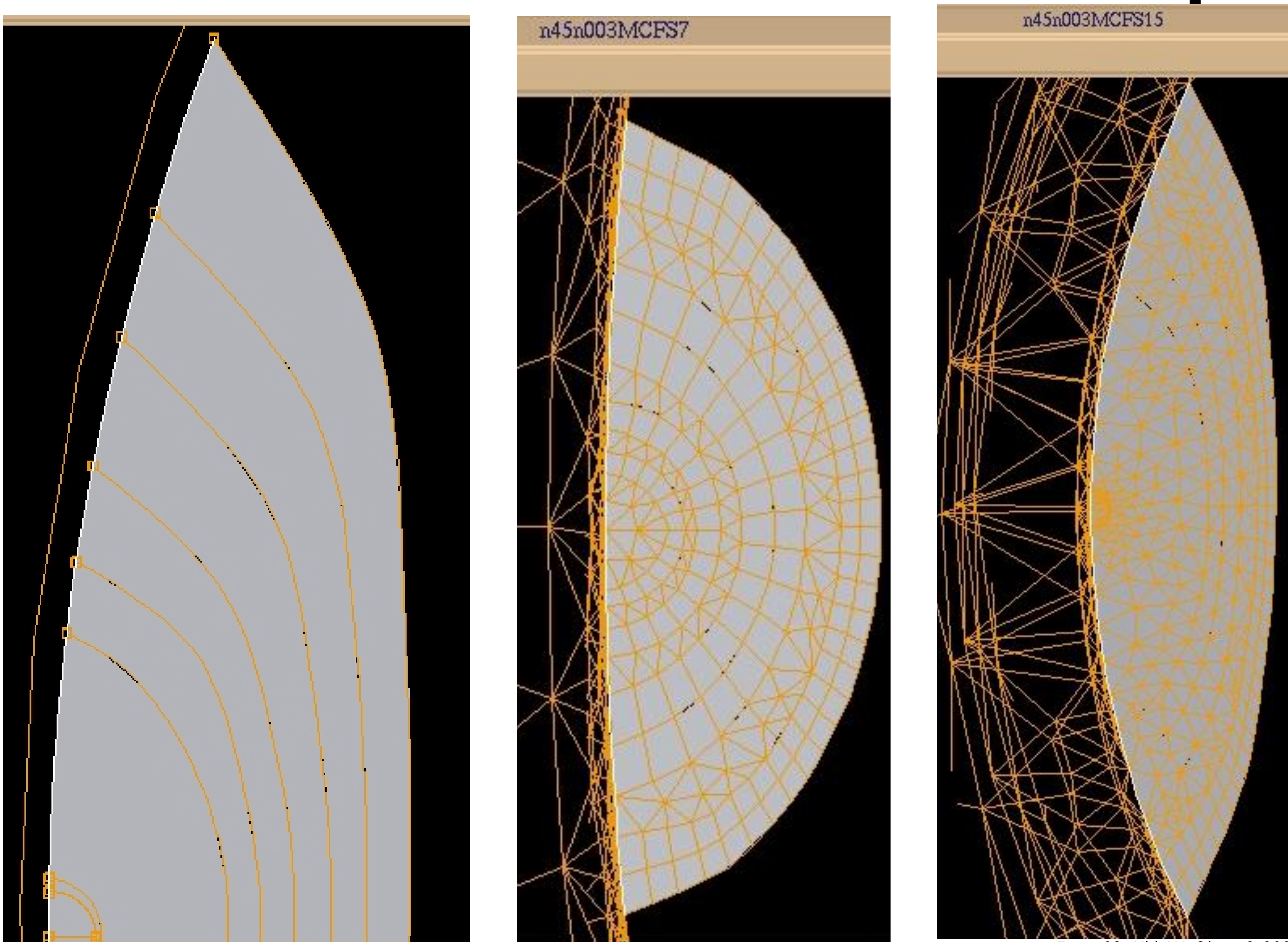
  (0.0 < a/d < 0.05)

- Crack Front Shape Changes w/Propagation
- Starts Elliptical & Gradually Changes to Flat
- Flat Crack Front K > Elliptical K > Circular K

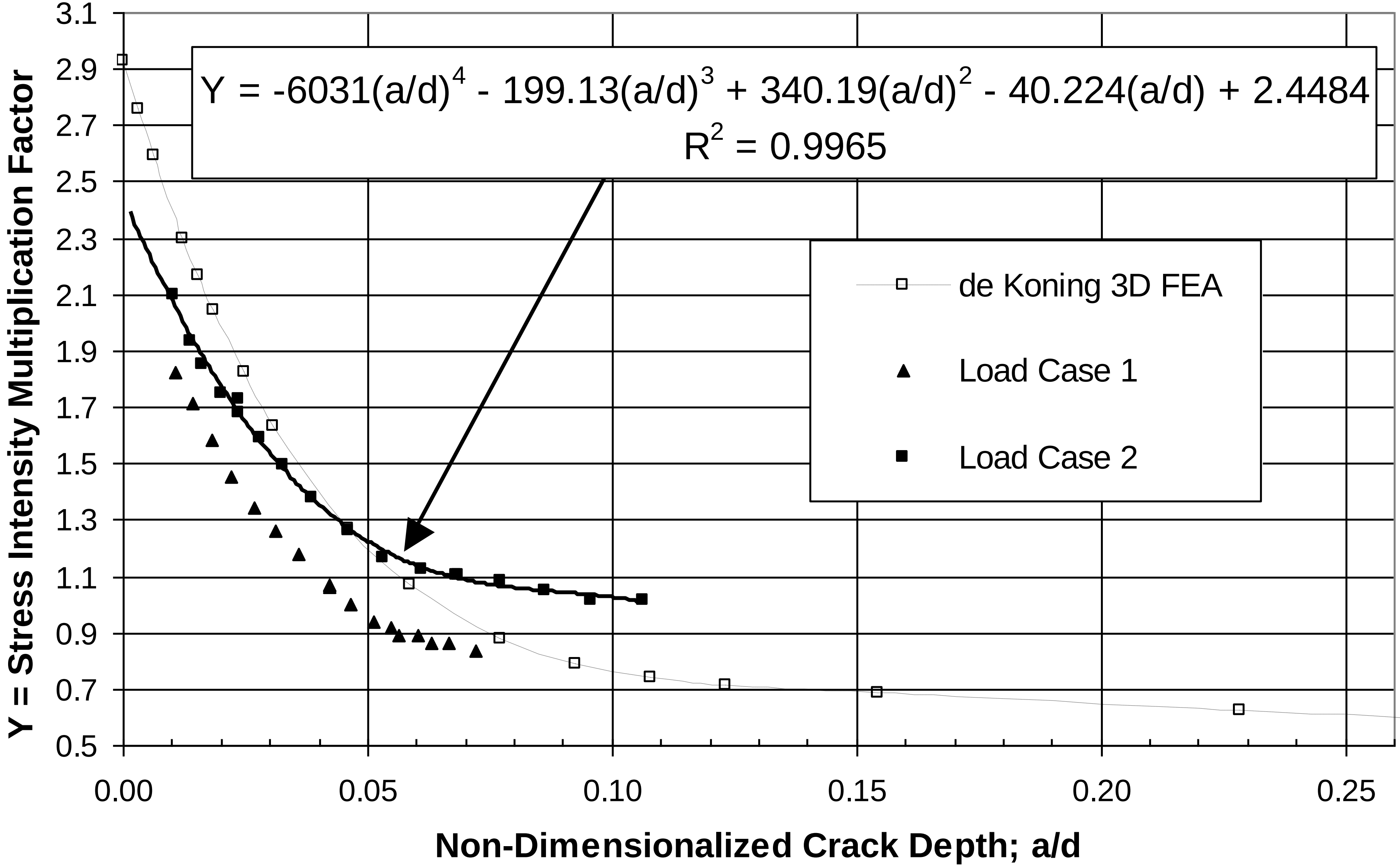
Load Case 1 Y(a/d) Prediction



Load Case 1 & 2 Crack Front Shape



Load Case 2 Y(a/d) Prediction



Summary of Numeric Predictions

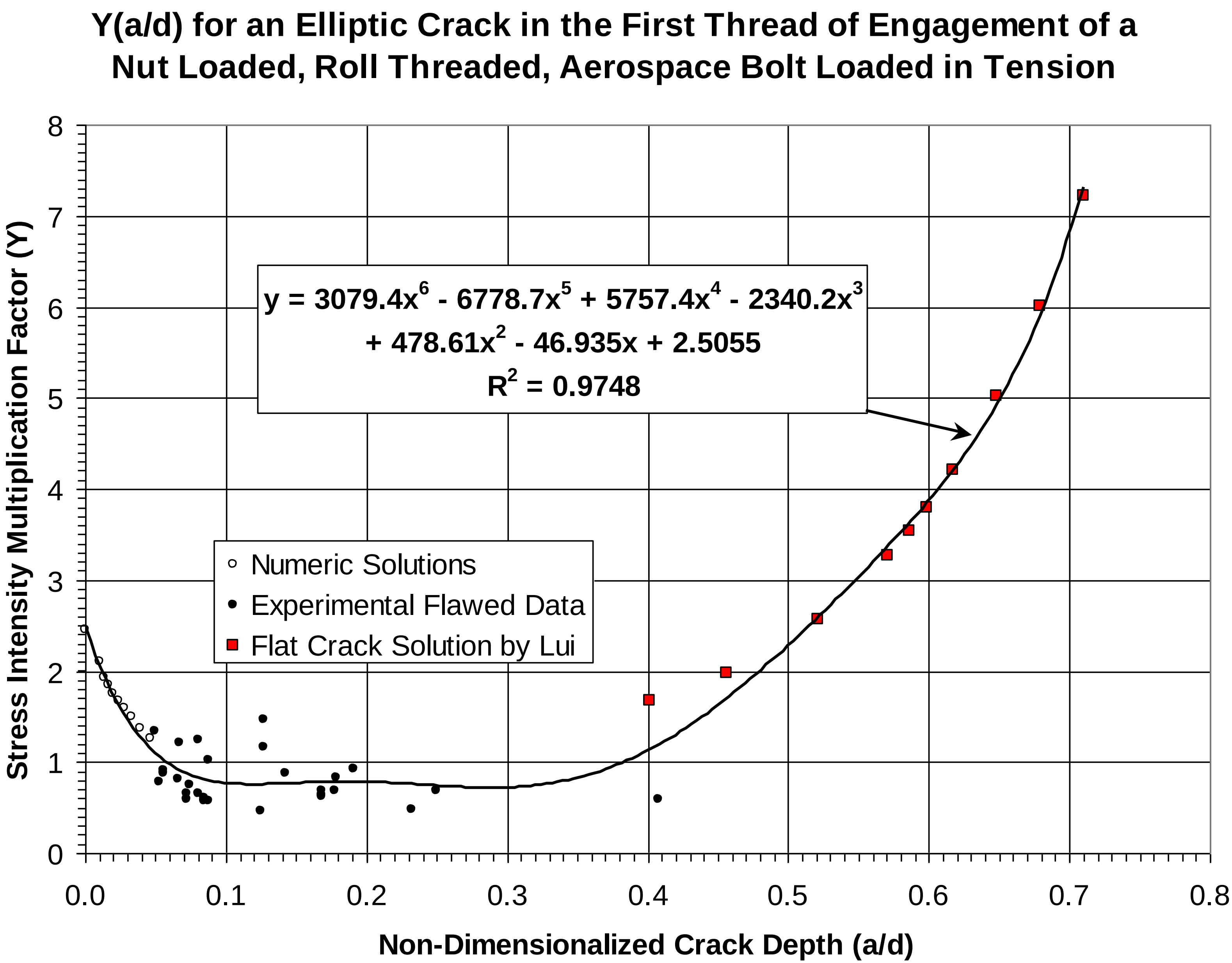
- Accounts for Measured Residual Stress
- Numeric Data between $0.009 < a/d < 0.11$
- Extrapolation of only 10% for Y(0.0)
- Complementary with Test Data for Final Y(a/d)
- Changing Crack Front (Elliptical to Flat)
- Load Case 2 Chosen for Conservatism

Analysis Limitations

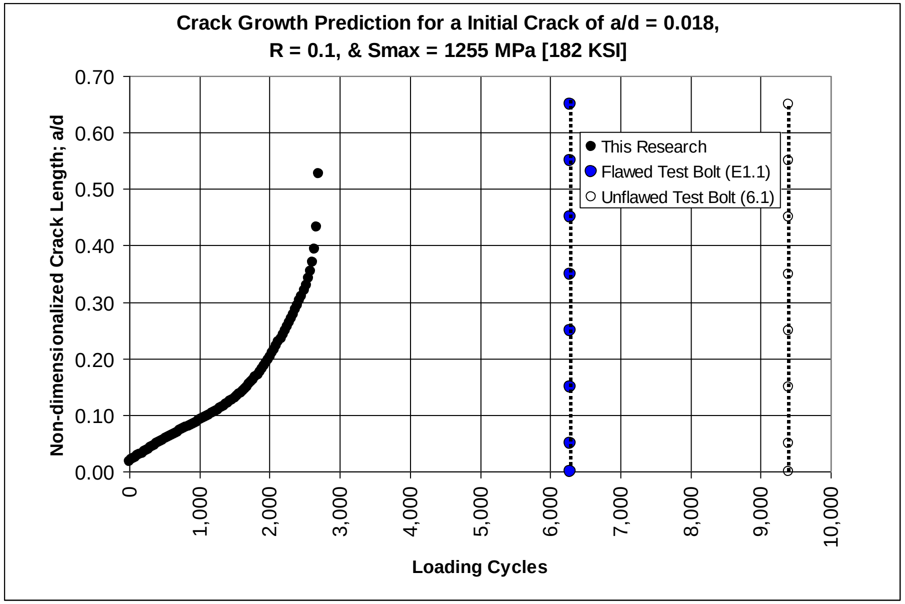
- Possible Over Prediction of σ, K, & Y (Due to Plasticity when $a/d < 0.04$)

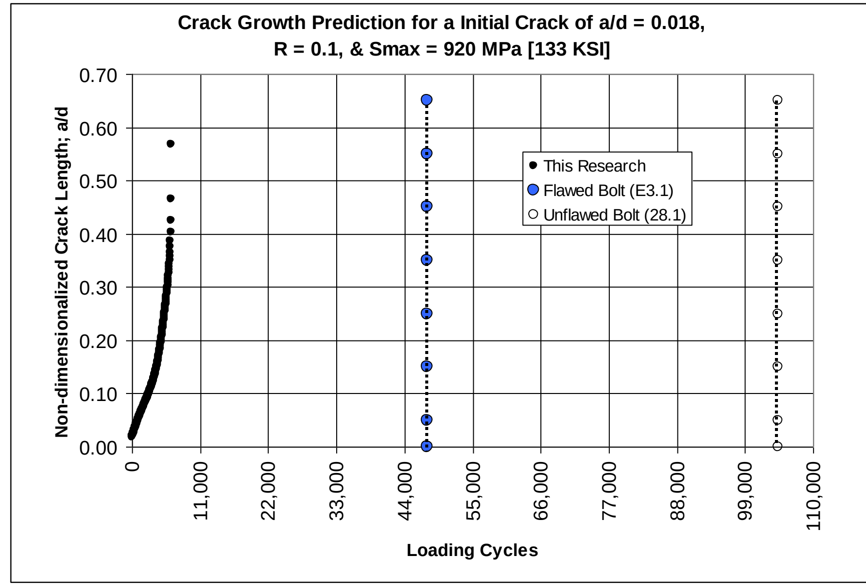
- The de Koning, Lof, & Schra Stress Field had:
  - No Contact on the Thread Flanks
  - Coarse Thread Root Mesh

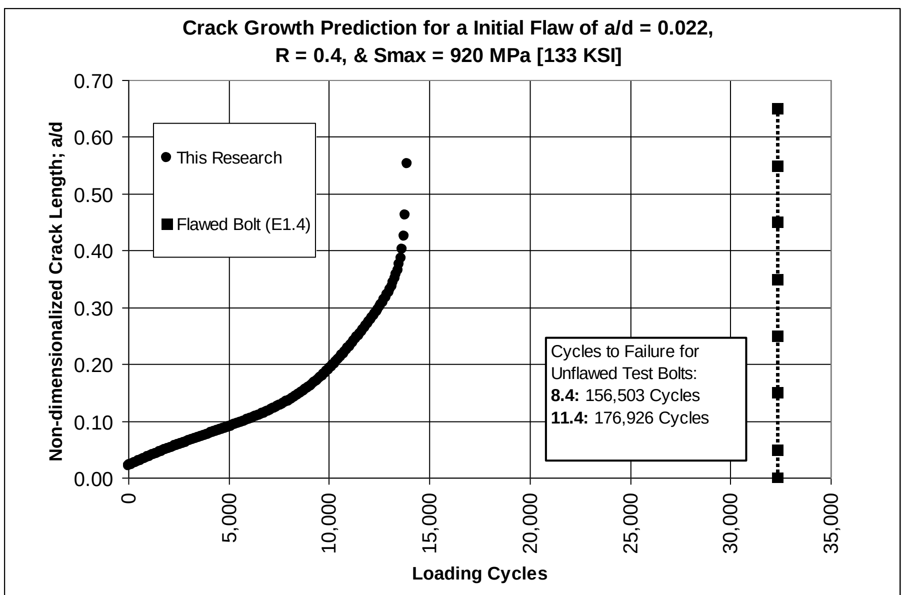
Y(a/d) for an Elliptical Crack

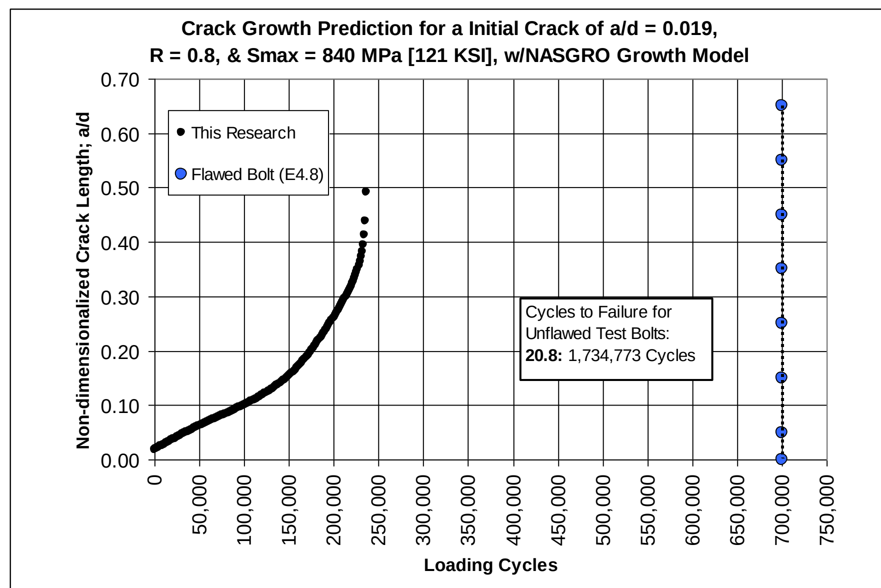


Life Prediction w/Walker Equation

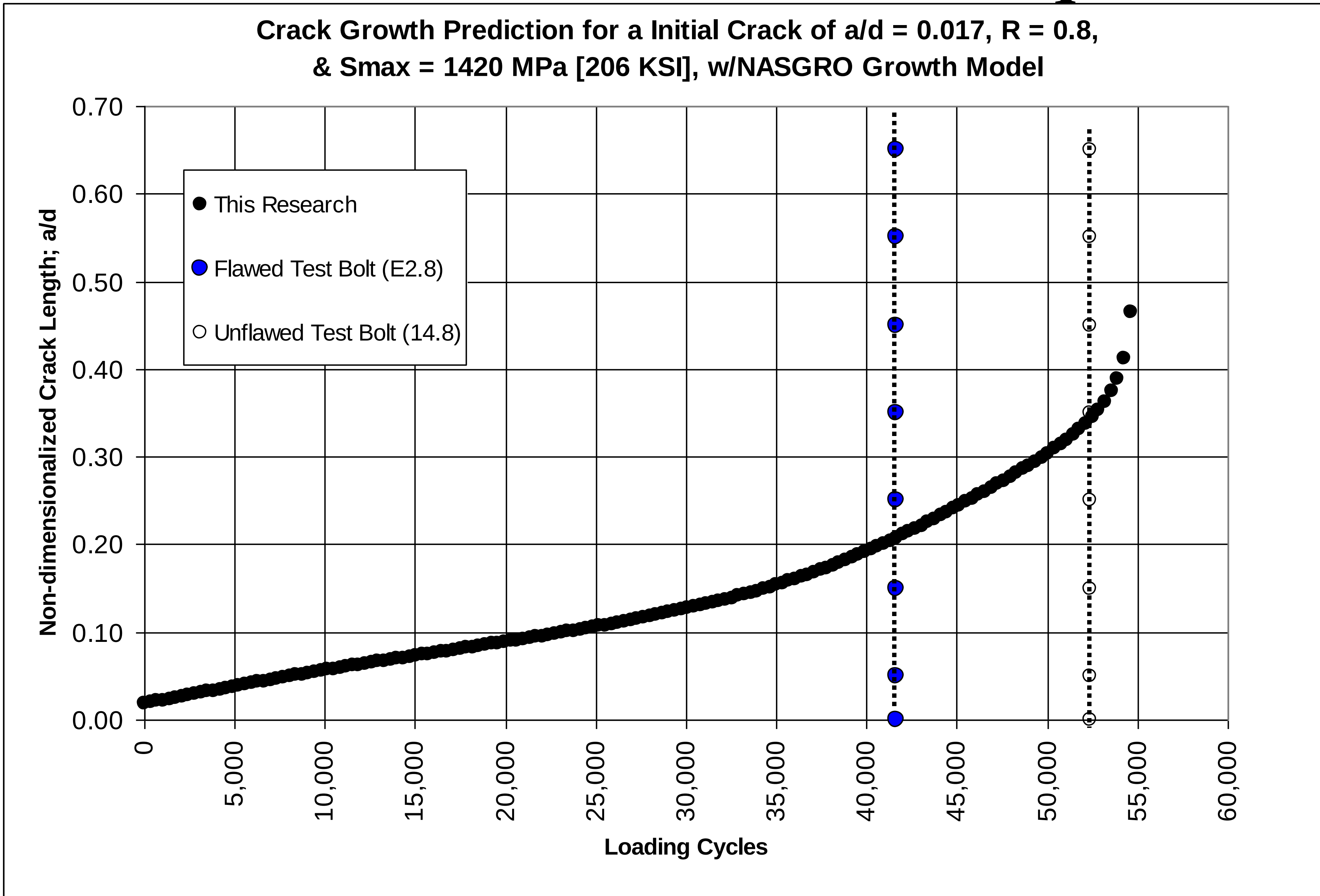




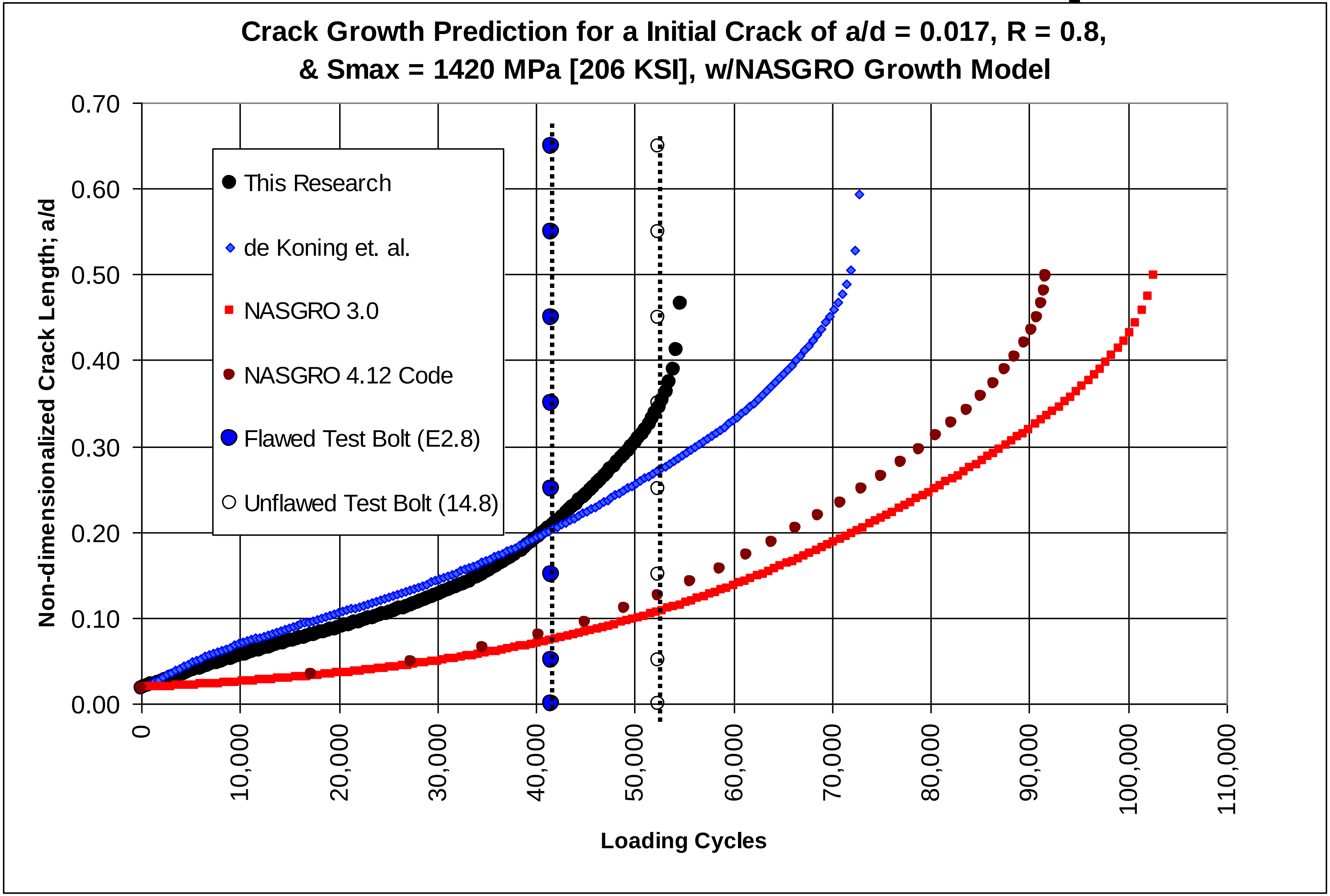




Life Prediction w/NASGRO Equation



Life Prediction w/NASGRO Equation

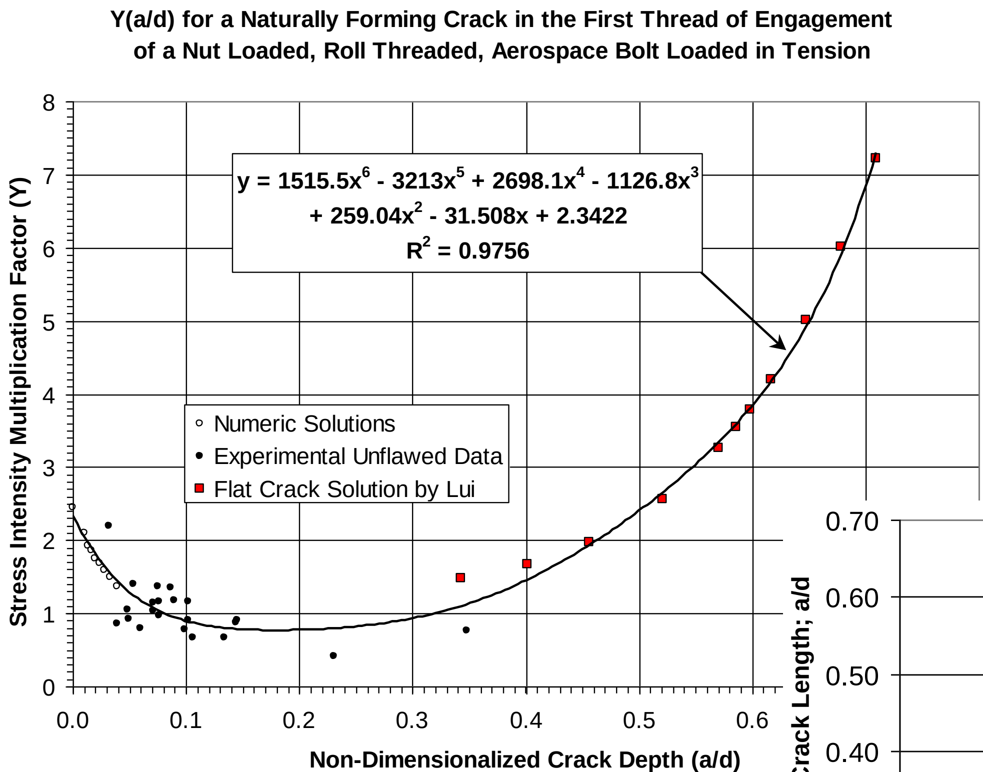


Synthesis of Results Summary

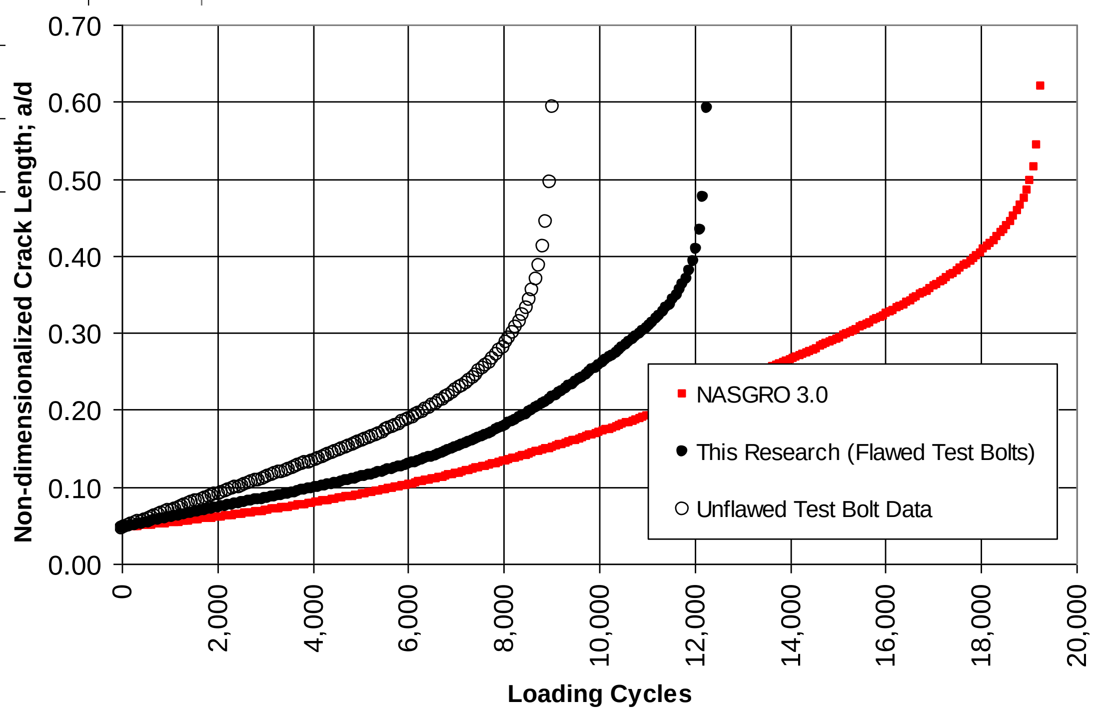
- Acceptable Composite Solution Fit ($R^2 > 0.8$)
- Conservative Y(a/d) Life Predictions w/R < 0.8
- Crack Initiation Cycles NOT Considered/Known
- Non-Conservative w/R > 0.8 & High Loads
- Y(a/d) or Y(a/d, R, σ)?

or Correction for High R &/or σ Needed?

Y(a/d) for Unflawed Test Bolts



Elliptic, Crescent, & NASGRO Circular Crack Life Predictions



- **Unflawed Test Bolt Data**
- **Case 2 Numeric Data**
- **Estimate Only**
- **Needs a Numeric Model**

Research Conclusions

- Typically Conservative Y(a/d) Solution

  (May Vary w/R or σ & Non-Conservative w/R>0.8)

- Crack Front Shape is Initiation Dependent

  (Discrete Surface Defect and No Defect)

- Elliptical to Crescent Crack Fronts

  (A Circular Assumption is Non-Conservative)

- Cannot Ignore Residual Stress from Roll Threads

  (Compressive to 65% of UTS)

Areas for Future Works

- Smaller (a/d < 0.05) Crack Growth Data (New Flaw?)
- Larger (a/d > 0.4) Crack Growth Data
- Even More Detailed Numeric Modeling
  - Contact on the Thread Flanks (Nut to Bolt)
  - Residual Stress Field w/in the FE Model
  - Elliptical & Crescent Shaped Initial Flaws
  - Use (Local) Elastic Plastic Crack Growth
- R > 0.5 Material Data & Use in Growth Models
- Verify Striation Spacing = da/dN for PH 13-8 Mo
- Know Crack Growth Life from a True Crack for Bolts

Striation Spacing ≈ da/dN

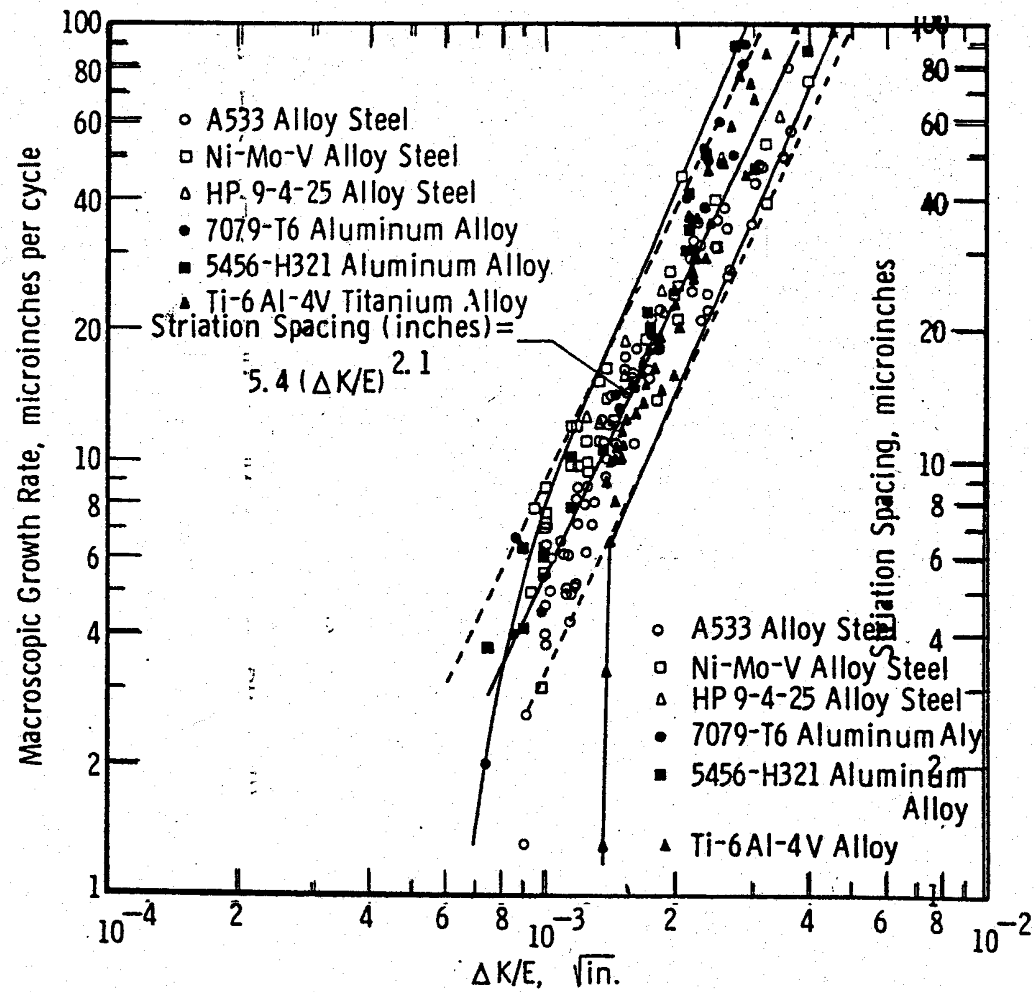
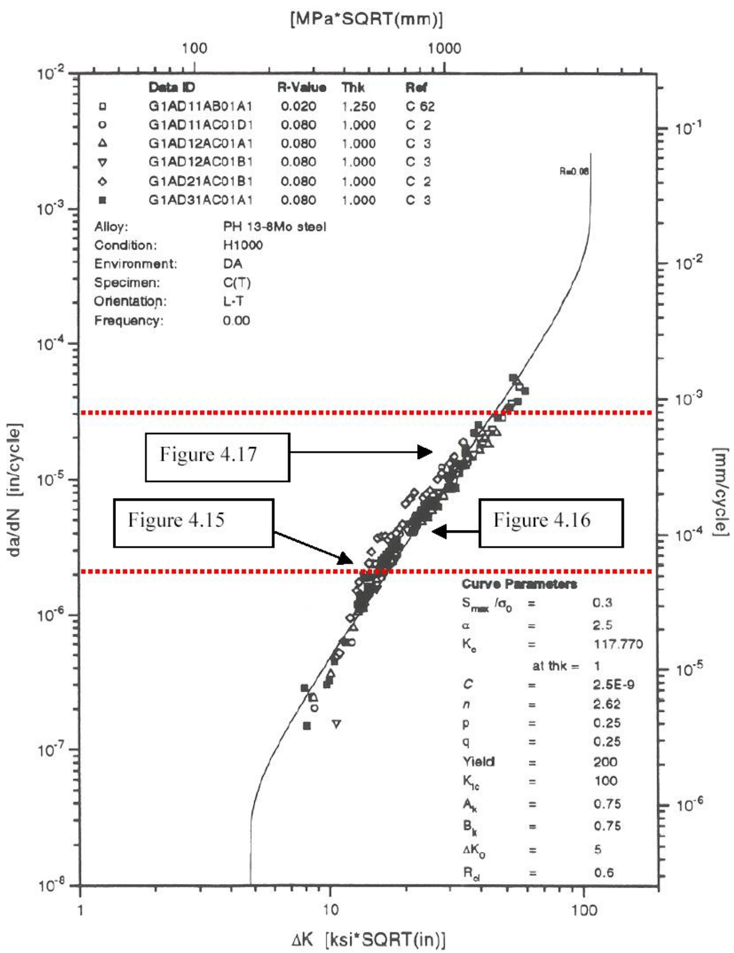
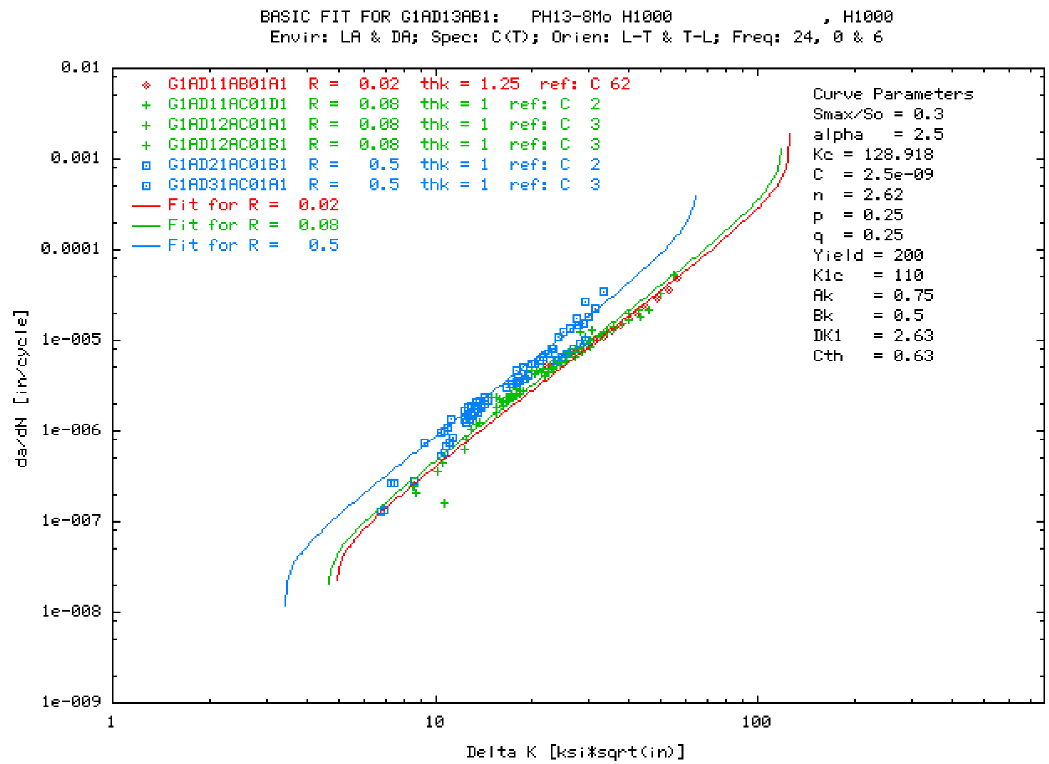


FIG. 9. Relationship of macroscopic crack growth rate to $(\Delta K/E)$ for three alloy steels, one titanium alloy and two aluminum alloys tested at 75 F.

Material Crack Growth Data





Recommendations for Future Work

Need More Experimental Data on True Aerospace Bolts:

a. Residual stresses within the thread root (confirming)

b. Cycles to total bolt failure (N_f) from a know size true crack

c. Fracture surface, discrete flaw crack growth rates when $a/d < 0.05$

d. Crack front shape in stainless steel aerospace bolts (confirming)

e. Material crack growth data when $0.7 < R < 0.9$

3D FEA of Bolts with Discrete Damage Needs Improvements:

a. Contact elements between bolt & nut teeth

b. Inclusion of residual compressive stresses from roll threading

c. Elastic-plastic analysis as needed in the thread root region

d. Initial crescent shape crack growth studies per the above

