# FATIGUE CRACK INITIATION ANALYSIS AND TEST FOR F-35 DESIGN

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# FATIGUE CRACK INITIATION ANALYSIS AND TEST FOR F-35 DESIGN

## ABSTRACT

The F-35 Joint Strike Fighter (JSF) is unique in aviation history as three different design variants, each with unique design requirements, are under development, yet all three are based on a common structural arrangement. Among the many design requirements are those dealing with structural integrity in general and durability fatigue life specifically. Two of the variants, the F-35B, which is designed for Short Takeoff and Vertical Landing (STOVL) capability, and the F-35C which is the Carrier Variant (CV) designed for aircraft carrier operations, must satisfy stringent criteria regarding the number of flight hours required for the formation of cracks at critical locations in both primary and secondary structure.

Strain-based fatigue crack initiation (FCI) analysis is used to establish the design allowable stresses and thereby satisfy the durability life requirements imposed on the STOVL and CV variants. This analysis method uses hysteresis loop tracking to determine the local stress-strain response at a given geometric detail, with the damage calculation then based on this local response. The FCI analysis procedure has been supported by the F-35 building block (BB) test program in three ways. First, the BB program has provided the fundamental material data (cyclic stress-strain and strain-life) data required to conduct the fatigue analysis. Second, crack initiation tests have been conducted at various applied strain ratios in order to calibrate the analysis (mean stress and strain effects). And third, coupon level spectrum FCI tests have been conducted in order to validate the analytical procedure.

In this presentation we begin with a brief overview of F-35 DaDT design requirements. We then provide a description of the FCI analysis algorithm, as well as an overview of the BB tests which serve to both inform and validate it. We note the very significant role that the BB test program plays in analysis validation and ultimately in design verification. We give particular attention to the effect that mean stress and mean strain have on crack initiation life and the manner in which the so called equivalent strain amplitude equation may calibrated for specific materials. We conclude by summarizing FCI analysis data for the STOVL wing.

# FATIGUE CRACK INITIATION ANALYSIS AND TEST FOR F-35 DESIGN

## ⇨ BACKGROUND / REQUIREMENTS

- FATIGUE CRACK INITIATION ANALYSIS
- FATIGUE CRACK INITIATION TESTING
- IMPLEMENTATION OF DESIGN REQUIREMENTS
- CONCLUSIONS

# BACKGROUND / REQUIREMENTS

- **JOINT STRIKE FIGHTER (JSF) concept features three variants of differing capabilities all derived from a common airframe design**
  - *F-35A – conventional take-off and landing (CTOL)*
  - *F-35B – short take-off and landing (CTOVL)*
  - *F-35C – carrier variant (CV)*

- **International development team: Lockheed Martin (prime), Northrop Grumman, BAES, and other partners**

- **Program is currently in the System Design and Development (SDD) Phase which began with contract award in Oct 2001**

- **Airworthiness certification and structural integrity is achieved through demonstration by analysis and test that a number of structural design requirements have been met or exceeded**

# THE THREE JSF VARIANTS




***Next Generation Fighter for US, UK and Int'l Customers***

**http://www.jsf.mil/gallery/gal_video.htm#x35**

# BACKGROUND / REQUIREMENTS

- **Structural integrity requirements are based on USG legacy standards, guidelines and specifications**

- **Specific requirements are defined in the F-35 Structural Design Criteria (SDC)**
  - *Requirements are coordinated across three variants for three different customers, each with a very unique set of performance / capability requirements*

- **Durability and Damage Tolerance (DaDT) certification for metallic structure primarily consists of demonstrating that the formation and growth of flaws, cracks, and other types of damage will not result in:**
  - *Functional impairment*
  - *Loss of operational capability, or*
  - *Loss of residual strength within the vehicle design life*

# BACKGROUND / REQUIREMENTS

- **For STOVL and CV variants, DaDT design requirements consist of**
  - ***Fracture Critical (FC) Parts*** *– more severe of*
    - Fatigue Crack Initiation (FCI) life greater than design life with scatter factor of 2.67
    - Fatigue Crack Growth (FCG) life from 0.01 inch flaw life greater than design life with scatter factor of 1.0
  - ***Maintenance Critical (MC) Parts***
    - FCI life greater than design life with scatter factor of 2.67
  - ***Normal Controls (NC) Parts***
    - FCI life greater than design life with scatter factor of 2.67
  - *All analyses are performed using Critical Point in the Sky (CPITS) spectrum (90% spectrum)*

FCI FOR F-35 DESIGN

# BACKGROUND / REQUIREMENTS

- **Two industry standard fatigue analyses are used in design**
  - *strain-based Fatigue Crack Initiation (FCI) analysis*
  - *Linear elastic fracture mechanics (LEFM) based crack growth analysis (used to address damage tolerance requirements on all variants)*

- **This discussion will focus on the role of FCI analysis and test in F-35 design**

# FATIGUE CRACK INITIATION ANALYSIS AND TEST FOR F-35 DESIGN

- BACKGROUND / REQUIREMENTS

⇨FATIGUE CRACK INITIATION ANALYSIS

- FATIGUE CRACK INITIATION TESTING

- IMPLEMENTATION OF DESIGN REQUIREMENTS

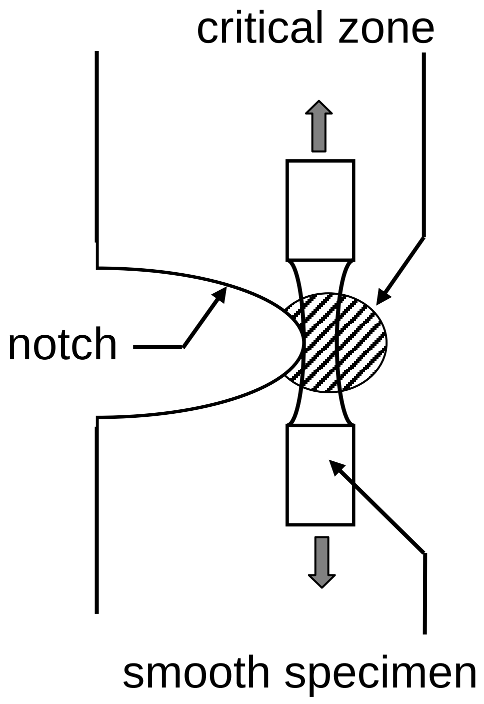
- CONCLUSIONS

# FATIGUE CRACK INITIATION ANALYSIS

- **Strain-life method assumes cyclic deformation of material at point of stress concentration (aka control point (CP)) is *STRAIN CONTROLLED***

- **This is generally true for a/c structures – yielding is very localized and is constrained by surrounding elastic body**

- **Strain-life method assumes local, strain controlled behavior at structural CP can be simulated with smooth (Kt=1) test specimen subjected to strain controlled loading**



# FATIGUE CRACK INITIATION ANALYSIS

- **FCI analysis based on STRESS SEVERITY FACTOR (SSF)**
  - *The stress concentration factor (SCF) at given geometric detail for given load type found by compounding*

$$K_{tA} = K_{tA\_2D} F_{A1} F_{A2}$$

  - *SCF for combined loads found by superposition*

$$K_{t\_total} = \frac{\sigma_{peak}}{S_{ref}} = \frac{1}{S_{ref}} \left[ S_A K_{tA} + S_B K_{tB} + S_C K_{tC} + \cdots \right]$$

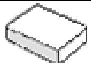
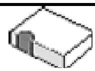
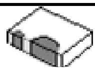
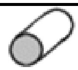
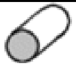
  - *SSF found by applying one or more empirical 'fatigue' factors to total SCF*

$$SSF = F_1 F_2 \left[ \frac{S_A}{S_{ref}} K_{tA} + \frac{S_B}{S_{ref}} K_{tB} + \frac{S_C}{S_{ref}} K_{tC} + \cdots \right]$$

# FATIGUE CRACK INITIATION ANALYSIS

- **SSF is calculated at three points for each structural detail: top surface, mid-plane and bottom surface, and unique values are calculated for tension and compression**

- **FCI tool uses library of pre-determined SSF solutions or user specified SSF**

| Geometry Code | Description |
|---|---|
| UA | User Defined |
|  PA | Finite Width and Thickness Plate |
|  HA | Open Hole in a Plate |
|  HB | Open Hole Adjacent to 2nd Hole in a Plate |
|  FA | Neat-Filled Hole in a Plate |
|  FB | Neat-Filled Hole Adjacent to 2nd Hole in a Plate |
|  LA | Lug |
|  CA | Solid Cylinder |
|  CB | Solid Cylinder with Circumferential Notch |
|  CC | Threaded Solid Cylinder |
|  CD | Hollow Cylinder |

# FATIGUE CRACK INITIATION ANALYSIS

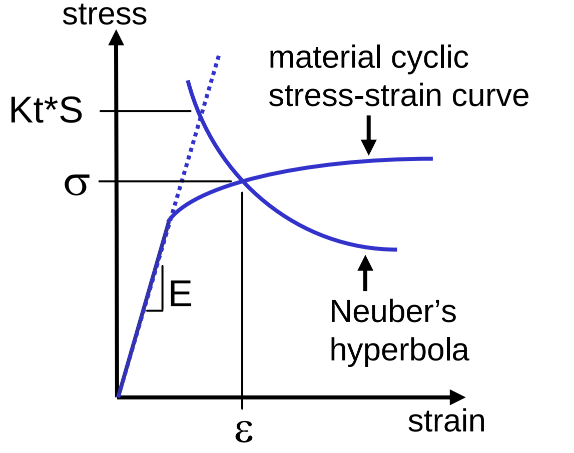
- **Neuber's rule is used to estimate local, stress-strain response based on applied, elastic stress**

$$\sigma\varepsilon = \frac{(SSF \cdot S)^2}{E}$$

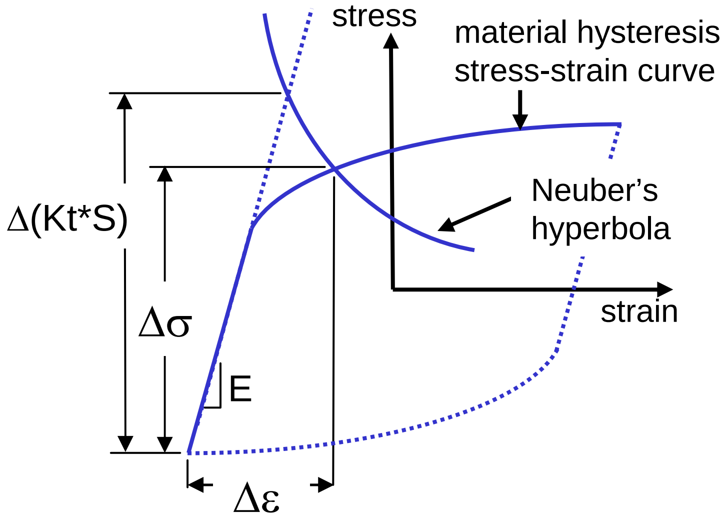
- **For cyclic analysis, Neuber's rule is written in terms of stress and strain ranges**

$$\Delta\sigma\Delta\varepsilon = \frac{(SSF_{max}S_{max} - SSF_{min}S_{min})^2}{E}$$

- **For each response calculation, origin of Neuber's hyperbola is placed at the end point of the previous excursion**




Neuber's rule for monotonic loading




Neuber's rule for cyclic loading

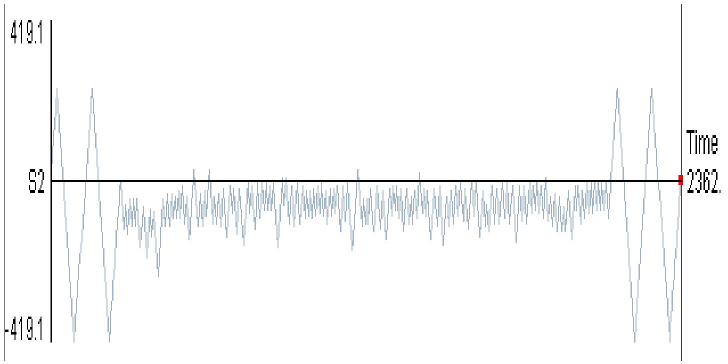
# FATIGUE CRACK INITIATION ANALYSIS

- **Local response stress and strain history significantly different than applied stress history**
  - *mean stress, mean strain shift*
  - *memory effect*
- **Assume damage increment is incurred each time a hysteresis loop is closed, calculate $R_\varepsilon$ and $R_\sigma$ for closed loop**

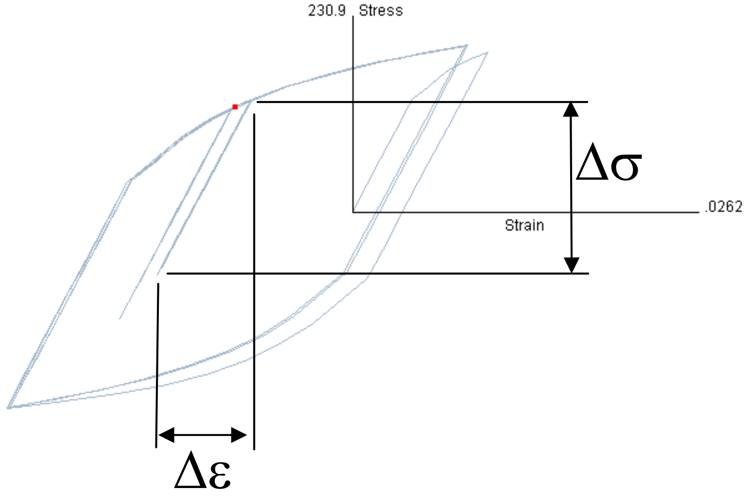
$$R_\varepsilon = \varepsilon_{min} / \varepsilon_{max}$$

$$R_\sigma = \sigma_{min} / \sigma_{max}$$

- **Local stress and strain ratios generally do not have same value as applied stress ratio**




applied stress history



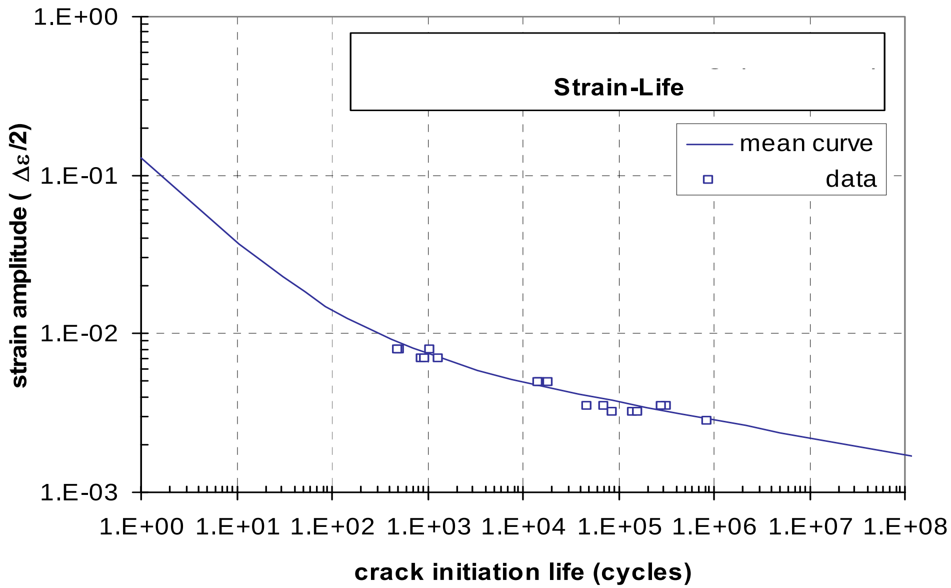

local stress-strain response

# FATIGUE CRACK INITIATION ANALYSIS

- **Damage increments are calculated based on constant amplitude material data curves that indicate strain amplitude vs no. cycles to crack initiation (aka strain-life curve)**
  - *Strain life curve is generated using smooth specimens subjected to constant amplitude, fully reversed ($R_\varepsilon$=-1) strain cycling*

- **In general, closed hysteresis loops have $R_\varepsilon \neq -1$ and $S_{mean} \neq 0$, thus a relation between arbitrary $R_\varepsilon$ and $R_\varepsilon = -1$ is needed**

- **This is referred to as the equivalent strain amplitude equation; it is required to determine equivalent, $R_\varepsilon$=-1 amplitude for any hysteresis loop**



# FATIGUE CRACK INITIATION ANALYSIS

- **Equivalent strain amplitude relations (cont'd):**
  - ***Original version of LOOPIN (NADC-81010-60) (now obsolete):***

$$\left(\frac{\Delta\varepsilon}{2}\right)_{\mathrm{equiv,R=-1}} = \left(\frac{\Delta\varepsilon}{2}\right) + 0.000655(1+\mathrm{R}_{\varepsilon}) + 0.197(1-\mathrm{R}_{\sigma})\frac{\sigma_{\mathrm{m}}}{\mathrm{E}}$$

  - ***revised equation (now in use on F-35)***

$$\left(\frac{\Delta\varepsilon}{2}\right)_{equiv\ ,R=-1} = \left(\frac{\Delta\varepsilon}{2}\right) + A\left(\frac{2\sigma_m\sigma_a}{|\sigma_m| + \sigma_a}\right)\frac{1}{E} + B\left(\frac{2\varepsilon_m\varepsilon_a}{|\varepsilon_m| + \varepsilon_a}\right)$$

  - ***Where mean stress coefficient, A, and mean strain coefficient, B, are calibrated to test data***

FCI FOR F-35 DESIGN

# FATIGUE CRACK INITIATION ANALYSIS

- **Damage increment is calculated as ratio of number of closed loops at given equivalent strain amplitude to number of cycles material can sustain at that amplitude – Palmgren-Miner rule**

$$d_i = \frac{n_i}{N}$$

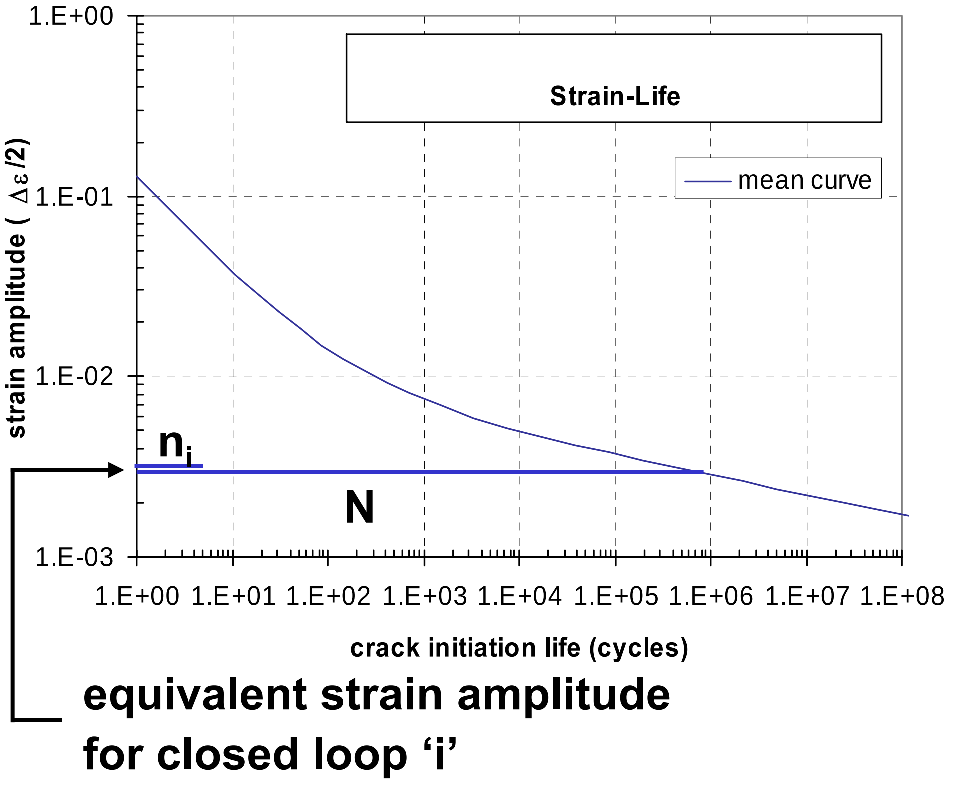
- **Total damage for the block found as linear sum of all damage increments**

$$D = \sum_i d_i$$

- **Calculated fatigue life**

$$N_i = \frac{1}{D}$$

- **This fatigue life is defined as time to form an 0.01 inch flaw**



# FATIGUE CRACK INITIATION ANALYSIS

- **Strain-life method has been implemented in numerous software programs**

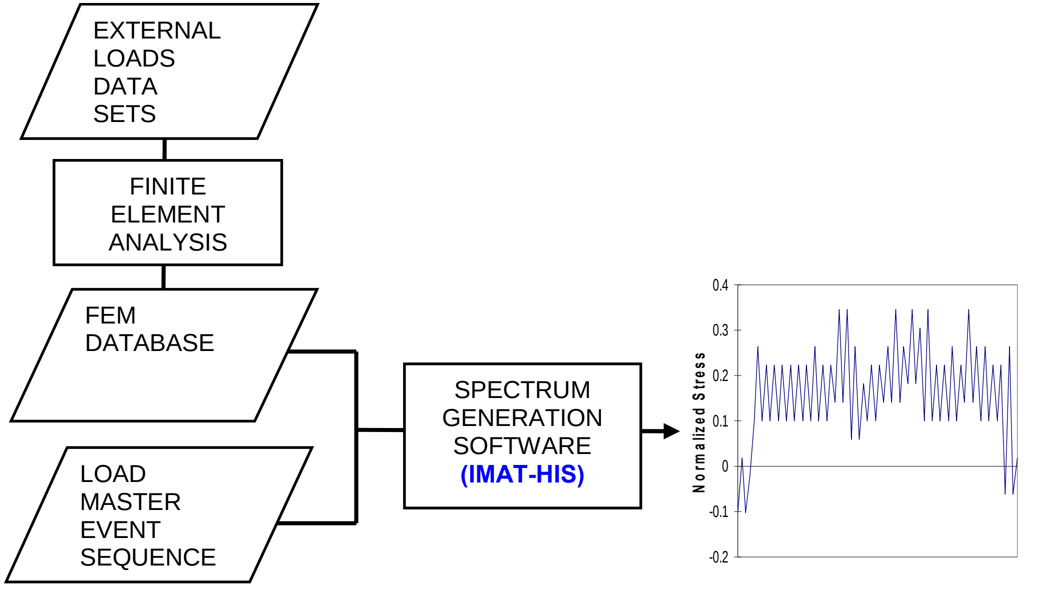
- **One program that has seen considerable use for military a/c is *LOOPIN* – initially developed by Northrop under USN contract – NADC-81010-60**

- **Version of LOOPIN in use on F-35 is based on original USN implementation (uses same loop tracking algorithm)**

- **This version of LOOPIN has been extensively modified and is highly automated – part of integrated durability and damage tolerance analysis tool set (IMAT)**

# IMPLEMENTATION OF DESIGN REQUIREMENTS

- **FCI analyses can be performed using FEM generated spectra**
- **Coarse grid finite element model (FEM) approach for generation of CP stress spectra**
  - *A coarse grid airframe FEM is used to generate element stresses for a wide range of fatigue load cases*
  - *Model results for each fatigue load case are stored in a FEM database*
  - *Master Event Sequence (MES) prescribes the sequence of load conditions representing design service usage for the aircraft*
  - *Complete stress sequence for any element in the FEM may be assembled by marrying FEM db and MES*



# FATIGUE CRACK INITIATION ANALYSIS AND TEST FOR F-35 DESIGN

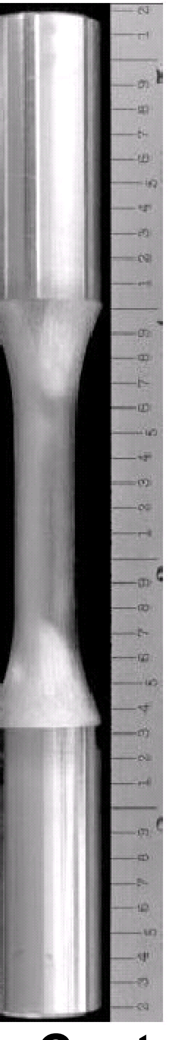
- BACKGROUND / REQUIREMENTS
- FATIGUE CRACK INITIATION ANALYSIS

⇨ **FATIGUE CRACK INITIATION TESTING**

- IMPLEMENTATION OF DESIGN REQUIREMENTS
- CONCLUSIONS

# FATIGUE CRACK INITIATION TESTING

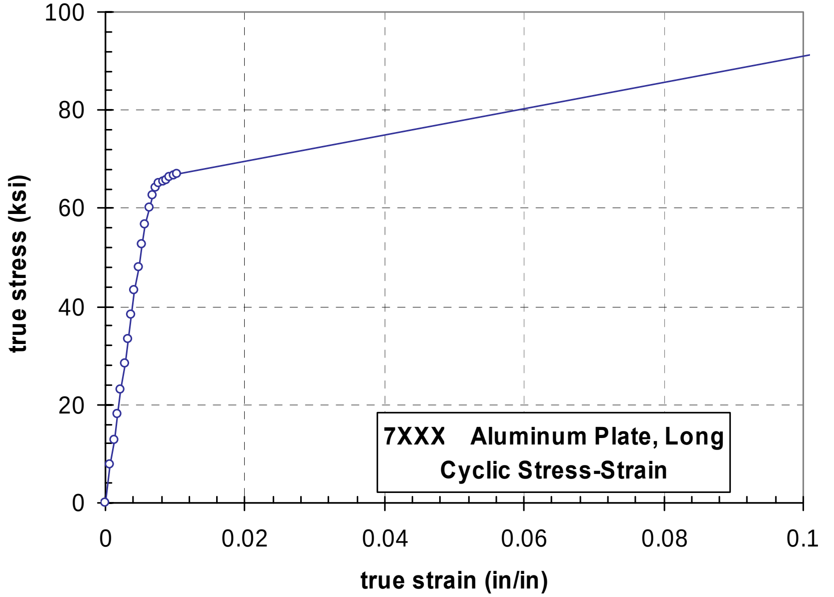
- **Three objectives for F-35 building block FCI tests**
  - ***Materials characterization*** *– define cyclic stress-strain and strain-life properties for critical materials*
  - ***Analysis calibration*** *– determine appropriate equivalent strain amplitude relationship for critical materials*
  - ***Analysis validation*** *– demonstrate that calibrated analysis reliably predicts fatigue crack initiation life for representative F-35 structural details, materials and loading spectra*

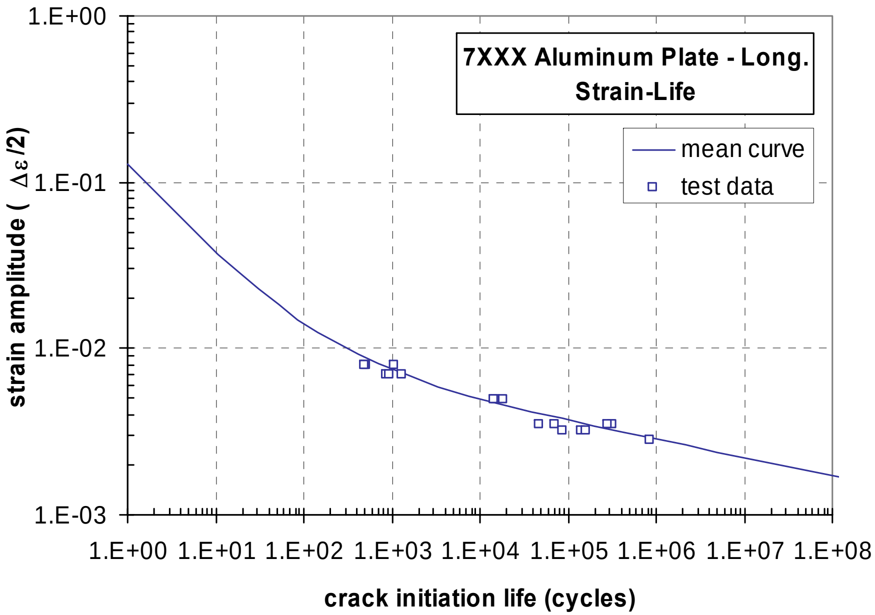


**Strain Control Fatigue Specimen ASTM E606**

# FCI FOR F-35 DESIGN
# FATIGUE CRACK INITIATION TESTING

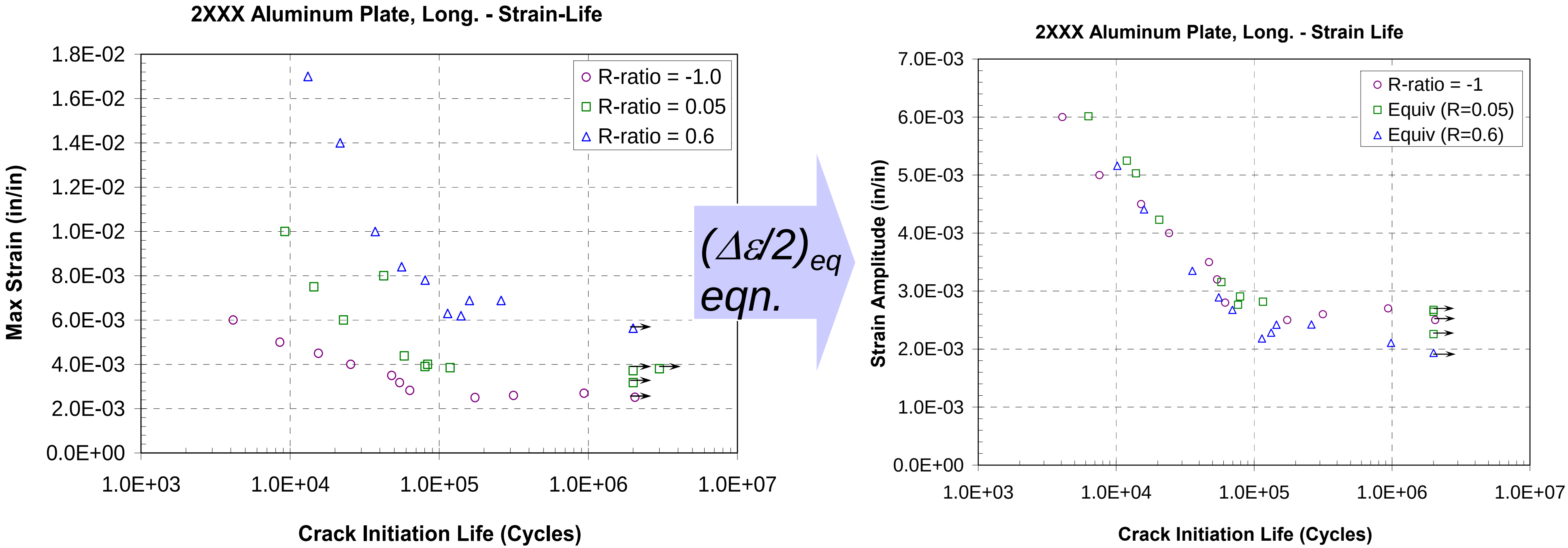
- **Materials Characterization:**
  - *Cyclic stress-strain curve*
    - *Describes stable hysteresis behavior*
    - *Locus of reversal points from a series of stable stress-strain hysteresis loops over a range of strain amplitudes*
    - *Hysteresis loops are assumed symmetric about both stress and strain axes (Masing's hypothesis)*
  - *Strain-life curve*
    - Quantifies number of cycles required for the formation of a 0.01" flaw
    - Based on constant amplitude, fully reversed, strain-controlled tests
    - Mean curve is drawn through the test points



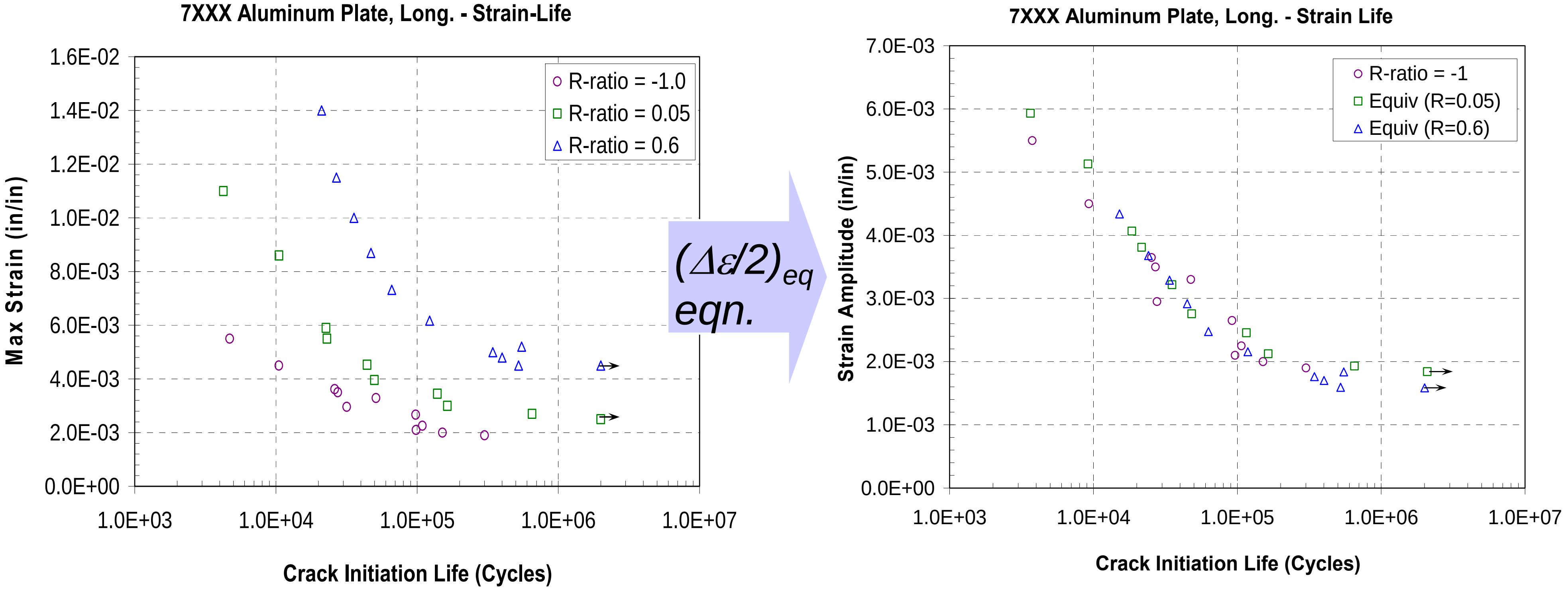
# FATIGUE CRACK INITIATION TESTING

- **Analysis calibration**
  - *Appropriate coefficients for* ***equivalent strain amplitude relationship*** *are found by calculating equivalent strain amplitudes for tests run at different strain ratios*
  - *Non-fully-reversed test data required*
  - *Calibration has been performed for critical materials*



# FATIGUE CRACK INITIATION TESTING

- **Analysis calibration (cont'd)**
  - *Calibration has been performed for critical materials*



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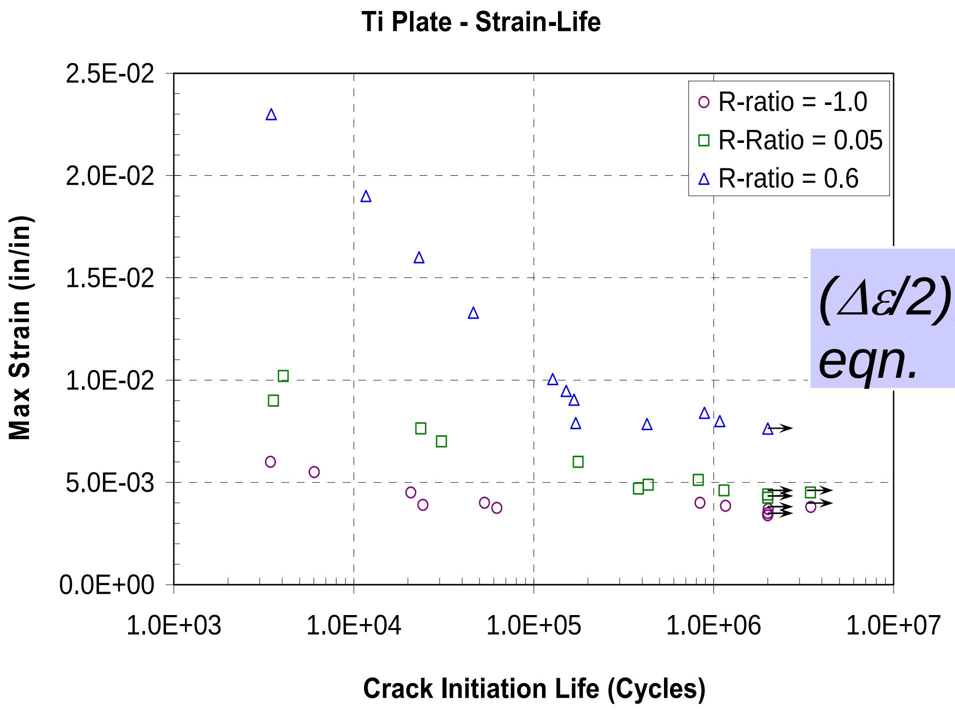
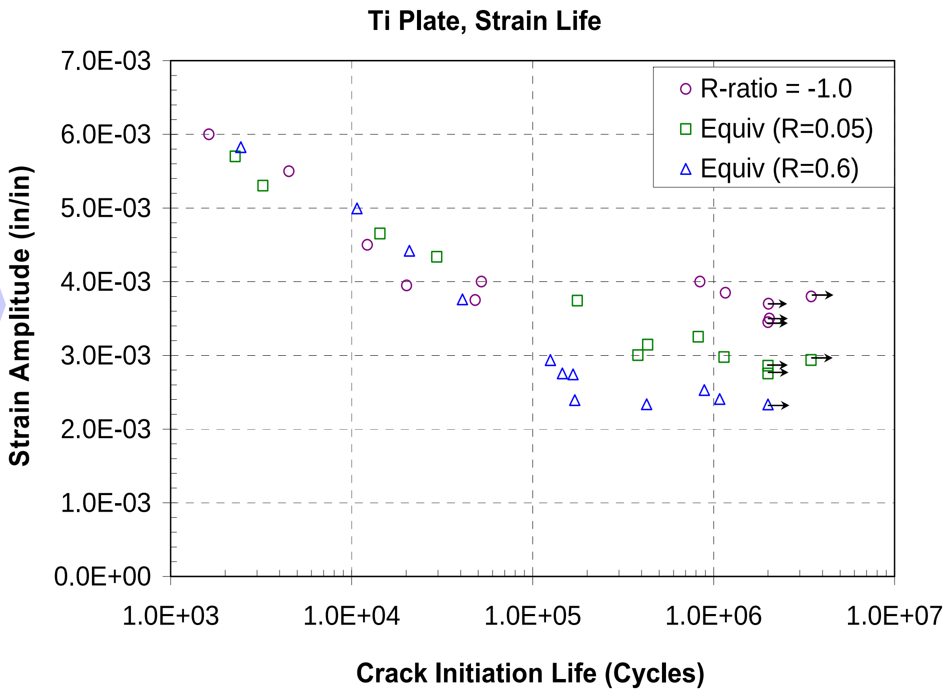



*$(\Delta\varepsilon/2)_{eq}$ eqn.*



# FATIGUE CRACK INITIATION TESTING

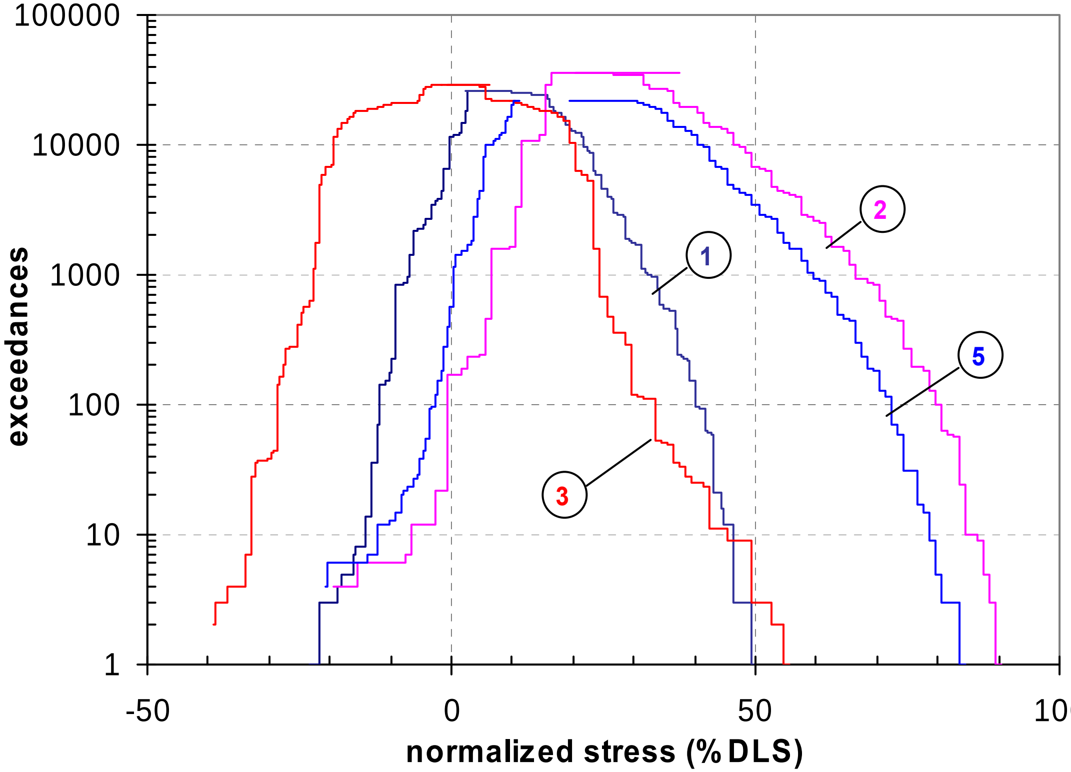
- **Analysis validation**
  - *FCI tests conducted for four different types of spectrum loading*
  - *Intended to represent the full range of spectrum types experienced in the F-35 airframe*

1 = fuselage bhd upper cap (FB)

2 = fuselage bhd wing attach (WBM)

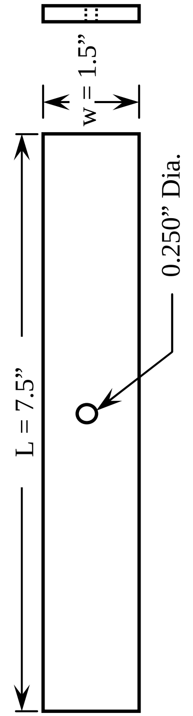
3 = vertical tail tip rib

5 = wing spar lwr cap, (WBM)

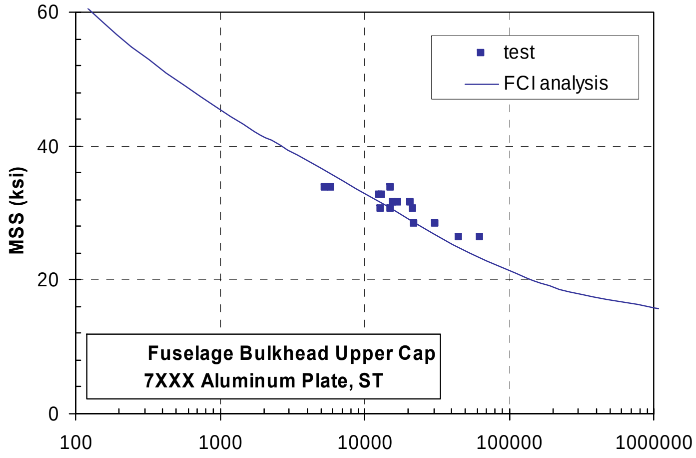


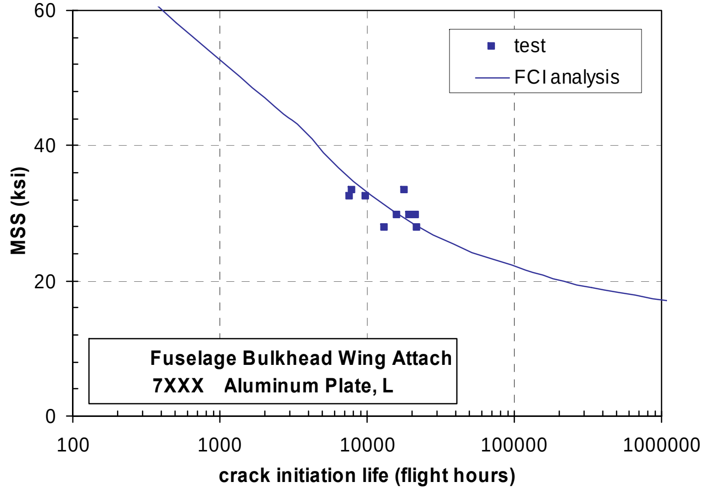
# FATIGUE CRACK INITIATION TESTING

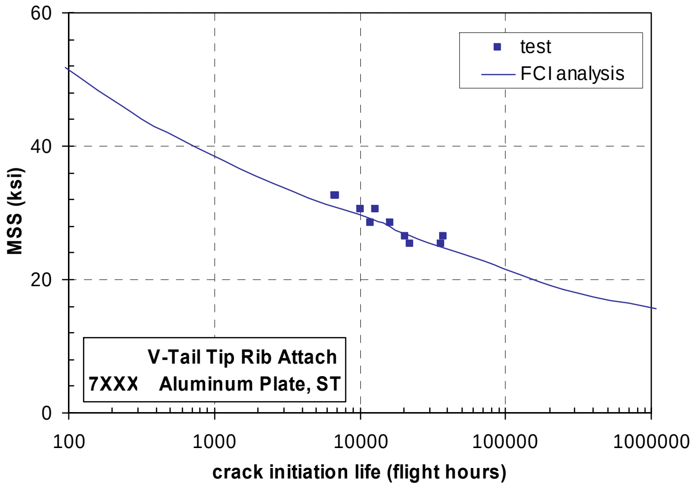
- **Analysis validation**
  - *FCI analysis for 7XXX aluminum alloy captures mean of BB test data*

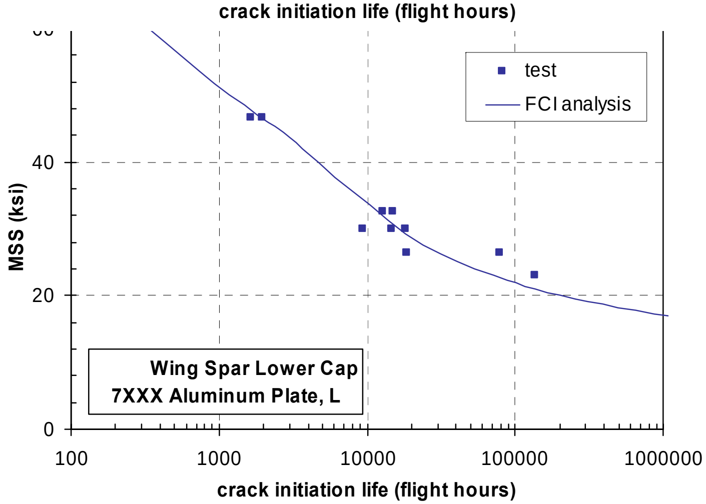



FCI Test Specimen Configuration



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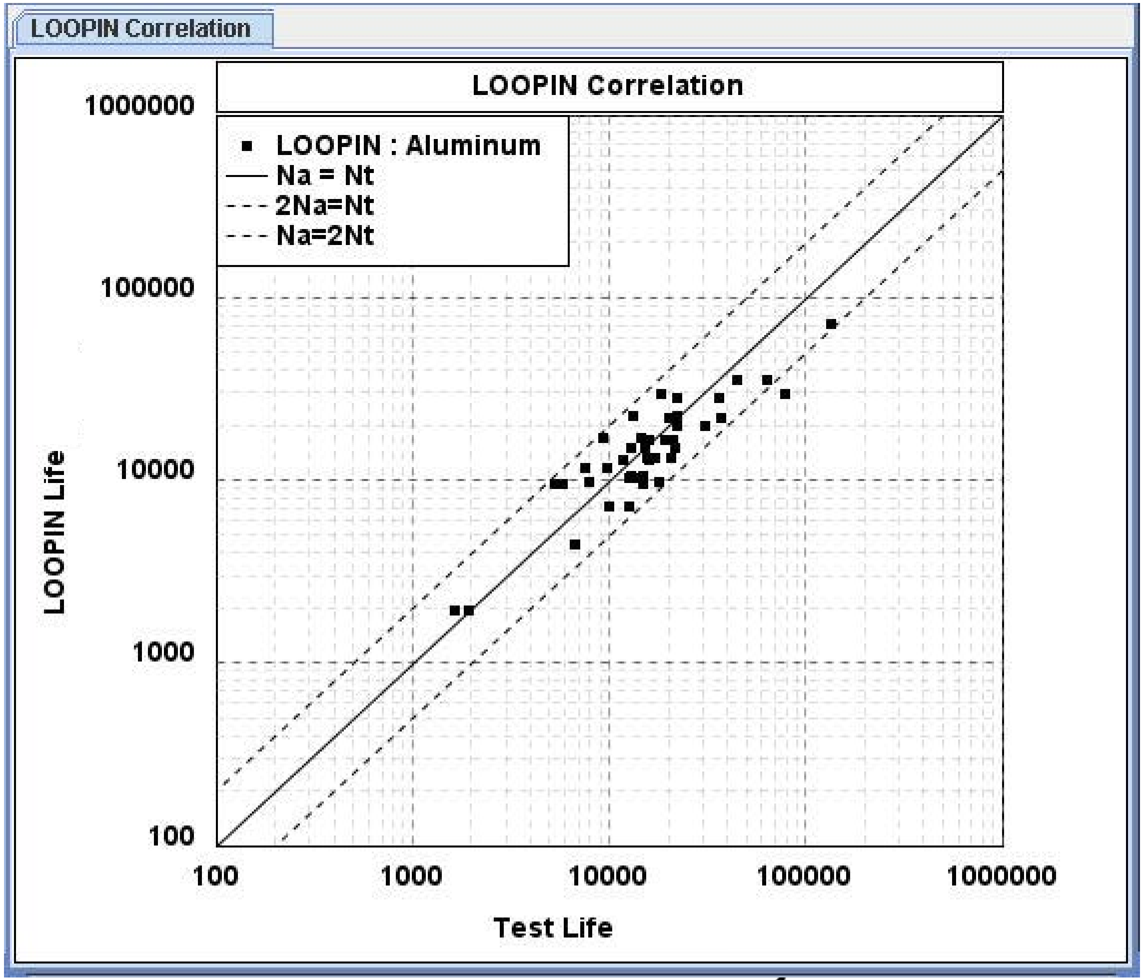


# FATIGUE CRACK INITIATION ANALYSIS AND TEST FOR F-35 DESIGN

- BACKGROUND / REQUIREMENTS
- FATIGUE CRACK INITIATION ANALYSIS
- FATIGUE CRACK INITIATION TESTING

⇨ **IMPLEMENTATION OF DESIGN REQUIREMENTS**

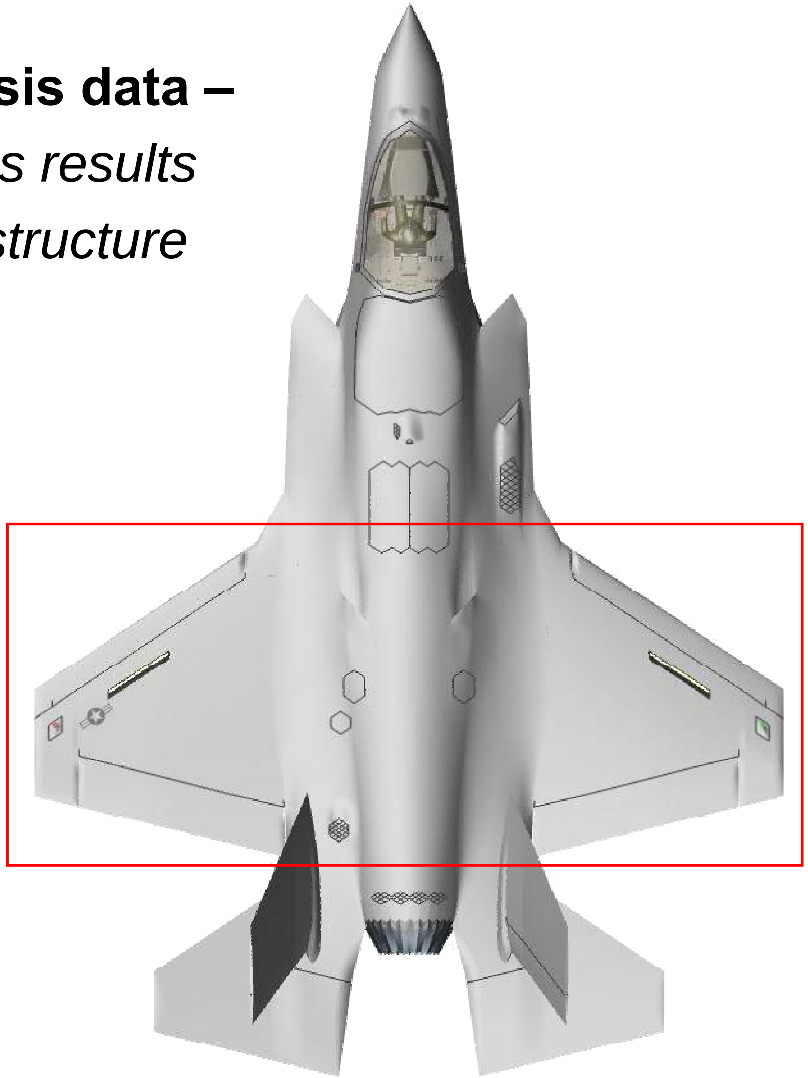
- CONCLUSIONS

# IMPLEMENTATION OF DESIGN REQUIREMENTS

- **Validated DaDT analysis tools are used to support the design process**
- **Depending on the variant type and the part classification, either FCI or FCG (or both) analyses will be used to generate a design allowable stress for each critical location on each part**
  - *allowable is specific to material and local spectrum*
  - *used to write DaDT margin of safety (MS)*
- **The design process consists (in part) of iterating the design, i.e. modifying the structural configuration, until all DaDT margins are positive**
- **It is the process of generating allowable stresses that are specific to F-35 materials and usage that imposes the DaDT requirements**

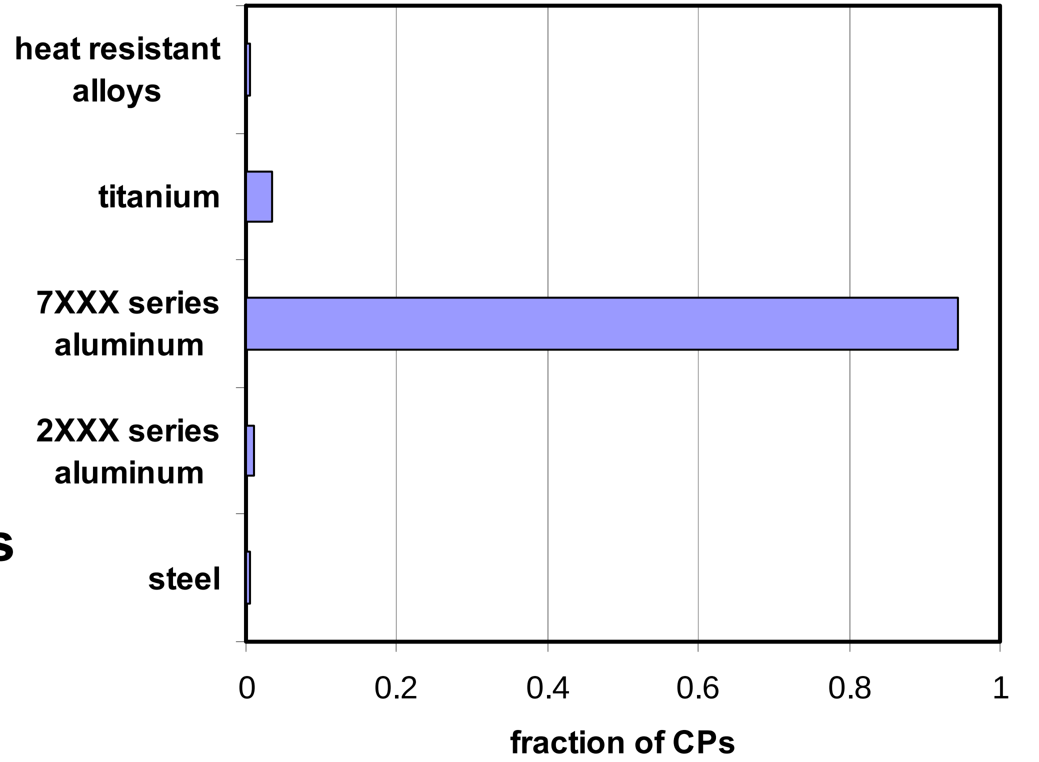
# IMPLEMENTATION OF DESIGN REQUIREMENTS

- **Overview of STOVL wing DaDT analysis data –**
  - *Over 5200 CPs with archived analysis results*
  - *Approx 200 CPs at which FCI sized structure*
- **FCI requirement is more likely to impact structure subjected to compression dominated loading**



# IMPLEMENTATION OF DESIGN REQUIREMENTS

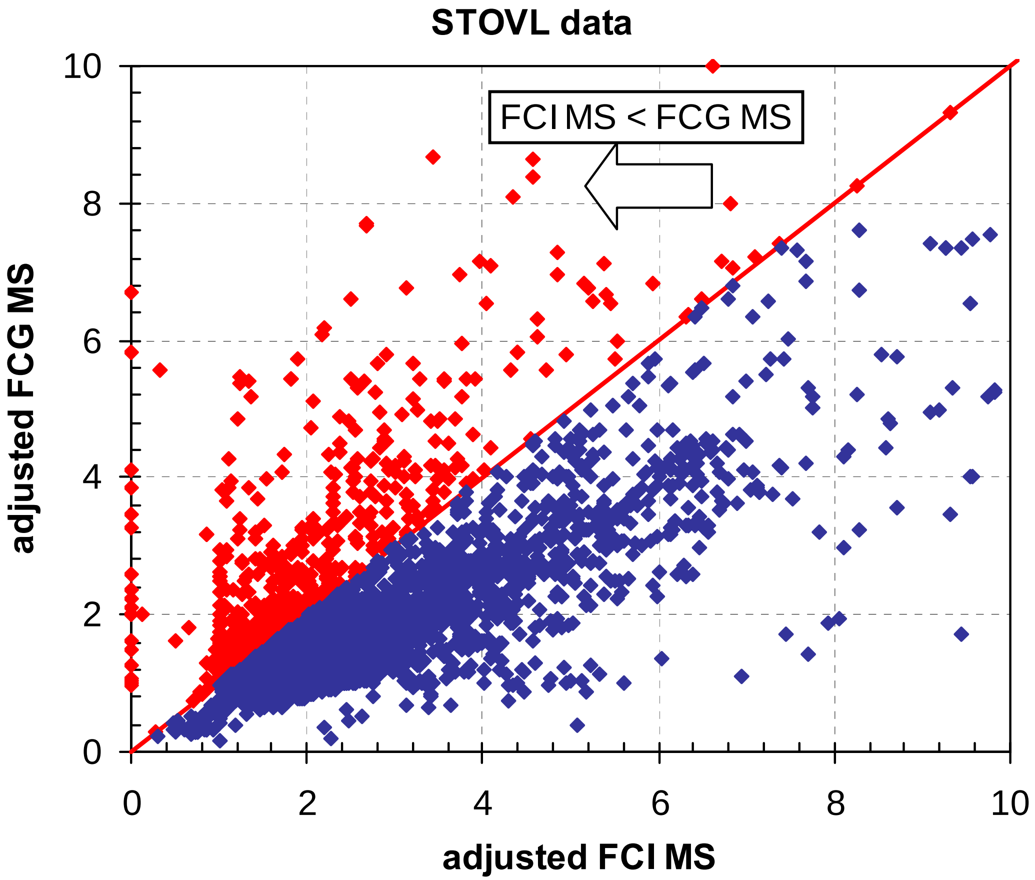
- **Overview of STOVL wing DaDT analysis data –**
  - *Over 5200 CPs with archived analysis results*
  - *Approximate material distribution:*
    - ***30 steel***
    - ***50 2XXX aluminum***
    - ***5000 7XXX aluminum***
    - ***180 titanium***
    - ***20 HR alloys***




**More than 90% of archived CPs in the wing are for 7XXX series aluminum**

# IMPLEMENTATION OF DESIGN REQUIREMENTS

- **Overview of STOVL wing DaDT analysis data –**
  - *Over 5200 CPs with archived analysis results*
  - *Approx 800 CPs at which FCI requirement more severe than FCG*




**FCI requirement is more severe than FCG requirement for about 15% of archived CPs in the wing**

# FATIGUE CRACK INITIATION ANALYSIS AND TEST FOR F-35 DESIGN

- **BACKGROUND / REQUIREMENTS**
- **FATIGUE CRACK INITIATION ANALYSIS**
- **FATIGUE CRACK INITIATION TESTING**
- **IMPLEMENTATION OF DESIGN REQUIREMENTS**

⇨ **CONCLUSIONS**

FCI FOR F-35 DESIGN

# CONCLUSIONS

- **Fatigue Crack Initiation (FCI) analysis method calibrated and validated during F-35 building block test program**
- **FCI design requirements met in very comprehensive manner using automated analysis tools**
- **FCI plays significant role in sizing primary structure for F-35 STOVL and CV**