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F-35 Full Scale Durability Modeling and Test

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F-35 Full Scale Durability Modeling and Test

ABSTRACT

The F-35 Joint Strike Fighter program includes three aircraft variants, one of which has been designed and built according to US Air Force requirements, and the other two of which have been designed and built according to US Navy requirements. For all three variants, a system design and development (SDD) configuration aircraft is being subjected to a full-scale durability (FSD) test. In each case, the complete airframe is being subjected to two lifetimes of 'severe' design spectrum loading, with maneuver, catapults/arrestments (carrier variant only) and buffet loads applied as separate, alternating 1000 flight hour blocks during the major test sequence. For the airframe tests, the buffet loads are applied quasi-statically; for the separate vertical tail component tests, they are applied dynamically. In addition, tests of doors and attachments (local tests) are conducted when the full airframe test is down for inspections (as required, for example, between the first and second lifetimes).

In this paper, we describe the manner in which the airframe tests were designed, including fatigue spectrum development and test adequacy analyses. In addition, we provide a summary of the test findings to date, along with a description of the analytical simulation for a typical finding. The paper includes an analysis vs test correlation summary that provides an indication of the validity of the fatigue crack initiation (FCI) and fatigue crack growth (FCG) analysis methods used to design the aircraft.

F-35 Full Scale Durability Modeling and Test

⇨ **INTRODUCTION**

- **DURABILITY & DAMAGE TOLERANCE ANALYSIS**
- **FULL SCALE DURABILITY TESTING**
- **TEST CORRELATION ANALYSES**
- **SUMMARY**

F-35 FSD Modeling and Test:
Introduction

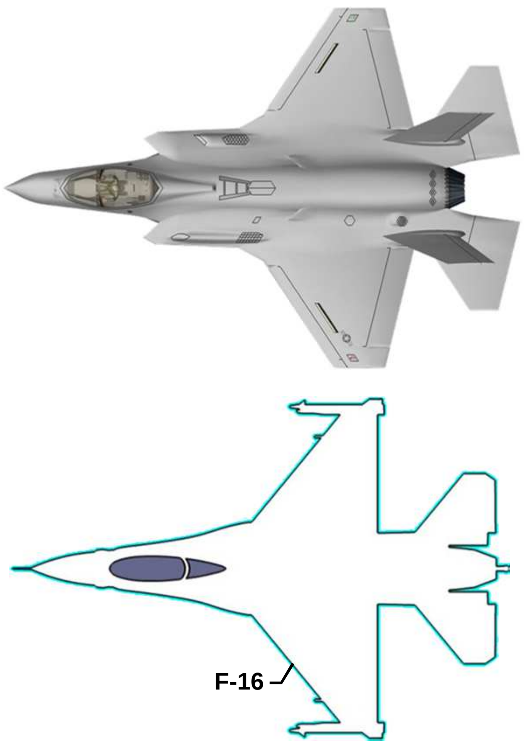
- **Three design variants are under development:**
  - ***F-35A – Conventional Takeoff and Landing (CTOL) aircraft, will serve as a multi-role fighter replacement for the US Air Force F-16 Falcon***
  - ***F-35B – Short Takeoff and Vertical Landing (STOVL) aircraft, will serve as a replacement for the well known AV-8B II Harrier "Jump Jet."***
  - ***F-35C – Carrier Variant (CV) aircraft, will be the first ever stealthy Naval fighter capable of aircraft carrier operations at sea***
- **Each has unique capabilities, yet each is derived from a common airframe design**
- **Airworthiness and structural integrity certification are achieved through demonstration by analysis and test that static strength, durability, and damage tolerance (and other) structural capability requirements have been met or exceeded**

F-35 FSD Modeling and Test:
Introduction

- **Three design variants based on a common airframe**

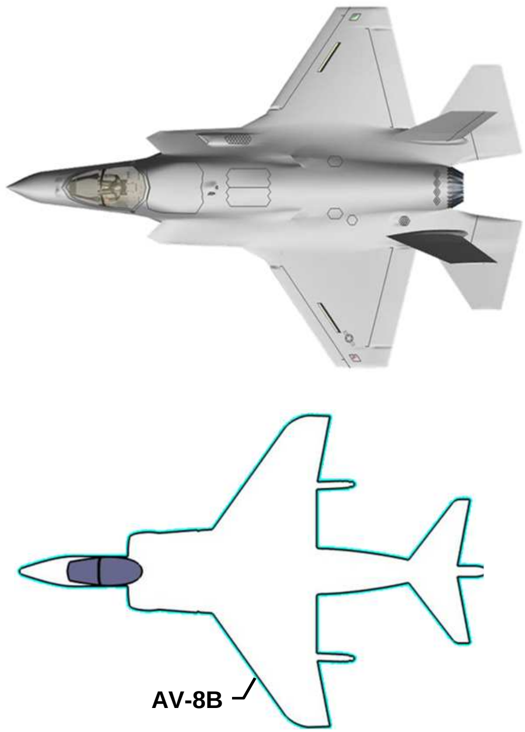
CTOL

Span (ft)	35
Length (ft)	51.1
Wing Area (ft^2)	460



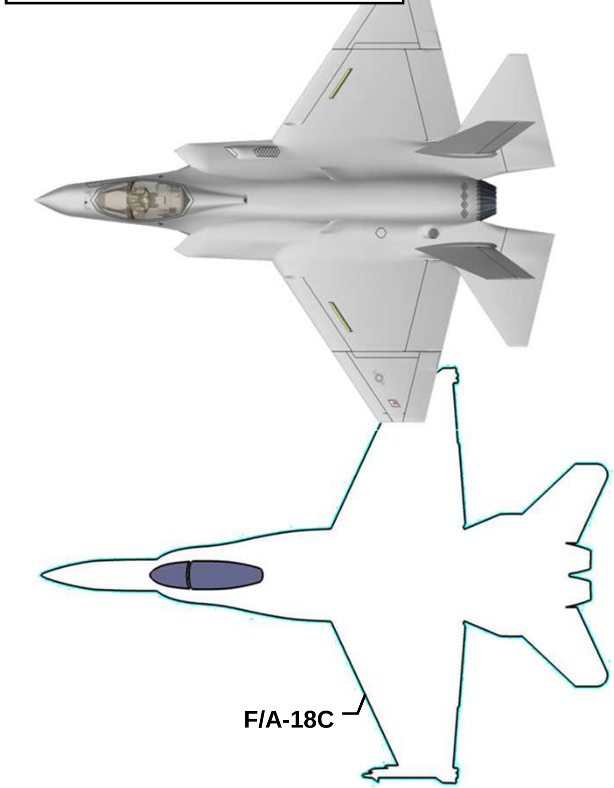
STOVL

Span (ft)	35
Length (ft)	51.1
Wing Area (ft^2)	460



CV

Span (ft)	43
Length (ft)	51.4
Wing Area (ft^2)	620

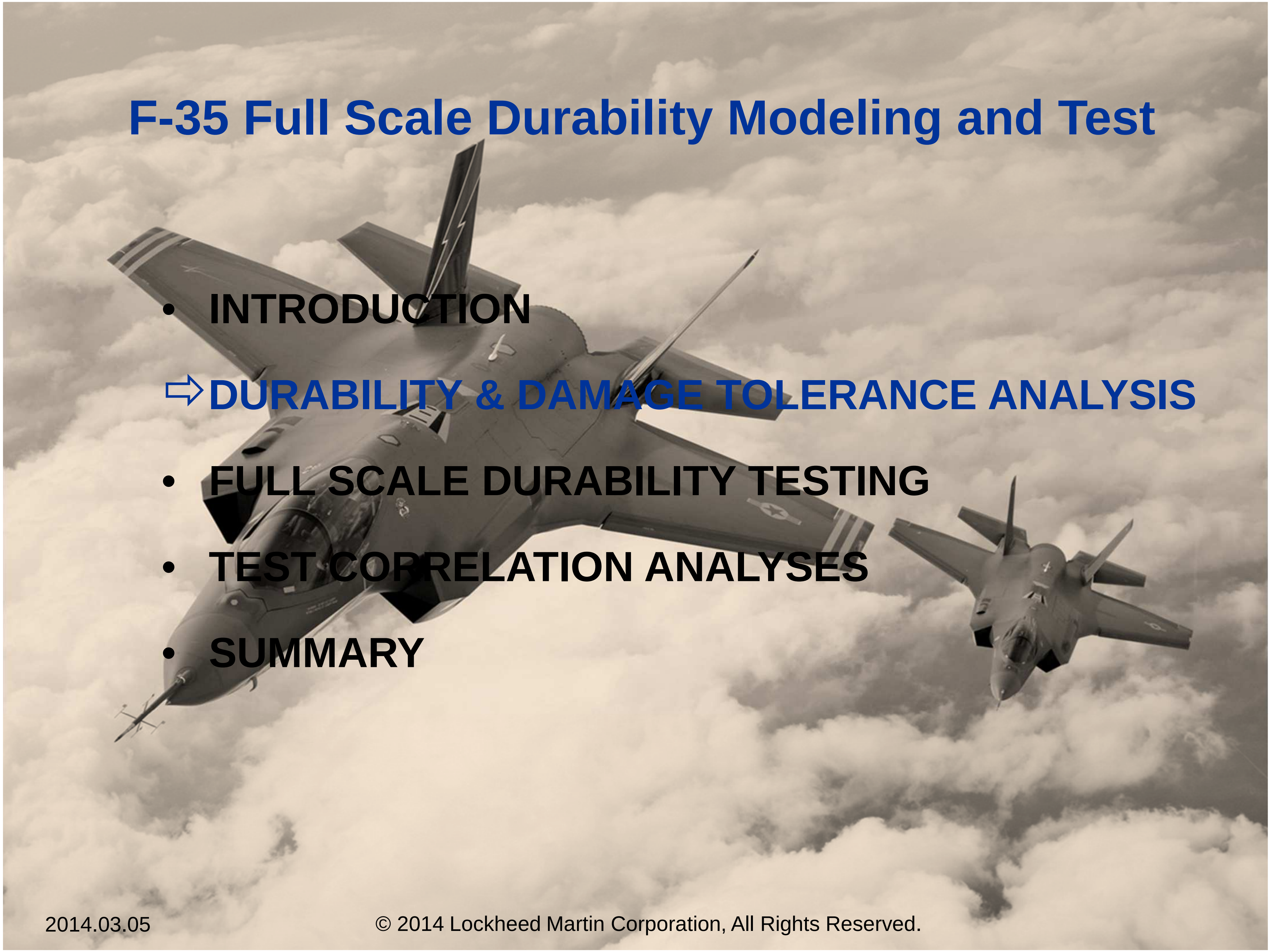


F-35 FSD Modeling and Test:
Introduction

- **Path to certification for each variant includes a long and complex sequence of building block test programs designed to:**
  - ***characterize materials,***
  - ***demonstrate structural concepts,***
  - ***validate design methods***

- **Certification requires full scale ground and flight tests which demonstrate the capability of the vehicle. The ground tests are laboratory tests in which fully instrumented aircraft are subjected to simulated ground handling and operational flight loads – for F-35 this includes:**
  - ***static tests for all three variants***
  - ***durability (fatigue) tests for all three variants***
  - ***simulated carrier landing (drop) tests***

- **Each F-35 FSD test must successfully complete two lifetimes fatigue cycling**



F-35 Full Scale Durability Modeling and Test

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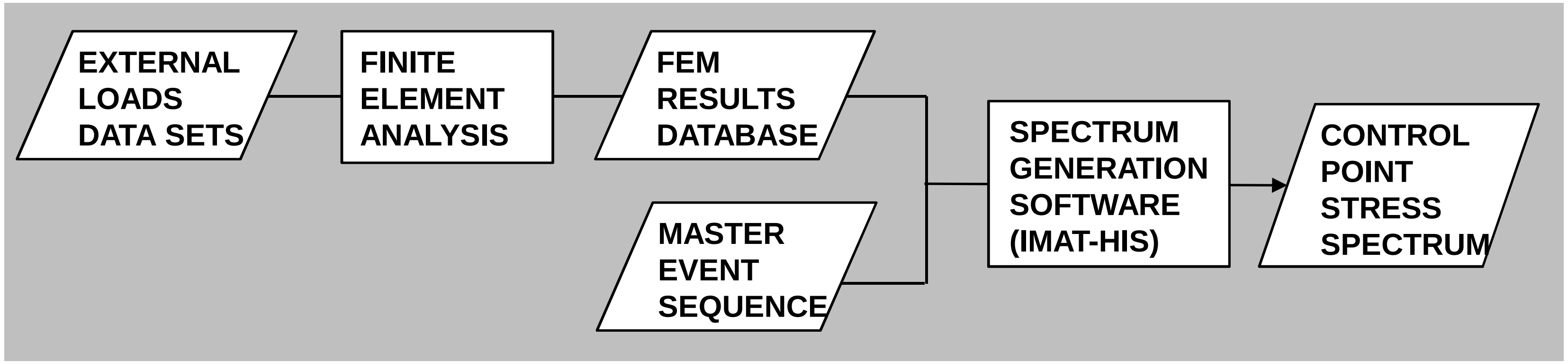
F-35 FSD Modeling and Test:
Durability & Damage Tolerance Analysis

- **All three of the F-35 variants have been designed using proven durability and damage tolerance (DaDT) design principles.**
- **For the CTOL aircraft:**
  - ***Durability requirement – 0.01 flaw to failure in 2 lifetimes using 90% spectrum***
  - ***Damage tolerance requirement – DT flaw to failure in 2 lifetimes using mean spectrum (where the initial DT flaw size is structure, geometry dependent)***
- **For the STOVL and CV aircraft:**
  - ***Durability requirement – formation of 0.01 flaw in 2.67 lifetimes using CPITS spectrum***
  - ***Damage tolerance requirement – 0.01 flaw to failure in 1 lifetime using CPITS spectrum***

F-35 FSD Modeling and Test:
Durability & Damage Tolerance Analysis

FATIGUE SPECTRUM GENERATION

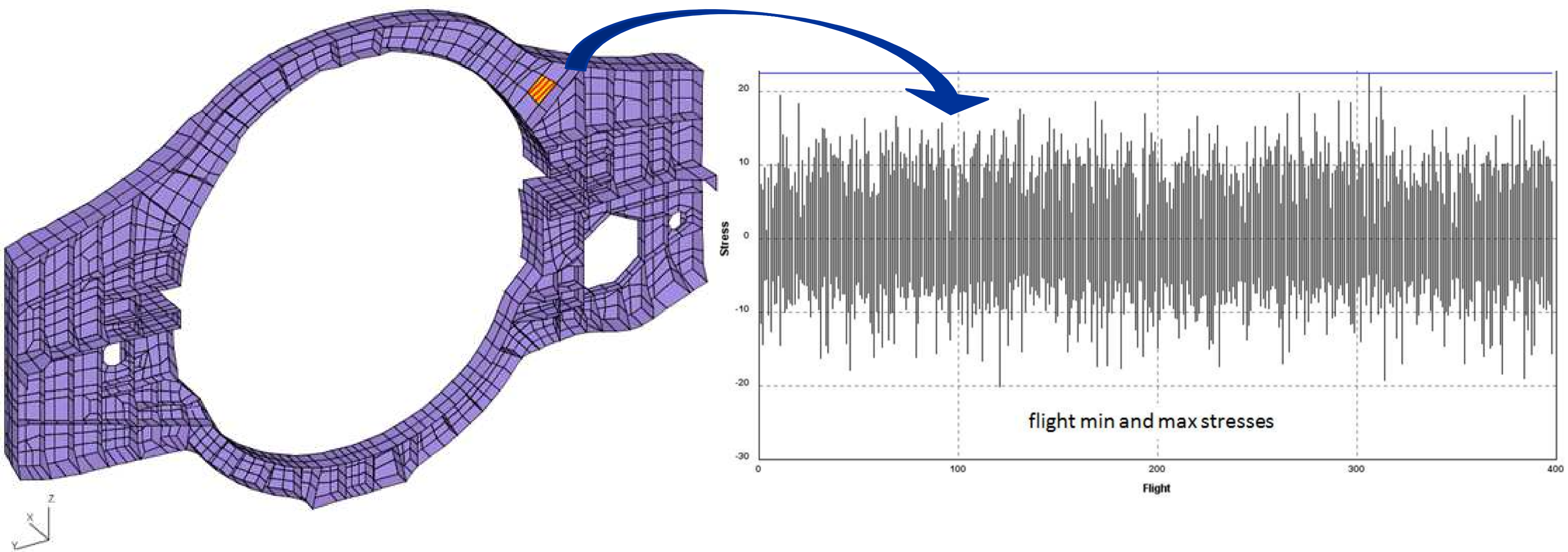
- **Fatigue analyses are performed using stress spectra which are generated using the air-vehicle FEM approach**
- **FEA are conducted for large number of fatigue load cases, results stored in FEM database**
- **Master event sequence (MES) defines aircraft usage**
- **Stress sequence is assembled by ordering the results for the selected element(s) for each fatigue load condition in the manner prescribed by the MES**



F-35 FSD Modeling and Test:
Durability & Damage Tolerance Analysis

FATIGUE SPECTRUM GENERATION (cont'd)

- **Stress at a control point is based on a given component of stress from a given element (or elements) in a finite element model (FEM)**
- **With coarse grid FEM approach, a stress spectrum can be automatically generated for virtually any element or combination of elements in the FEM**



F-35 FSD Modeling and Test:

Durability & Damage Tolerance Analysis

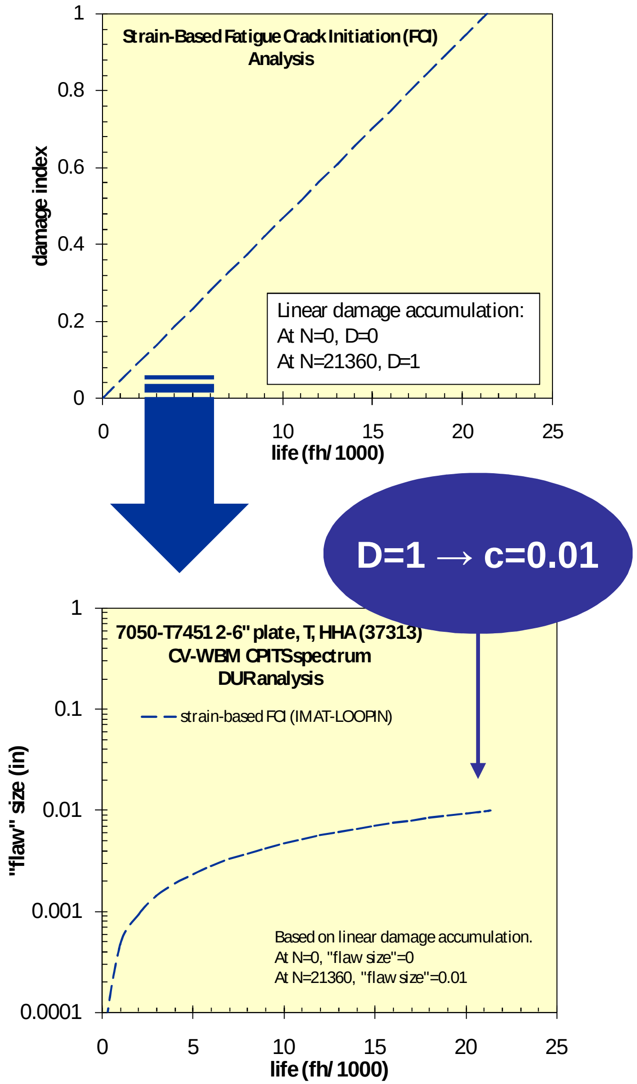
FATIGUE CRACK INITIATION (FCI) ANALYSIS

- **FCI analyses are performed using the computer program LOOPIN, originally developed for the U.S. Navy**
- **Standard hysteresis loop tracking, strain-based damage accumulation methodology developed by Dowling and others**
- **Compound stress concentration factor (SSF) is computed for each control point geometry:**
  - ***Superposition used when multiple load types (bypass, bending, bearing) are present***
  - ***In-phase variation of load types is assumed***
  - ***The applied stresses for each cycle in the fatigue load spectrum are scaled by the SSF to determine the local or notch stress.***
- **Neuber's rule used in conjunction with the material cyclic stress-strain curve to determine the cyclic stress-strain response at the notch or stress concentration**

F-35 FSD Modeling and Test:
Durability & Damage Tolerance Analysis

FATIGUE CRACK INITIATION (FCI) ANALYSIS

- **Mean stress and stress amplitude and mean strain and strain amplitude defined for each closed hysteresis loop**
- **Equivalent, fully-reversed (R=-1) strain amplitude is calculated using one of several mean stress and strain corrections**
- **Damage increment calculated for each closed loop as ratio of applied vs allowable cycles, total damage for the spectrum found by summing damage increments (Palmgren-Miner rule)**
- **Calculated crack initiation life is defined as the number of cycles required for the accumulated damage value to reach 1.0.**



F-35 FSD Modeling and Test:
Durability & Damage Tolerance Analysis

FATIGUE CRACK GROWTH (FCG) ANALYSIS

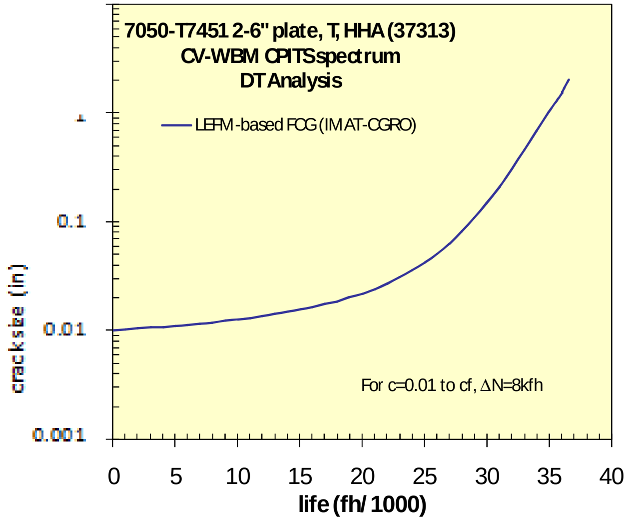
- **FCG and residual strength analyses are based on the standard LEFM approach**
- **This analysis uses the crack tip stress intensity factor (SIF) as the single fracture parameter:**
  - ***subcritical crack growth rates are based on SIF range,***
  - ***failure is based on the fracture toughness, the critical value of SIF***
- **The FCG analysis tool will generate SIFs for the selected geometry, crack type, and loading. The SIF is written in terms of the reference stress and one or more geometric boundary / loading correction terms.**
- **As with the FCI analysis, when multiple load types are applied simultaneously, superposition is used to calculate a total SIF, and as in that case, all load types are assumed to cycle in phase with one another.**

F-35 FSD Modeling and Test:

Durability & Damage Tolerance Analysis

FATIGUE CRACK GROWTH (FCG) ANALYSIS (cont'd)

- **Fatigue crack growth rate (FCGR) is found using the effective SIF range. Crack growth increment is found based on the number of applied cycles and the crack size is increased accordingly**
- **Process is repeated on a cycle-by-cycle basis until failure is predicted or the crack reaches a geometric boundary.**
- **The calculated crack growth life is defined as the number of cycles required to grow the crack from a specified initial size to the final size.**



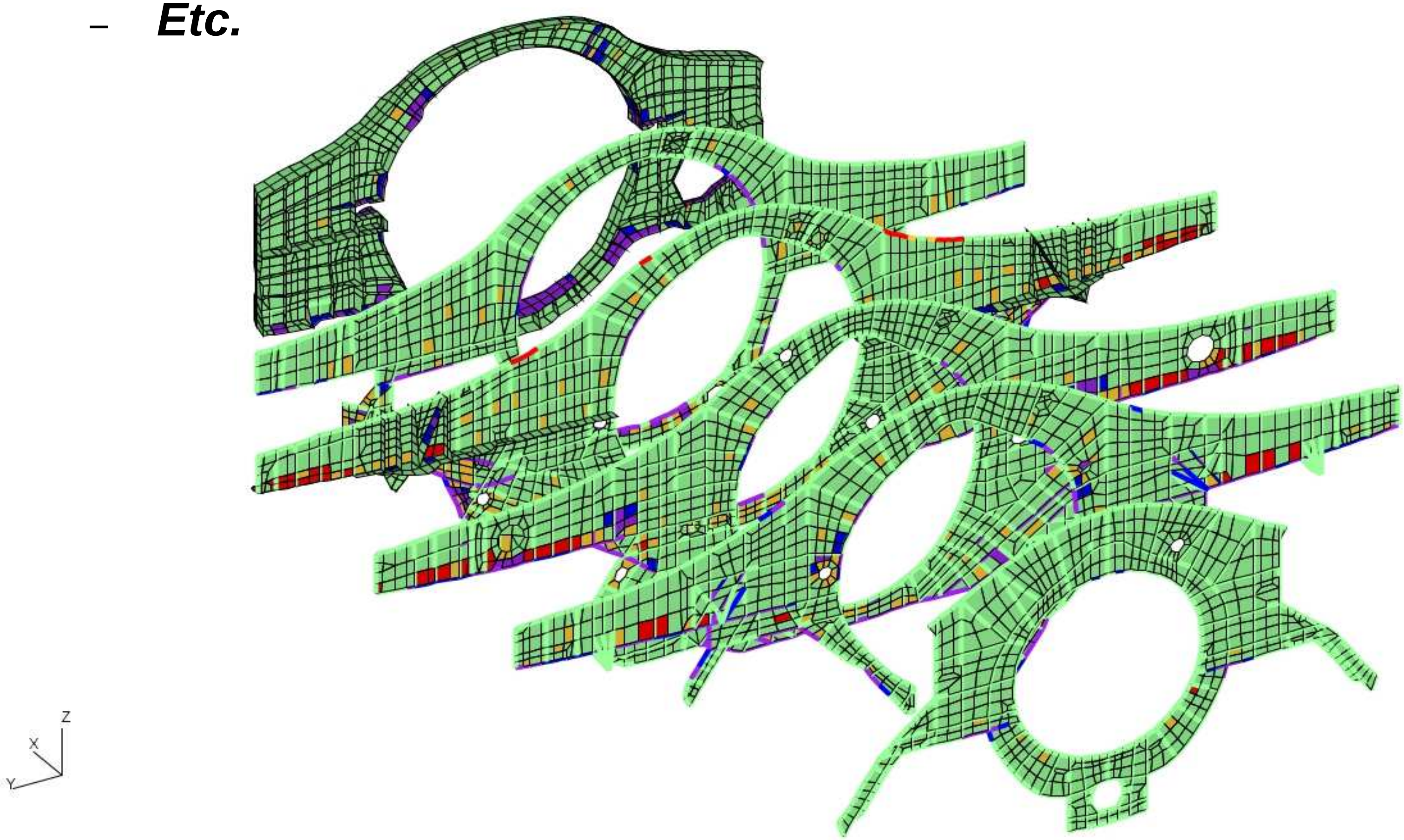
F-35 FSD Modeling and Test:
Durability & Damage Tolerance Analysis

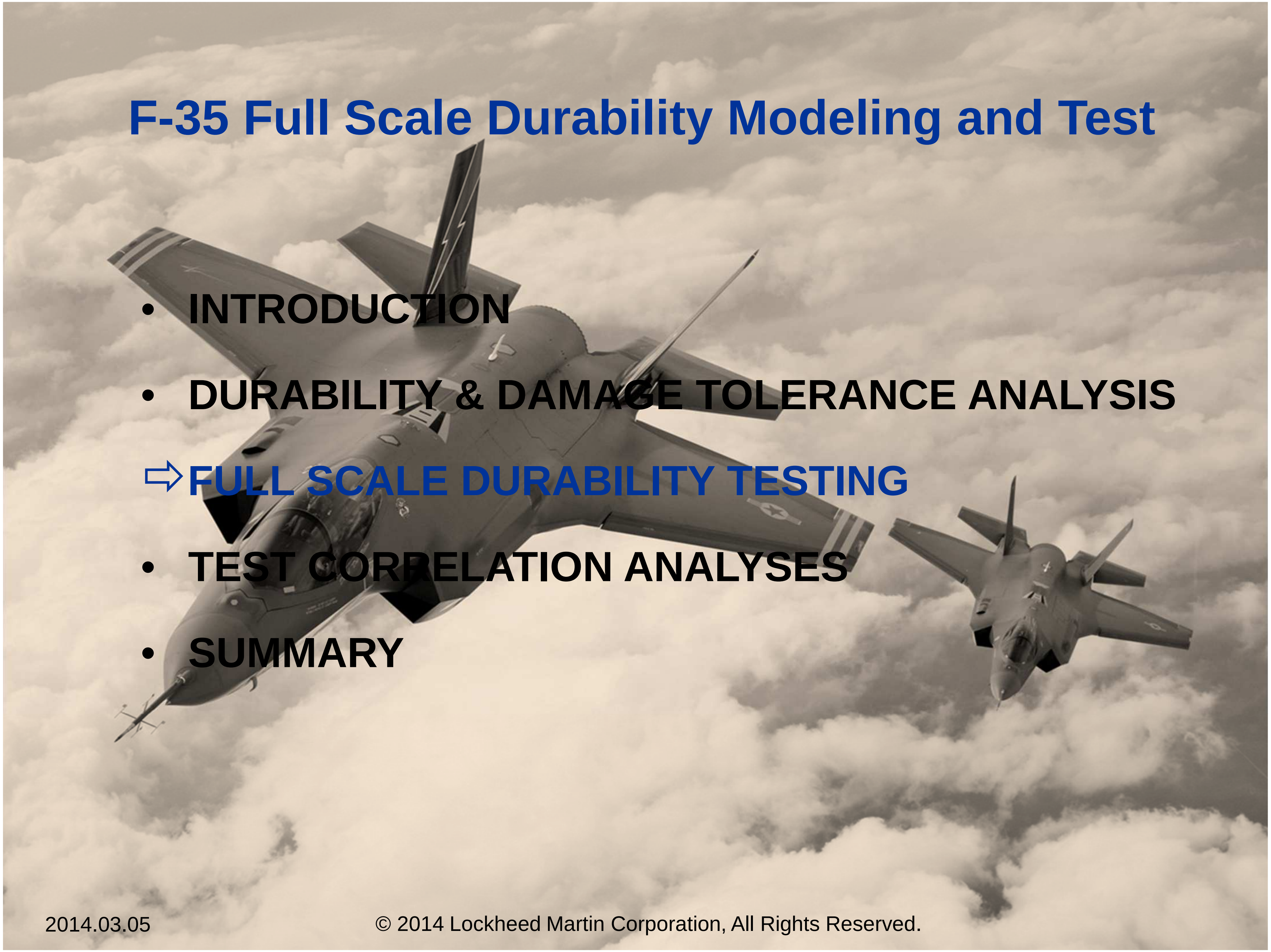
FCI AND FCG ANALYSIS VERIFICATION AND CALIBRATION

- **FCI analysis method & implementation (software) validated during building block test program – model calibrated (primarily via adjustment of the equivalent strain amplitude equation coefficients) so as to capture the mean spectrum crack initiation behavior observed in test**
- **FCG analysis method & implementation (software) validated during both legacy and F-35 building block test programs – calibration was achieved via appropriate selection of load interaction parameters for F-35 materials and spectra. FCG model calibrated so as to capture the mean spectrum crack growth behavior observed in test.**
- **Calibrated models used throughout BTP to support structural sizing via the generation of FCI- and FCG-based design allowable stresses**

F-35 FSD Modeling and Test:
Durability & Damage Tolerance Analysis

- **Automated DaDT analysis software system allows very comprehensive coverage of entire airframe:**
  - ***Generation of design allowable stresses***
  - ***Calculation of margins of safety***
  - ***Etc.***





F-35 Full Scale Durability Modeling and Test

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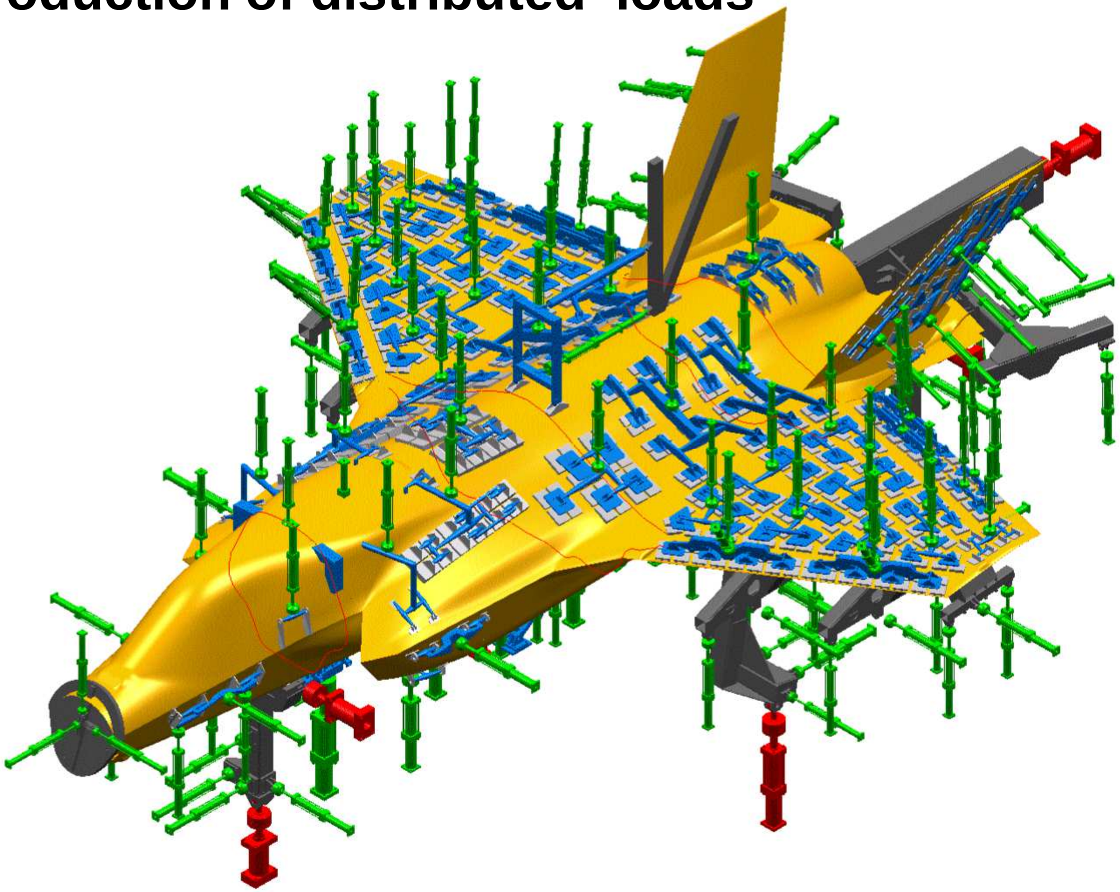
F-35 FSD Modeling and Test:
Full Scale Durability Testing

- **Full scale fatigue tests are currently underway for CTOL, STOVL and CV variants**
- **Each test includes maneuver, buffet, cockpit and fuel tank pressurization, and take-off, landing and ground loadings, for the CV variant, both catapult and arrest loadings are included**
- **The fatigue spectra for the FSD tests were derived from design load conditions and master event sequence (MES)**
- **Significant challenge in ground test of a complete airframe is the simulation of aerodynamic pressures, inertial loads, and internal pressures using a system of discrete loading rams or jacks.**

F-35 FSD Modeling and Test:
Full Scale Durability Testing

- **For the F-35 FSD tests, the loads are applied using a system of approximately 150 load jacks which are tied directly to structural hard points for the direct introduction of load, or to whiffle-trees for the introduction of distributed loads**



F-35 FSD Modeling and Test:
Full Scale Durability Testing

TEST DEVELOPMENT :

- **The jack loads required to simulate each of the design fatigue conditions were defined and then applied to a vehicle level finite element model (FEM) of the test article**
- **FCG analyses were conducted at critical points and exhaustive, comprehensive spectrum severity analyses were conducted throughout the airframe, in order to establish**
  - ***the level of truncation required to reduce the number of load points in the test spectrum as required to meet schedule constraints,***
  - ***the associated level of compensation (stress scaling) required to return the spectrum damage rates to their pre-truncation levels, and***
  - ***the expected damage contributions due to maneuver and buffet loading, which had to be applied separately in the test.***

F-35 FSD Modeling and Test:
Full Scale Durability Testing

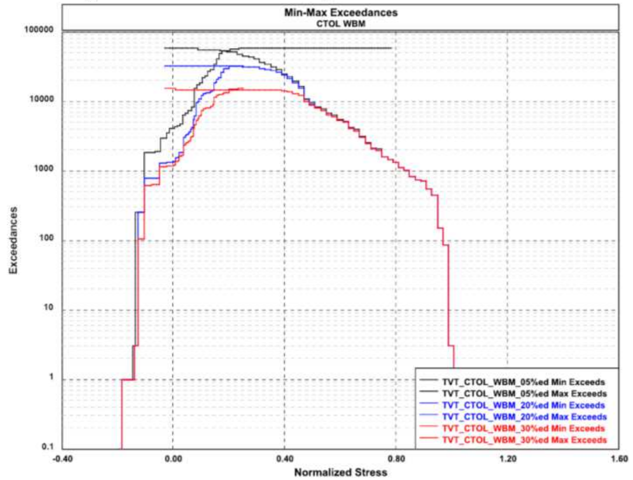
TEST DEVELOPMENT (cont'd):

- **FSD test spectrum truncation was accomplished using multi-channel method: stress vs. time histories for multiple reference control points subjected filtering algorithm simultaneously**
- **Process repeated for a range of truncation levels until the target cycle count (based on the allowable test duration) had been achieved**
- **Reference control point analyses were re-run with the truncated spectra and a range of scale factors in order to determine the level of 'compensation' required to return each spectrum to its pre-truncation severity.**
- **Truncation studies conducted separately for maneuver and buffet**
  - ***maneuver loads are quasi-static***
  - ***buffet response loads are dynamic, but are applied quasi-statically in F-35 FSDT***

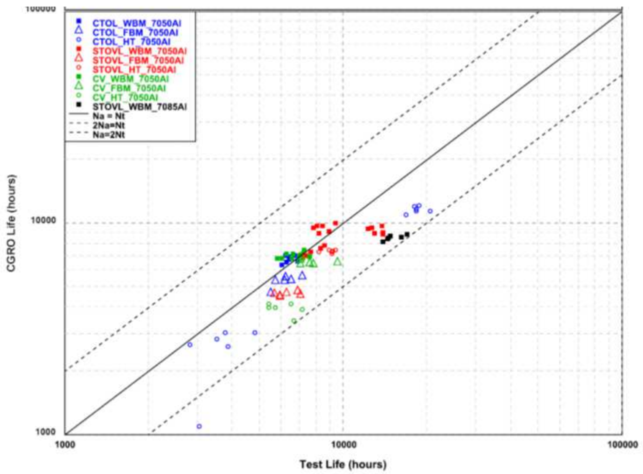
F-35 FSD Modeling and Test:
Full Scale Durability Testing

TEST DEVELOPMENT (cont'd):

- **Acceptability of FSD truncation / compensation levels was assessed experimentally in extensive, coupon-level, truncation verification test (TVT) program**
  - ***five spectrum types for each of the three variants***
  - ***maneuver and buffet tested separately***
  - ***three material types***
  - ***FCI and FCG***

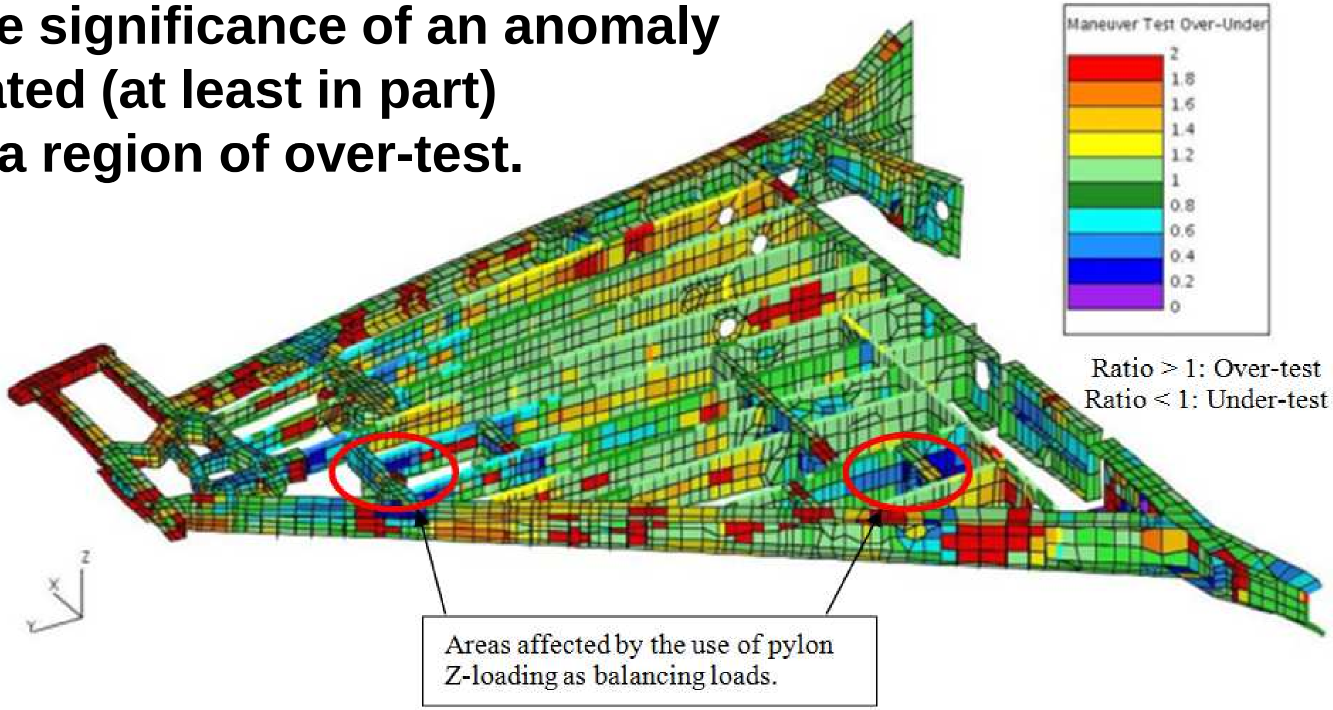


- **TVT program demonstrated that calculated relative fatigue lives for un-truncated vs. truncated and compensated spectra, were accurate to within the normal scatter bands (factor of 2) expected for FCI and FCG analyses**



F-35 FSD Modeling and Test:
Full Scale Durability Testing

- **Extensive test adequacy analyses were conducted to ensure that damage rates in the critical regions in the test article were comparable to those in the SDD aircraft**
- **Typically not possible to achieve a damage ratio of 1 throughout the entire airframe**
- **This is an important consideration during the assessment of test anomalies: the significance of an anomaly may be mitigated (at least in part) if it occurs in a region of over-test.**



F-35 FSD Modeling and Test:
Full Scale Durability Testing

TEST DEVELOPMENT (cont'd):

- **Buffet spectra consist of blocks of constant amplitude cycles:**
  - ***amplitudes and cycle counts derived from structural response stress distributions (psd) for each buffet affected region of the aircraft and for one or more dominant buffeting modes***
  - ***stress amplitudes are low and frequencies are high***
- **Not practical to run maneuver and buffet tests with the same jack configurations and loading frequencies, so entire FSD test spectrum development process was performed separately for each**
- **As each test is conducted, displacement and strain measurements are taken to monitor load paths and detect damage**
- **In addition, detailed inspections are conducted at regular intervals to identify and monitor damage initiation and growth**

F-35 FSD Modeling and Test:
Full Scale Durability Testing

- **CV test article in fixture**

F-35 FSD Modeling and Test:
Full Scale Durability Testing

INITIAL TEST FINDINGS

- **At the completion of one lifetime of testing (1LOT), there were a number of findings on each test – *as expected***
- **F-35 FSD test experience as of 1LOT has been consistent with legacy experience; in fact the rate of findings at 1LOT was at or slightly below that for comparable legacy fighter aircraft**
- **This demonstrates the utility of the full scale ground test program:**
  the purpose of these tests is to
  1) identify points in the structure that do not meet the durability requirements,
  2) correct, and when possible test, solutions for deficiencies,
  3) demonstrate that the overall vehicle design is sound.

F-35 FSD Modeling and Test:
Full Scale Durability Testing

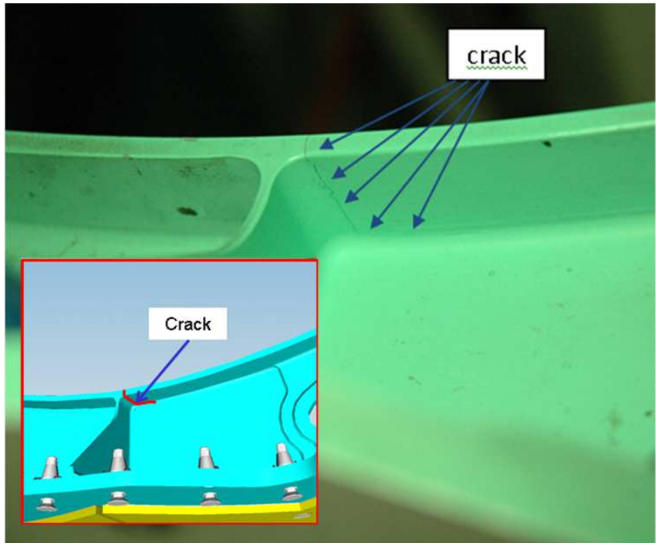
INITIAL TEST FINDINGS (cont'd)

- **In most cases, anomalies have been due to cracking at a geometric detail or stress concentration that was either not analyzed, or was incorrectly analyzed during SDD.**
- **These appear to be local, non-systemic 'escapes' in an otherwise sound design. None of the root cause analyses performed to date have indicated that any fundamental or widespread issues exist with any of the three variants.**
- **Examination of the data also reveals that the majority of the anomalies have been the result of crack formation at surface stress concentrations (as opposed to cracking at fastener holes).**
- **Likely a direct result of the increased use of unitized structure and points to the need for increased attention to the kinds of details that are formed (fillet radii, steps, compound Kts, etc.) when this design approach is used.**

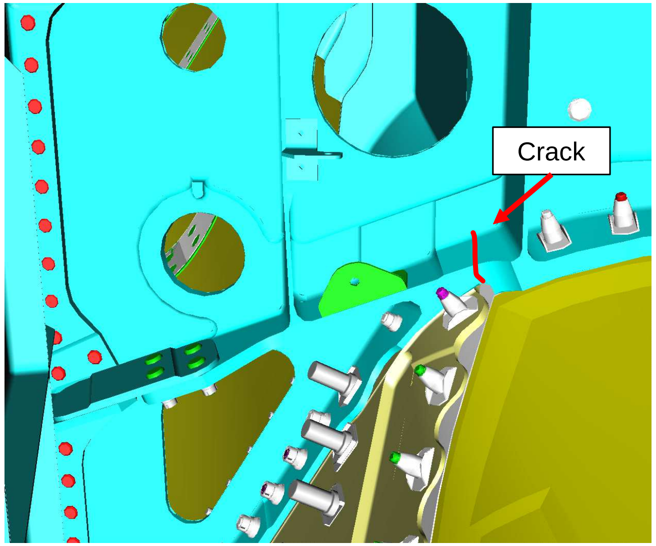
F-35 FSD Modeling and Test:

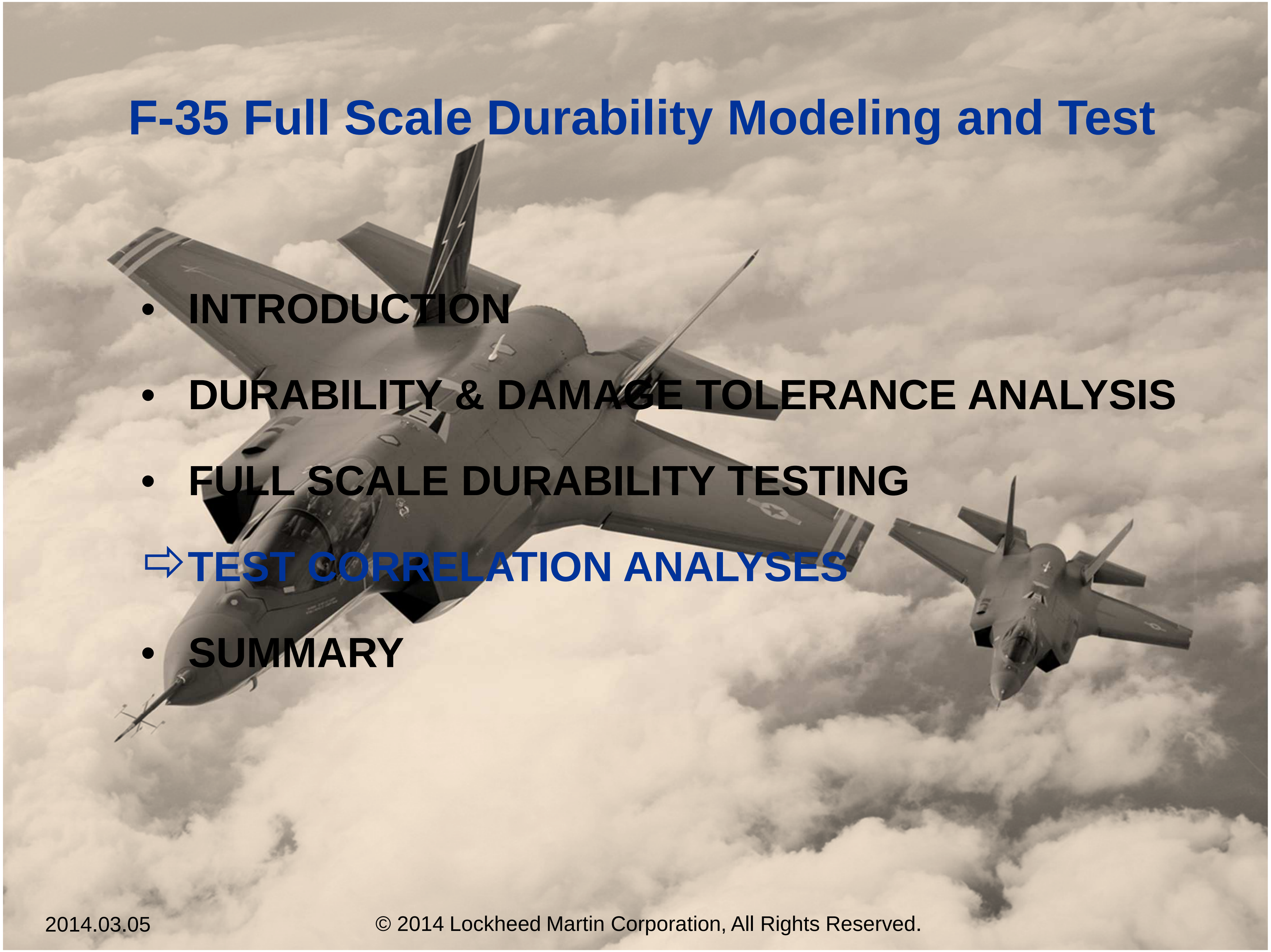
Full Scale Durability Testing

- **Example test finding – crack at fillet radius – major cause(s)**
  - ***curved beam bending effects,***
  - ***longeron "kick" load***



- **Example test finding – crack at cap joggle – major cause(s)**
  - ***missed Kt***
  - ***poor cg-FEM***





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F-35 FSD Modeling and Test:
Test Correlation Analyses

- **At the time of every major test finding, a root cause analysis (RCA) is performed in order to identify the cause(s) of the anomaly, as well as to ensure that the problem is sufficiently well understood to allow valid corrective actions to be taken. This includes both repairs to the test article and modifications and/or redesigns to production aircraft if required.**
- **A critical part of each RCA is an analytical simulation of the observed crack formation and growth behavior.**
- **The test findings and the simulations thereof provide the opportunity to evaluate every aspect of the F-35 DaDT approach, this includes but is not limited to:**
  - ***characterization of fatigue related mechanical properties,***
  - ***generation of fine grid FE models for the definition of control point stress distributions,***
  - ***development of CP stress spectra based on one or more finite element component stresses from the vehicle level FEM of the test article.***

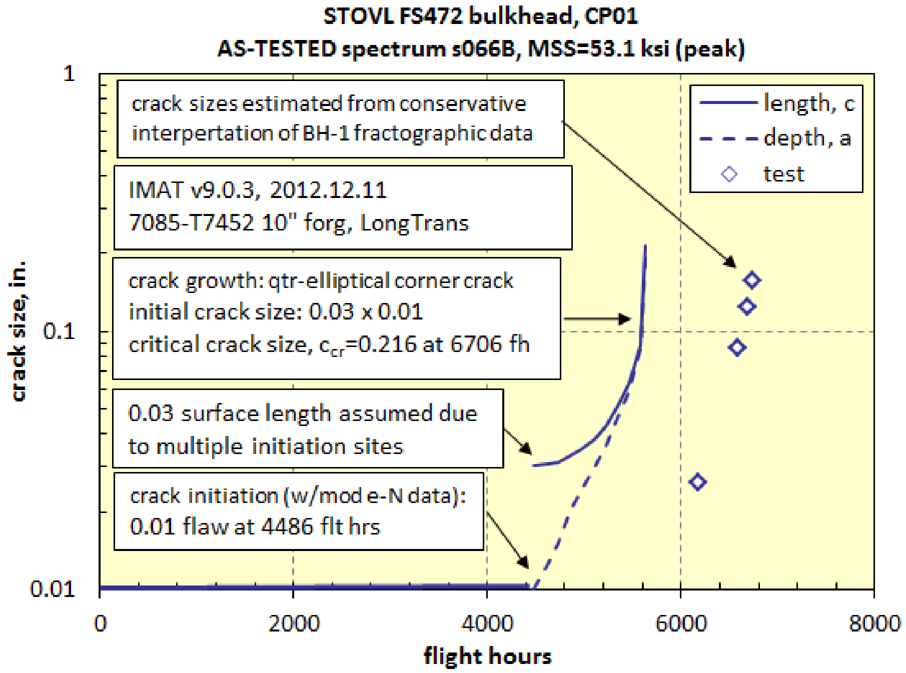
F-35 FSD Modeling and Test:
Test Correlation Analyses

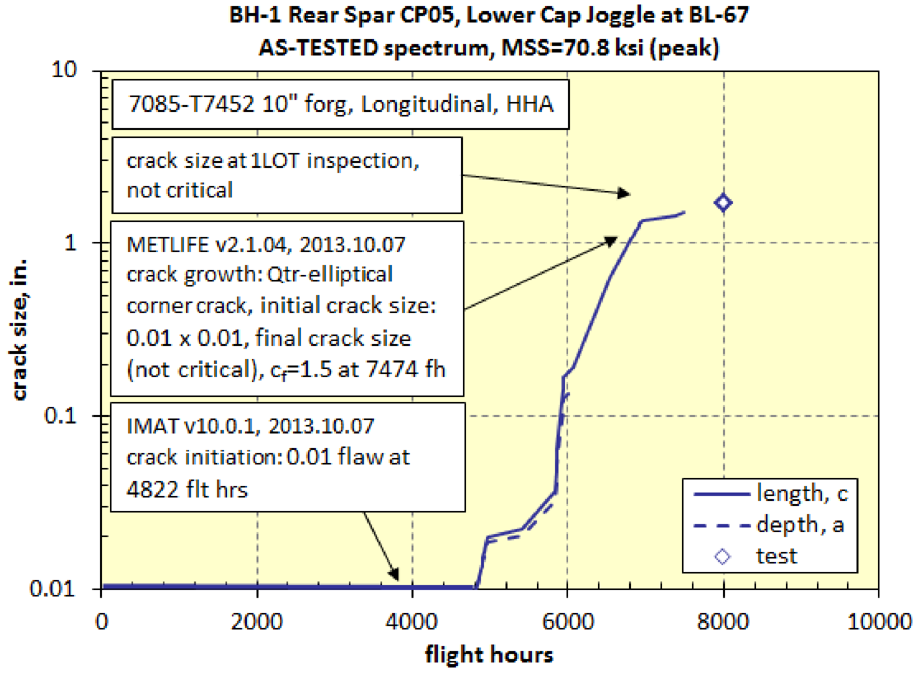
- **To a lesser extent, it also includes evaluation of the FCI and FCG analysis algorithms themselves, though most of the development / validation activity for the analysis tools was, by necessity, done during the building block test program when the various critical parts of each model could be studied in isolation and at the coupon level.**

- **It is very important to make the distinction between FCI and FCG analyses that are performed in order to demonstrate compliance with design requirements, and those that are performed in order to simulate a known cracking event. In the former, the FCI life or FCG life alone must meet or exceed the design life requirement. In the latter, since the durability tests involve the natural formation of cracks, the correlation analysis is based on the sum of the calculated FCI and FCG lives.**

F-35 FSD Modeling and Test:
Test Correlation Analyses

- **For each major test finding, both FCI and FCG life calculations have been made and the total compared against the observed data**

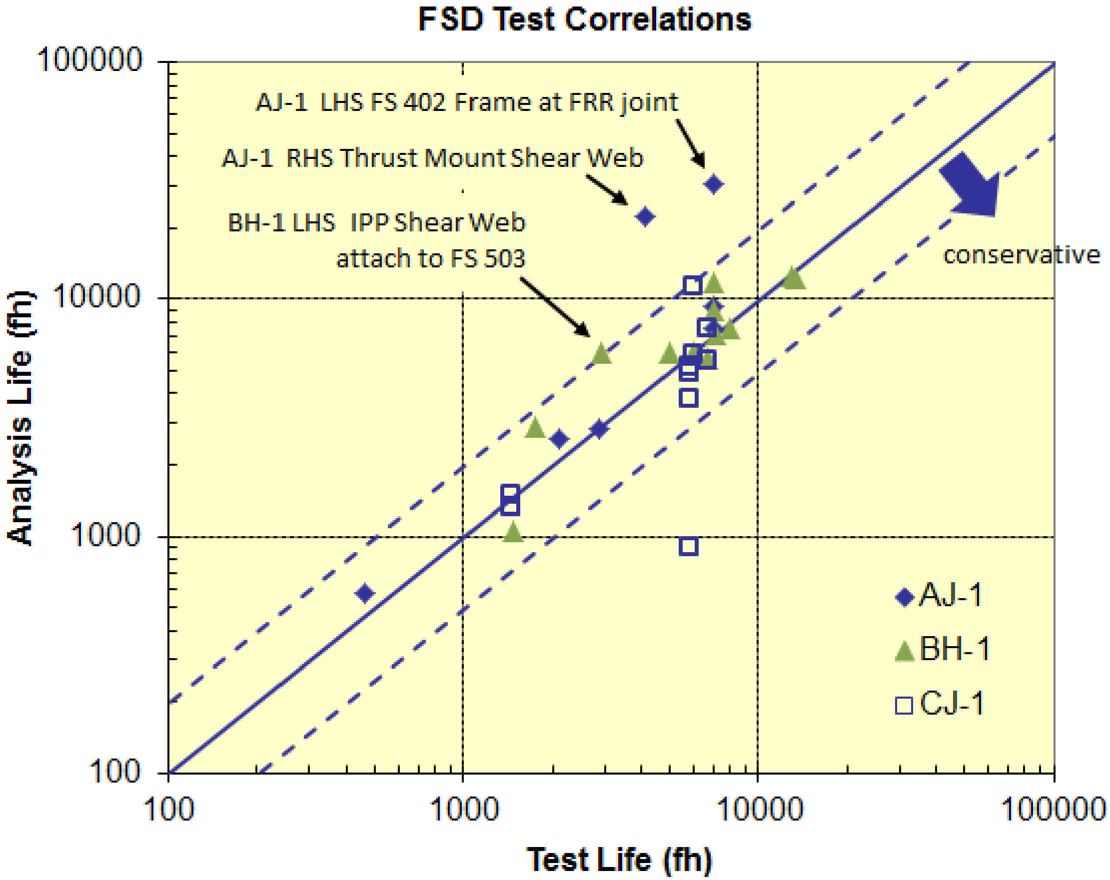


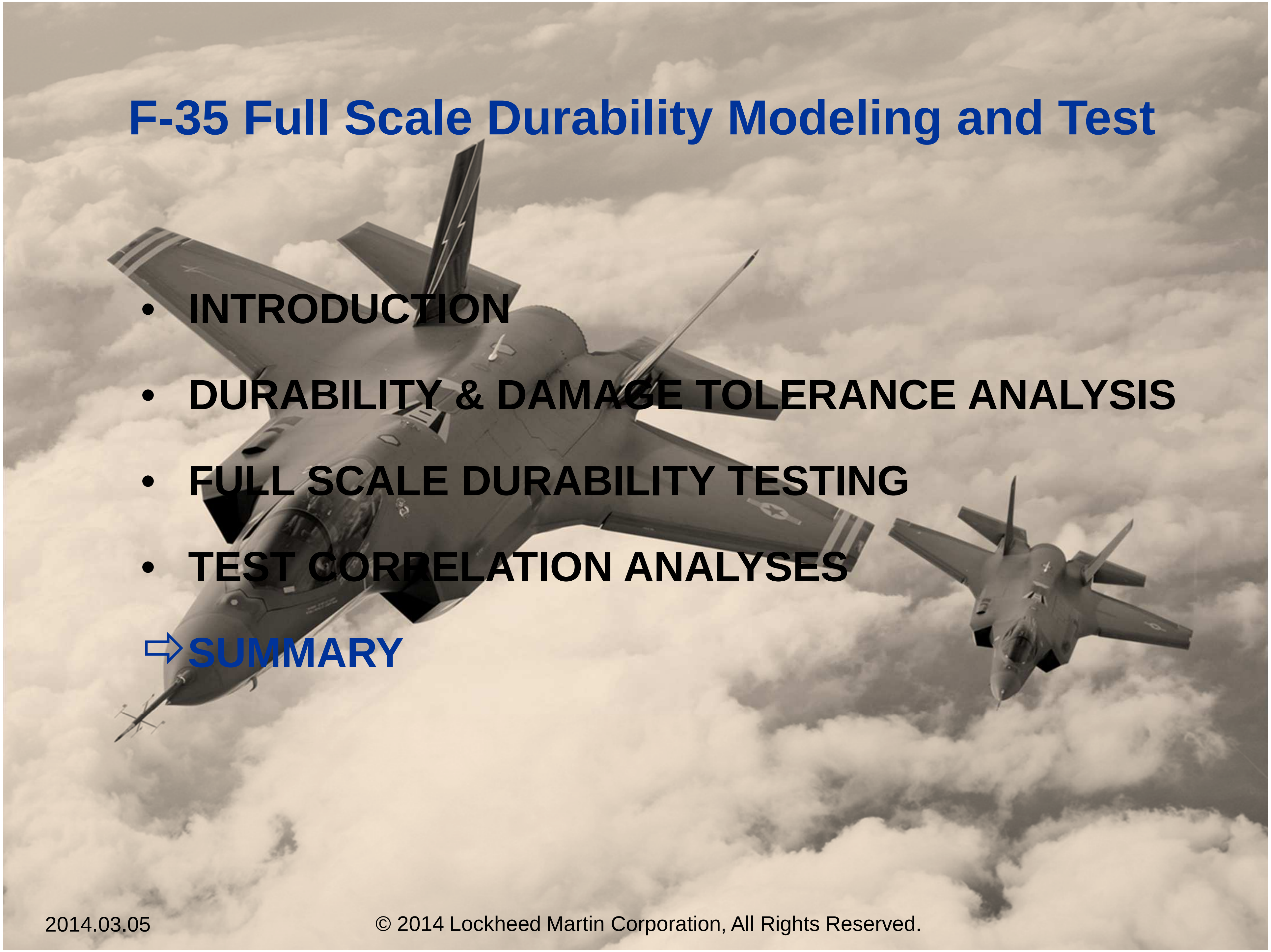


F-35 FSD Modeling and Test:
Test Correlation Analyses

- **For the majority of the findings at 1LOT, with the application of any corrections / revisions identified during the respective RCAs, the computed total lives (FCI+FCG) have been in good agreement with the test findings**

- **Correlation plot (computed life vs. test life) for all major findings on the three FSD tests shows that all but three fall within life scatter factor of two**





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- **TEST CORRELATION ANALYSES**

⇨ **SUMMARY**

F-35 FSD Modeling and Test:
Summary

- The F-35 Joint Strike Fighter is being designed and built in accordance with the durability and damage tolerance design philosophy prescribed in MIL-STD-1530C and JSSG-2006.
- With the support of a building block test program, the analytical tools required to support the design and manufacture of the airframe, as well as the development of the FSD test program, were developed and calibrated.
- Three full scale durability tests have been developed and are currently underway. The results of these tests are expected to demonstrate the adequacy of the design for the prescribed operating environments and usage scenarios.
- Findings from the first lifetime of testing for each of the three variants have identified a number of structural issues which have been corrected, both on the respective test articles and for production aircraft.

F-35 FSD Modeling and Test:
Summary

- **The rate of test findings through 1LOT has been consistent with that from comparable legacy programs**

- **F-35 experience has shown once again that the DaDT design process coupled with full scale durability testing is essential and effective for the production of aircraft which are both safe and economical to operate**