Integration of Ground and Flight Testing on F-35 Lightning II Program
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Lockheed Martin Aeronautics
Acknowledgements

• Robert J. Burt, F-35 Chief Structures Engineer
• Phil Gross, F-35 Deputy Chief Structures Engineer
• Pablo Guerrero, F-35 Structural Test Planning
• Marguerite Christian, F-35 Static Test Technical Lead
  – John Bradley, CTOL
  – Todd Bevan, CV
  – Jim Doyle, STOVL
  – Don Whiteley, STOVL
• Steve Owens, F-35 Structural Certification
F-35 Program Overview

• Family of Three Air Vehicle Variants, with Similar Structural Arrangements
  – *Each Variant is Designed To Satisfy the Requirements of a Separate Military Branch*
  – *F-35A = Conventional Take-Off and Landing (CTOL) Variant*
  – *F-35B = Short Take-off and Vertical Landing (STOVL) Variant*
  – *F-35C = Carrier Variant (CV)*

• Simultaneous Development and Testing the Three F-35 Variants Provides Both Opportunities and Challenges
  – *Opportunities – Commonality & Efficiencies*
  – *Challenges – Resource & Schedule Concurrency*
F-35 Variant Planform Comparison

**STOVL**
- Span (ft): 35
- Length (ft): 51.2
- Wing Area (ft\(^2\)): 460

**CTOL**
- Span (ft): 35
- Length (ft): 51.4
- Wing Area (ft\(^2\)): 460

**CV**
- Span (ft): 43
- Length (ft): 51.5
- Wing Area (ft\(^2\)): 667
F-35 Structural Ground Test Program

- Full Scale Static & Durability Test of Each Variant
  - *Six Full Scale Test Airframes*
  - *Four Commonly Designed Test Fixtures*
  - *CV Static Test Airframe Also Used as Drop Test/Barricade/Live Fire Article*
- Proof Tests Conducted on Each Variant’s Loads Instrumented Flight Test Aircraft
  - *Provides Larger Initial Flight Envelope*
  - *Reduces Early Flight Test Dependency on Static Test*

F-35 Structural Test Program Is A Key Element of a Rigorous and Disciplined Structural Integrity Program
F-35 Full Scale Tests
Locations & Fixture Sharing

LM Fort Worth, US

- STOVL Static
- STOVL Durability
- CV Static

BAES Brough, UK

- CTOL Static
- CV Durability
- CTOL Durability

Vought, Grand Prairie TX, US

- CV Drop

Locations & Fixture Sharing:
- LM Fort Worth, US
  - STOVL Static
  - STOVL Durability
  - CV Static
- BAES Brough, UK
  - CTOL Static
  - CV Durability
  - CTOL Durability
- Vought, Grand Prairie TX, US
  - CV Drop
Test Fixture Design Commonality
Enabled by Structural Similarity

• Similarity of Airframe allows efficiencies in load arrangement design as well as load condition development
  – Common Fuselage Bulkhead Stations
  – Similar Wing & Tail Box Planforms (STOVL & CTOL)
F-35 Load Case Selection Process

• Comprehensive Set of Load Conditions Selected For Strength Certification of Each Variant
  – Selected to Exercise All Major Components, Control Surfaces, Weapons Hardpoints and Flight Opening Doors

• Two Independent Processes Used To Determine Candidate Load Cases For Static Testing
  – External Loads Process
    • External Load Envelopes At Specified Section Cuts Used To Identify Critical Loading Conditions
    • Provided Earlier Support for Test Fixture Design
  – Strength & Stability Margin Process
    • Critical Margins And Failure Modes Reviewed to:
      – Confirm Selections from External Loads Process
      – Referee Between Similar Conditions

• Candidate Load Conditions from the Two Processes Consolidated To Define Final Load Cases Considering:
  – Structural Symmetry & Similarity
  – Load Case Similarity
  – Discrete Load Sources
External Load Case Selection Process

- 15 Integrated Load Envelopes Used in Selection Process
- Perimeter of the Load Envelopes Initially Selected to Provide Early Guidance For Test Fixture and Load Actuator Design (Over 100 Cases)
- Candidate List Selection Based on Knowledge of Primary Structural Drivers and Symmetry
  - Reduced to 30 - 45 Conditions Depending on Variant
  - Load Arrangement Refined to Improve Match of Selected Conditions
External Load Section Cut Locations

Wing Tip
Wing Mid
Wing Root
Fwd Fuse
Ctr Fuse
Aft Fuse
VT Mid Span
VT Root
HT Bending Moment
HT Hinge Moment

Control Surface Hinge Moments For LEF, TEF & Rudder Also Used
Strength & Stability Margin Based Selection

- Each Structural Analysis Team Reviewed Their Stress Analysis for Critical Loadings
  - Emphasis on Stability Related Margins
  - Preference to Conditions Which Drive Large Areas of Structure
  - Considered Only Loads Which Can Be Represented on Full Scale Static Test
- Review of Critical Margins Confirms Adequacy of Envelopes Chosen for External Loads Review
  - Used to Referee Between Similar Cases Near Envelope Perimeter
  - Ensures All Critical External Load Drivers Have Been Addressed
    - Prompted the Evaluation of LHS and RHS Boom External Load Envelopes
# CTOL Global Test Load Conditions

| Mach | Alt | Nz   | Maneuver & Description                              | Wing Root | Wing Midspan | LEF | TEF | EEF | CF | AF VBM/LBM | AF VBM/T | Booms | LH Boom | RH Boom | HT | VT Root | VT Midspan | Rudder |
|------|-----|------|-----------------------------------------------------|-----------|--------------|-----|-----|-----|----|-----------|-----------|-------|--------|---------|--------|-------|---------|----------|--------|
| Med  | SL  | Min  | RT - R Symmetric Pull-Up/Push-Over                  | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Max  | RT - R Symmetric Pull-Up/Push-Over                  | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Max  | RT - R Symmetric Pull-Up/Push-Over                  | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Min  | RT - R Symmetric Pull-Up/Push-Over                  |           | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Max  | RR - R 360 deg Roll, Full Rate                      | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Max  | PL - L Roll Pull-Out, Full Rate                     |           | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Low  | SL  | Max  | A3 - Abrupt Pull-Up/Push-Over Type 3                | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Max  | RW - R Trim Open-Close Weapon Bay Doors             | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Min  | OL - L Yaw Gust                                     | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| High | Alt | Man  | RR - R 360 deg Roll, Full Rate                      | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Man  | RL - L 360 deg Roll, Full Rate                      | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Low  | Alt | Man  | RR - R 360 deg Roll, Full Rate                      | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Max  | RT - R Symmetric Pull-Up/Push-Over                  | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| High | Alt | Man  | RT - R Symmetric Pull-Up/Push-Over                  | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Min  | RW - R Trim Open-Close Weapon Bay Doors             | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| High | Alt | Man  | QL - L 180 deg Roll, Full Rate                      | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Low  | SL  | Max  | RT - R Symmetric Pull-Up/Push-Over                  | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Max  | A1 - Abrupt Pull-Up/Push-Over Type 1                | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Max  | HS - Hammer Shock                                  | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Man  | PR - R Roll Pull-Out, Full Rate                     | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Man  | QR - R 180 deg Roll, Full Rate                      | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Man  | RL - L 360 deg Roll, Full Rate                      | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Man  | RR - R 360 deg Roll, Full Rate                      | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Man  | QL - L 180 deg Roll, Full Rate                      | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Man  | RL - L 360 deg Roll, Full Rate                      | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| High | Alt | Man  | QL - L 180 deg Roll, Full Rate                      | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
| Med  | SL  | Man  | SR-R Sideslip                                       | X         | X            |     |     |     |    |           |           |       |         |         |        |        |          |         |
STOVL Local Static Tests

- Cockpit Pressure
- NLG Doors
- Nose Landing Gear Backup Structure
- Refuel Probe Back-up Structure and Mechanism
- Lift Fan Exhaust
- Vane Box
- Outboard WBD Inboard WBD and Cradle
- Fuel Tank Pressure
- Boarding Ladder Door
- Fwd Fuse Side Skin
- Lift Fan Mounts
- Lift Fan Inlet
- Aux Air Inlet
- Hoist
- Engine Mount-Fwd Upper
- Outboard Store Sta 4/8
- Fwd MLG Door
- MLG Inboard Trunnion Support Structure
- MLG Drag Brace Interface at FS450
- MLG Outboard Trunnion Support Structure
- RCN Door Attach Structure
- Wing-Pylon Sta 9
- Wing-Pylon Sta 10
- Wing-Pylon Sta 11
- Engine Thrust Mount
- Jacking
- 3 BSN Doors
Structural Similarity Enables Cross-Variant Verification Testing

• CV & CTOL
  – Weapons Bay Doors, RGA, & Backup Structure
  – Canopy
• STOVL & CTOL
  – Main & Nose Landing Gear Doors
  – Gear Door Uplocks
• STOVL & CV
  – Air Refuel Probe
• Tri-Variant
  – Engine Mounts
  – Wing Pylons & Hardpoints
## Results of Load Case Selection

<table>
<thead>
<tr>
<th></th>
<th>CTOL</th>
<th>STOVL</th>
<th>CV*</th>
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<tbody>
<tr>
<td>Fuselage Group</td>
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<td>Wing Group</td>
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<td>Tail Group</td>
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<tr>
<td>Total Full Airframe Cases</td>
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<tr>
<td>Local Tests</td>
<td>34</td>
<td>51</td>
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</table>

*CV Load Case Selections are Still Preliminary
F-35 Program Information
Non Export Controlled Information – Releasable to Foreign Persons

F-35 Schedule Integration

- An Integrated Flight & Ground Test Program Has Been Developed
  - **Key Flight Envelope Expansion Milestones Defined**
  - **Test Conditions Sequenced to Support Progressive Flight Clearance Build Up**
  - **Proof Testing Incorporated to Provide Early Flight Envelope to 80% DLL for Loads Monitored Aircraft**
Expanded View of STOVL Schedule

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<td>Phase 0 – Cockpit &amp; Fuel Tank Pressure &amp; Vane Box</td>
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<td>Phase 1 – CPO &amp; AAI</td>
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<td>Phase 2 – NLG, LFI, LFE Doors</td>
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<td>Phase 3 – Refuel Probe &amp; Weapons Bay Doors</td>
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<td>Phase 4 – 115% &amp; 150% DLL Full Airframe Maneuver &amp; 3BSM Conditions</td>
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<td>Phase 5 – MLG &amp; RCN Door Local Conditions</td>
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<td>Phase 6 – Tow, Taxi, MLG, Store Hard Point, &amp; Boarding Ladder; Local Conditions</td>
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<td>Phase 7 – Engine and LF Mounts, Tie Down, Jacking &amp; Hoisting; Local Conditions</td>
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## Expanded View of CV Schedule

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<td><strong>CG-1 Drop/Static/Barricade/Live Fire Test</strong></td>
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- **Cal/Proof Test**
- **CF-1, CF-2 Cabin & Tank Pressure Proof Test**
- **AF-1**
- **AF-2**
- **CF-1 Drop/Static/Barricade/Live Fire Test**
- **Cal/Proof Test**
- **CF-3 Cabin & Tank Pressure Proof Test**

### Phases:
- **Phase 0** - Cockpit & Fuel Tank Pressure
- **Phase 1** - Cats, Traps, MWB stores & LG BU Structure
- **Phase 2** - CPO & NLG Doors
- **Phase 3** - Strain Surveys & 6 Maneuver Conditions to 115% & 150% DLL
- **Phase 4** - 115% & 150% DLL Maneuver Conditions
- **Phase 5** - 115% & 150% DLL Local Conditions

### Key Events:
- A/C Delivered To Lab
- Monitored A/C 80% ALE
- Un-Monitored A/C 64% ALE
- Monitored A/C 100% ALE
- Un-Monitored A/C 80% ALE
- Roll-In Mk-7/E-28/JBO at LKE
- Ship Suitability-Wave-Off & Bolter Performance & Deck Handling
- Static Test Report Complete

### Special Tests:
- **Phase 5**
  - Barricade Test
- **Phase 6**
  - Live Fire Test

### Notes:
- Sea Trials - Initial (includes ferry to/from ship) w/C3
Summary

• F-35 Structural Test Program Benefits from Structural Similarity
  – Common Test Fixture Designs
  – Common Test Load Development Processes
  – Cross-Variant Verification Testing of Certain Structural Components

• Load Case Selection Process Ensures Static Test Adequacy
  – Earlier Support for Development of Test Arrangement
  – Additional Confidence in Resulting Selections

• Structural Test Program Developed to Support Flight Test Requirements
  – Test Conditions Are Deliberately Sequenced to Provide Timely Support for Key Flight Envelope Expansion Milestones
  – Proof Tests of the Loads Instrumented Aircraft Incorporated to Provide Earlier Flight Envelope Expansion

F-35 Structural Ground Test Program Has Been Developed as Part of a Thorough and Disciplined Structural Integrity Program
Questions