Finite Element Analysis on the F-35 Lightning II Program

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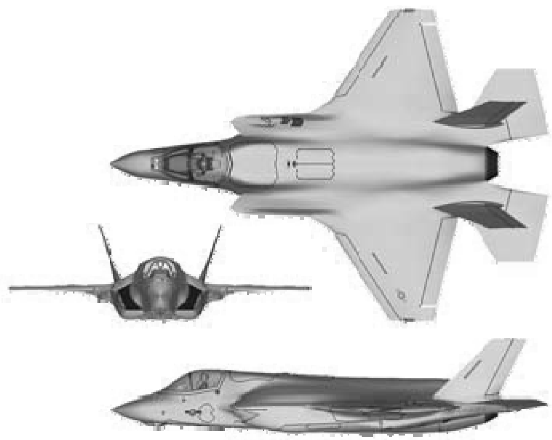
ABSTRACT

Fifth generation fighter aircraft, such as the F-35 Lightning II Joint Strike Fighter, have unique design challenges not found in earlier generations of aircraft. Finite Element Analysis plays a primary role in solving these design challenges, ensuring structural integrity of the aircraft and certifying it ready for flight in accordance with and support of a rigorous ASIP Master Plan. Finite Element Analysis on the F-35 relies on lessons learned from the development of legacy aircraft and breaks new ground in the effects of temperature and removable panels on aircraft internal load distributions. This presentation provides an overview of Finite Element Analysis on the F-35 Lightning II Joint Strike Fighter: the maturation of the Finite Element Models to support the progressive phases of the F-35 Aircraft Structural Integrity Program, the execution of consistent solutions across company and team boundaries, and the delivery of results to structural analysts around the world.

The F-35 Lightning II Joint Strike Fighter

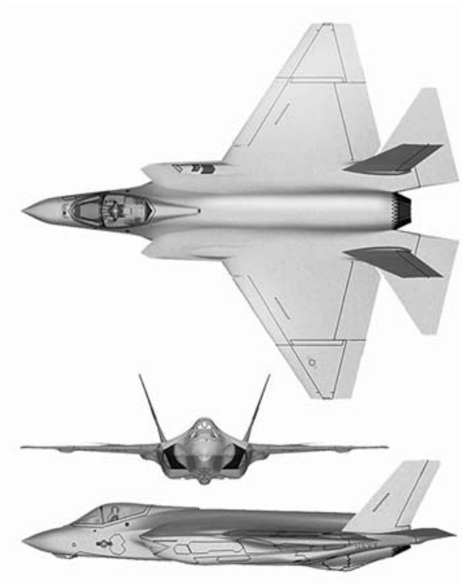
F-35A CTOL

Span....................35 ft / 10.67 m
Length.................. 51.4 ft / 15.67 m
Wing area ....460 ft² / 42.7 m²
Combat radius........> 590 n.mi / 1,093 km
Range...............~ 1,200 n.mi / 2,222 km



F-35B STOVL

Span....................35 ft / 10.67 m
Length.................. 51.2 ft / 15.61 m
Wing area ....460 ft² / 42.7 m²
Combat radius........> 450 n.mi / 833 km
Range...............~ 900 n.mi / 1,667 km



F-35C CV

Span....................43 ft / 13.11 m
Length.................. 51.4 ft / 15.67 m
Wing area ....668 ft² / 62.06 m²
Combat radius........> 600 n.mi / 1,111 km
Range...............> 1,200 n.mi / 2,222 km

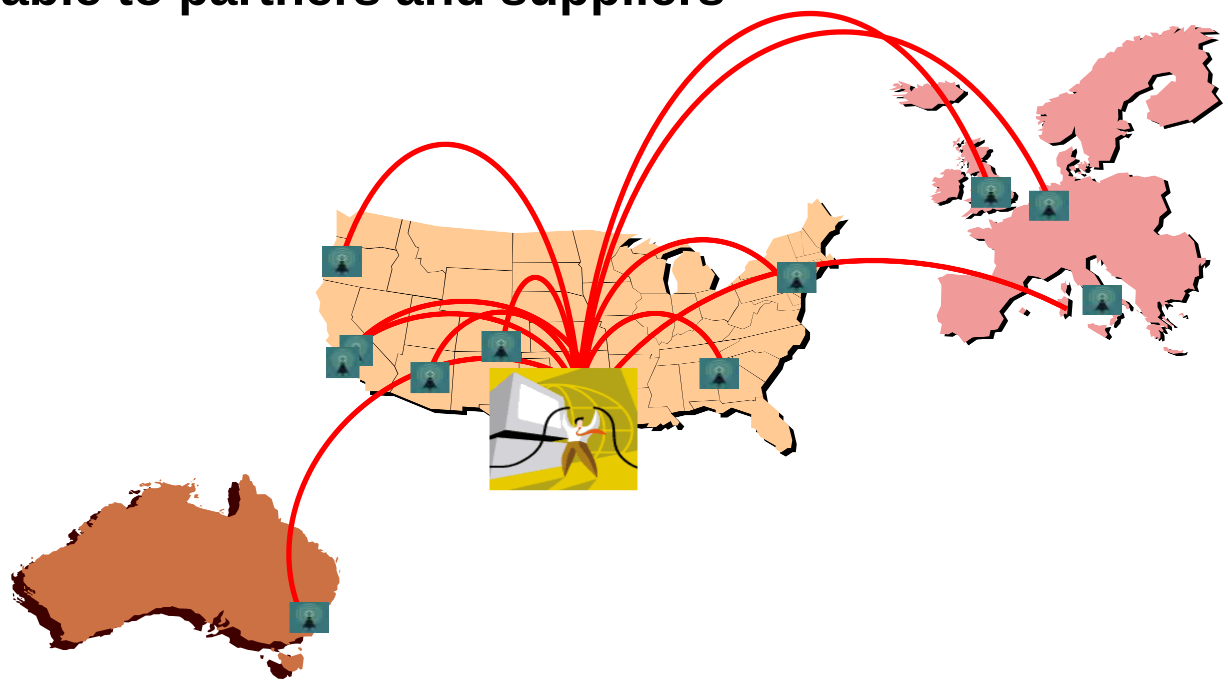
F-35 Common Model Set Provides a Common Baseline.

- **The F-35 Air Vehicle Model set provides a baseline for numerous disciplines:**
  - ***Strength and Service Life Analysis***
  - ***Aeroelasticity and External Loads***
  - ***Flutter and Dynamics***
  - ***Acoustic Fatigue***
  - ***Thermal Analysis***

- **Internal loads solution results form a common baseline for all structural analysts across all teams and companies developing the airframe on the F-35 program.**
  - ***Solved in Fort Worth, Texas and results distributed world-wide.***
  - ***Provides a configuration-controlled common source for all internal loads and loading/boundary conditions for follow-on linear and non-linear medium/fine grid models and solutions.***

Internal Loads Data Storage And Delivery

- **Storage & distribution of internal loads datasets**
  - ***Includes Finite Element Models, applied loads, and internal load databases***
  - ***Configuration controlled on dedicated loads data server***
  - ***Accessed by structural analysts worldwide through encrypted network***
- **Internal loads data released in Fort Worth is instantaneously available to partners and suppliers**



F-35 ASIP and FEA

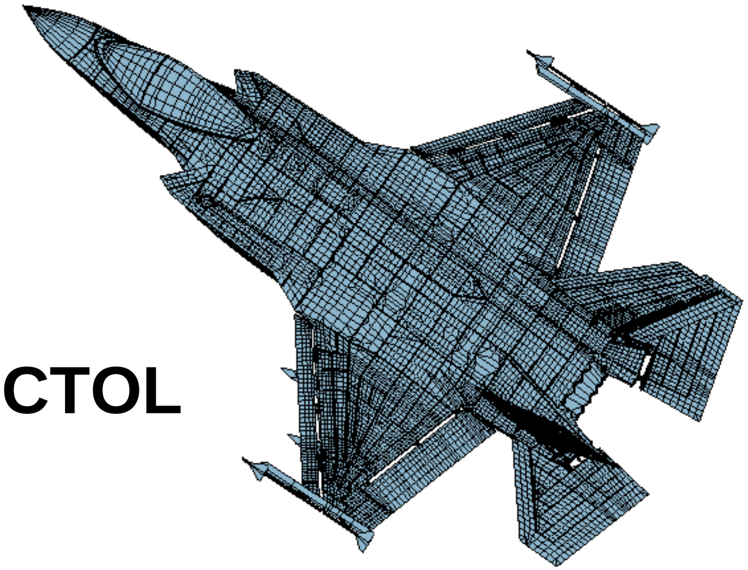
- **The accuracy required of a Finite Element Model changes through the life cycle of the aircraft:**
  - ***Highly detailed Finite Element Models can be extremely cost effective on mature, post-development aircraft programs.***
  - ***For an aircraft in development, model accuracy must be commensurate with design maturity.***

- **F-35 model fidelity and accuracy is iterated and improved upon as required to support the progressive phases of the F-35 Aircraft Structural Integrity Program:**
  - ***Pillar 1 - Design Information & Development Planning***
    - Preliminary design and FEM development
    - Initial structural analysis evaluation
  - ***Pillar 2 - Design Analysis and Development Test***
    - Incorporation of detail design concepts into the Finite Element Model.
    - Analysis of the design for formal Build-to-Package release
  - ***Pillar 3 - Full Scale Testing***
    - Finite Element Model validation through correlation to ground test.
  - ***Pillar 4 - Certification and Force Management Development***
    - Evaluation of the as-designed airframe for Strength Summary and Operating Restrictions
    - Incorporation of information developed through flight and ground test.
  - ***Pillar 5 - Force Management***
    - Future program activities

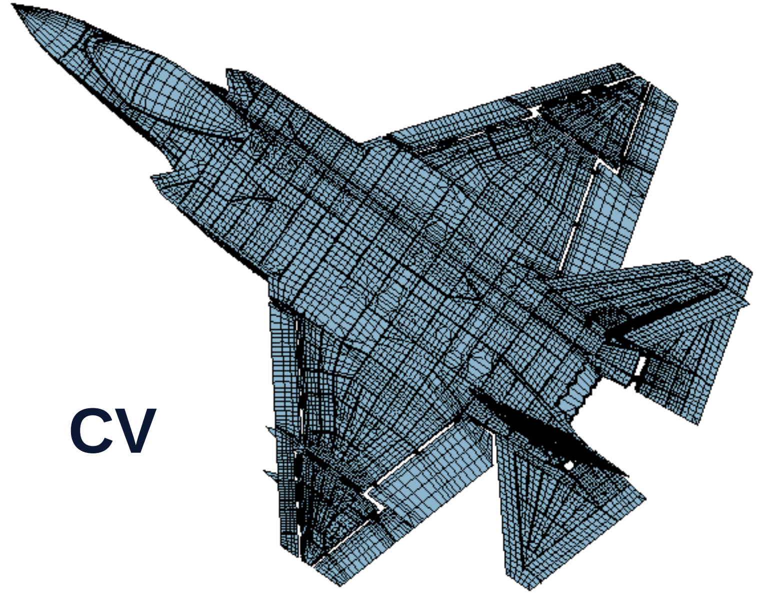
F-35 Model Development, Preliminary Design: Phase 0 to Build-to-Package Internal Loads (ASIP Pillars I & II)

F-35 Configuration 240-1 FEMs
(Circa 2002 – 10 Months after Contract Award)

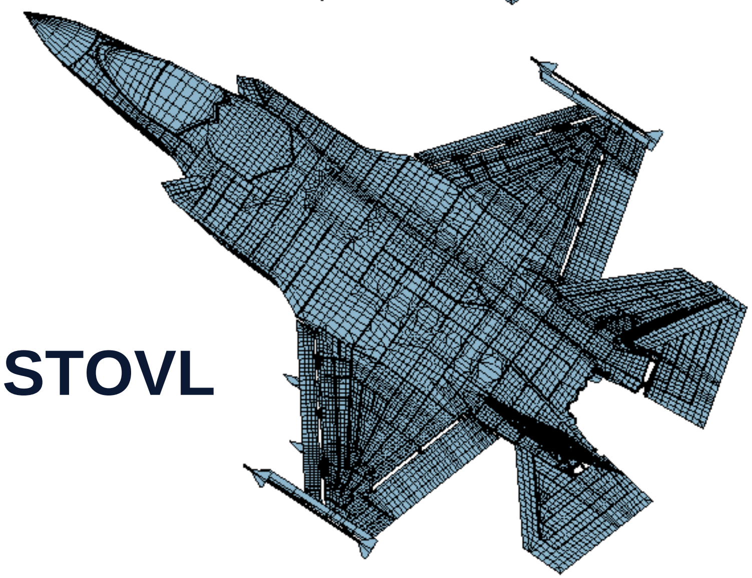
CTOL



CV



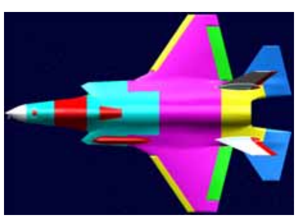
STOVL



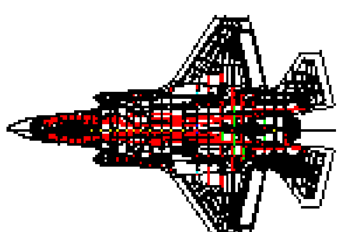
	CTOL	STOVL	CV
Nodes	35K	37K	38K
Elements	63K	64K	69K
DOF	186K	198K	203K

Preliminary FEM Development

- **Starting Point of the FEM Process**
  - ***Air Vehicle Geometry Received as CATIA Datasets***
    - Outer Mold Line (OML) Surfaces
    - 2-D Structural Configuration Layouts
    - External Access Door/Panel Seam Geometry
  - ***Additional Geometry Defined in Configuration Description Document***
    - Control Surface and Door Hinge Lines
    - Engine, Landing Gear Attachments, Etc.
  - ***Design Details are Generally Immature or Non-existent***

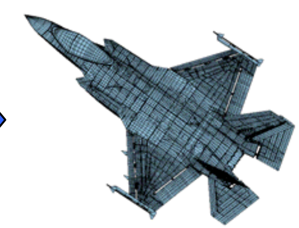


OML Surfaces



Structural Configuration

Configuration Description Document



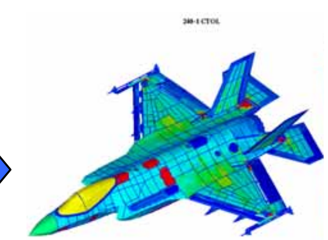
Unsized FEM

Automated Structural Sizing System (AS3)

- Used for Preliminary Sizing
- Iterative Process Uses Element Thickness and Area to Converge on Minimum Weight, Fully Stressed Design
- Developed at LM Aero
- Integrated with MSC/NASTRAN, TMP/SLIM, and IDAT Tool Suite (internally developed analysis tool set).
- Computes Finite Element Properties Required to Satisfy User Specified Structural Analysis Criteria

Unsized FEM

+ AS3 + AS3 Sizing Constraints + External Loads →

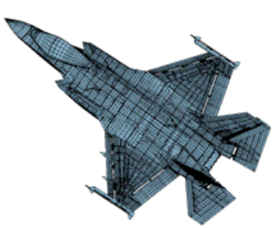


Preliminary Sized FEM

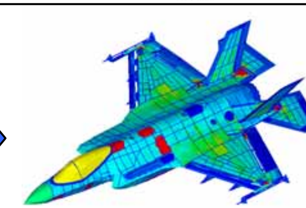
Automated Sizing Methodology

- **Structural Constraints**
  - ***DADT Stress Cutoffs (Metals)***
  - ***DADT Strain Cutoffs (Composites)***
  - ***Flat and Curved Panel Buckling***
    - Skins, Floors, Webs
  - ***Flat Panel, Non-Linear Pressure Analysis***
    - Fuel Tanks, Cockpit, Inlet Duct

- **Producibility Constraints**
  - ***Ply Drop-Off Rate Limit***
  - ***Min/Max Ply Percentages***
  - ***Equivalent Properties Enforced by Element Set (P-Link)***
  - ***Element Minimum Gage (Area/Thickness)***
  - ***Element Minimum Stack Thickness***
  - ***Smooth Adjoining Element Property Transitions***



Unsized FEM + **AS3** + **AS3 Sizing Constraints** + **External Loads** →



Preliminary Sized FEM

Preliminary Sizing -> BTP Sizing

- **After release of preliminary AS3 sized models and internal loads, Aircraft sizing and configuration is analyzed and iterated upon by…**
  - ***Strength and Life analysis,***
  - ***Flutter and Dynamics***
  - ***External Loads and Aeroelasticity***

- **To produce the configuration and sizing which become the basis for "Build-to-Package" (BTP) Finite Element Models and internal Loads**

Changes in Idealization from Preliminary to BTP

- **In addition to capturing layout and design changes developed during the preliminary design phase, the BTP Finite Element Models also had significant improvements in idealization:**
  - ***Modified Panel Effectivity Assumptions***
    - Narrowed overlapping assumptions to reduce conservatism and save weight.
  - ***Increased Mesh Density and mesh refinement***
    - Improved model accuracy and better positions the FEM for strain gage correlation (lessons learned from legacy aircraft).
  - ***Developed Air Vehicle Thermal Induced Internal Loads***
    - Provides consistency of analysis method for thermal induced loads across the air vehicle.

Increased Use of 2.5D Idealization In Parts with Wide Flanges

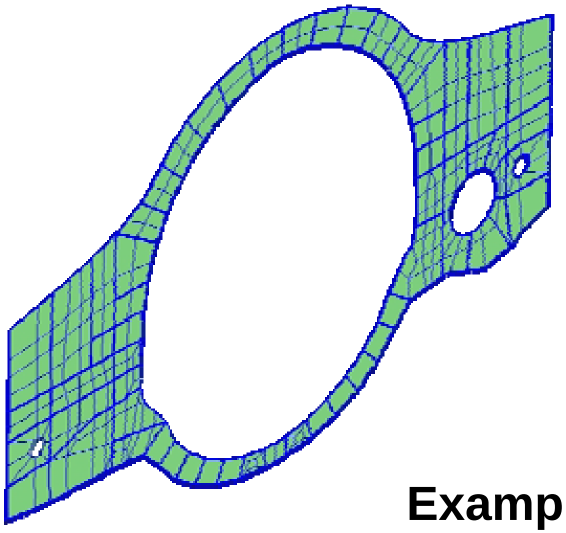
STOVL Preliminary FEM

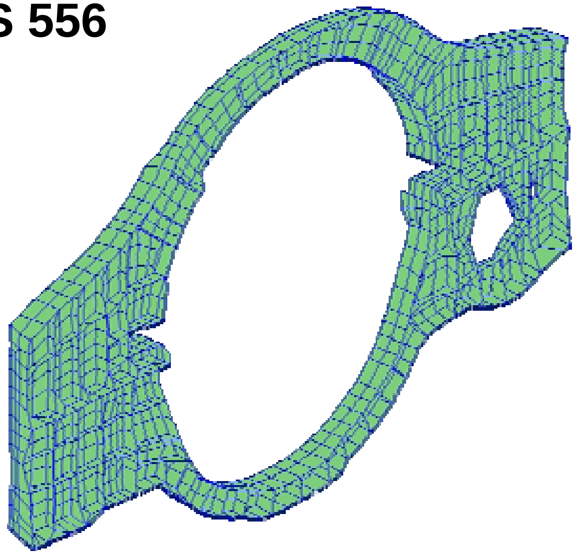
(2D Webs & 1D Flanges)

STOVL BTP FEM

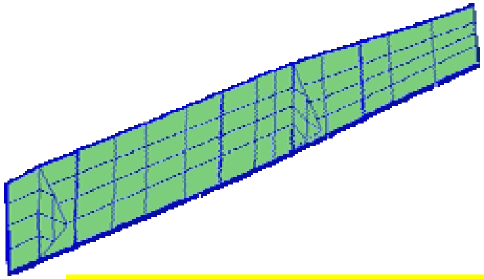
(2D Webs & 2D Flanges)

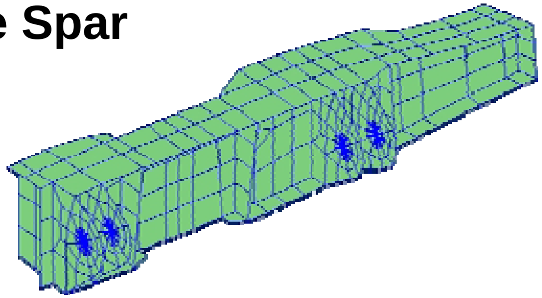
Example: FS 556





Example: HT Hinge Spar





2.5D = Using 2D Elements to represent 3D objects

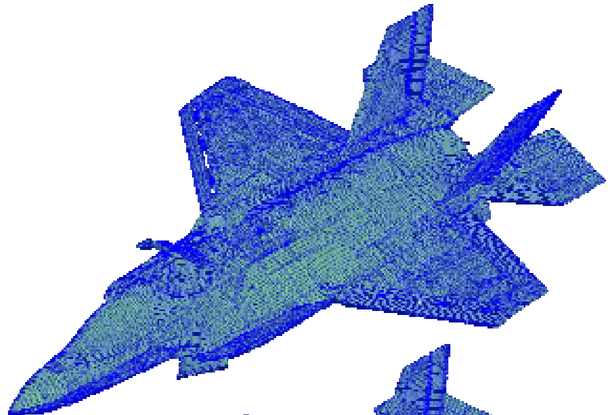
Thermal Load Increment Solutions

- **New for the BTP internal loads releases, thermal solutions were developed for Air Vehicle.**
- ***Based on the Finite Element Model used for the mechanical solutions but with modifications:***
  - *Composite skins/edges removed and re-attached with springs elements.*
  - *Added temperature dependent material properties (Modulus, CTE)*
- **Selected Temperature Conditions:**
  - *Distributed temperature profile flight conditions*
  - *Cold soak constant temperatures*
  - *Hot soak constant temperatures*
- **Internal Load results available as stand alone thermal conditions AND thermal combined with mechanical loads.**
  - *Ultimate Thermal+Mechanical uses 1.25 ultimate factor on thermal.*
  - *Short Part correction factor may be adjusted to represent other factors and/or short part corrections.*

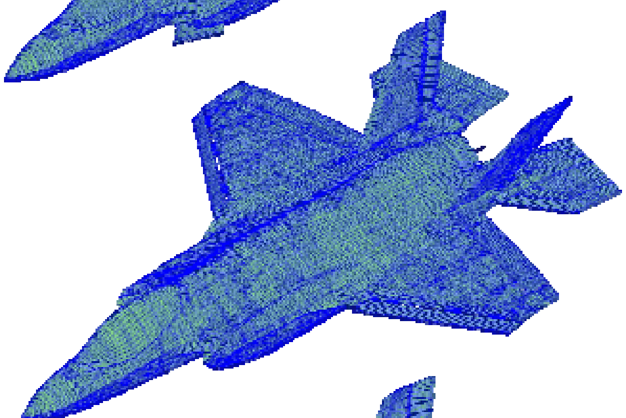
Build-to-Package Internal Loads

(Circa 2005, 48 months after contract award)

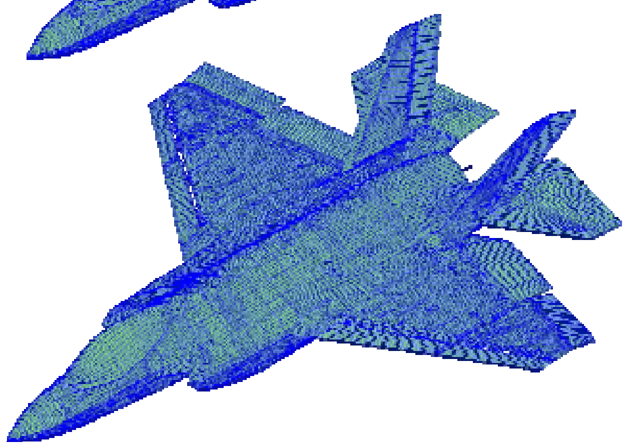
STOVL BTP FEM:
- **162K Nodes**
- **221K Elements**
- **21,329 Load Combinations**



CTOL BTP FEM:
- **158K Nodes**
- **213K Elements**
- **14,555 Load Combinations**

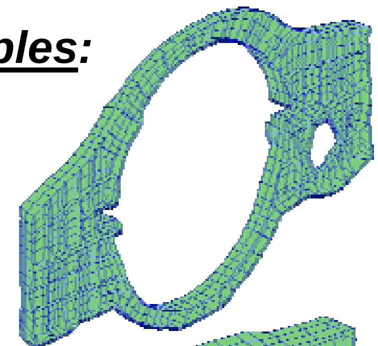


CV BTP FEM:
- **175K Nodes**
- **240K Elements**
- **25363 Load Combinations**

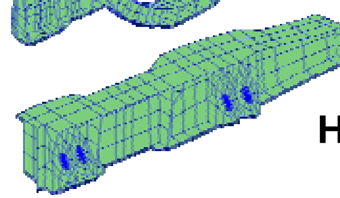


High Fidelity Models Include:
- ***2.5D Mesh In Key Areas***
- ***Mesh Density Established To Facilitate Future Test Correlation***

Examples:



Bulkhead



HT Hinge Spar

- **Complete Air Vehicle Structural Representations**
- **Moveable Control Surfaces and Major In-Flight Opening Doors**
- **Overlapping Assumptions for Removable Panel Effectivity**
- **Structural Sizing Provided By Structural Analysts (not by automated methods)**

F-35 Model Development, As Released Design: Strength Summary And Operating Restriction and Pre-Test Prediction Internal Loads (ASIP Pillars III & IV)

As Released Design Finite Element Models

- **After release of Build-to-Package Design datasets, the aircraft Finite Element Models are updated to the "as released" configuration:**
  - ***All Airframe structural parts reviewed and updated as necessary.***
  - ***Vendor supplied stiffness and models updated (Landing Gears, Propulsion Systems, Actuators, etc.)***

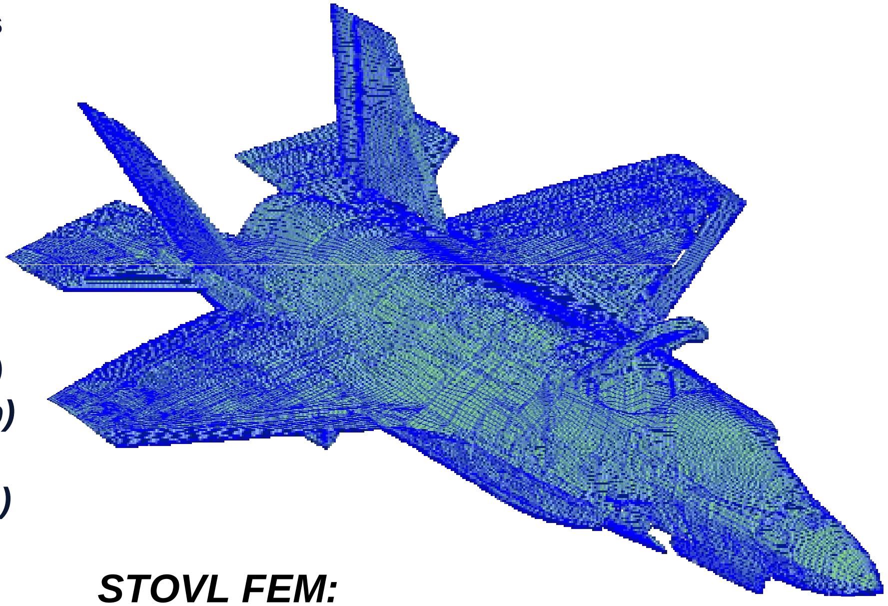
- **Aircraft Finite Element Models prepared for test correlation and Strength Summary and Operating Restrictions.**
  - ***Flight Test configurations modeled and evaluated***
  - ***Ground Test configurations modeled and used for:***
    - Pre-test predictions
    - Pre-test sensitivity studies to show effects of areas of significant variability on strain predictions and facilitate error bound estimates
    - Post-test correlation of test results to FEA predicted results.

STOVL Air Frame Finite Element Model

- **STOVL aircraft structure is solved in numerous configurations based on parameters specified for any given load condition:**
  - ***LEF Angle***
  - ***Flaperon Angle***
  - ***Rudder Angle***
  - ***Horizontal Tail Angle***
  - ***Weapon Bay Door Position (4 per ship)***
  - ***Lift Fan Inlet Door Position***
  - ***Lift Fan Exhaust Door Position (2 per ship)***
  - ***Auxiliary Inlet Door Position (2 per ship)***
  - ***Nozzle Door Position (2 per ship)***
  - ***Landing Gear Door Position (6 per ship)***
  - ***Landing Gears– Up/Down (3 per ship)***
  - ***Engines (1 per ship, 2 total)***
  - ***Weapon Carriage Adapters (8 per ship)***
  - ***Panel Effectivities (2 Levels)***

- **Rotatable control surfaces and in-flight-opening doors, can be solved at any angle through coordinate system parameter inputs but are solved in ± 2.5° degree buckets to reduce the number of solutions.**

- **Removable panels analyzed with overlapping assumptions validated through test.**



STOVL FEM:

- **180,000 Nodes**
- **260,000 Elements**
- **1,080,000 Degrees of Freedom**
- **26,194 Load Conditions**
- **2300 configurations of control surface, door and gear positions.**

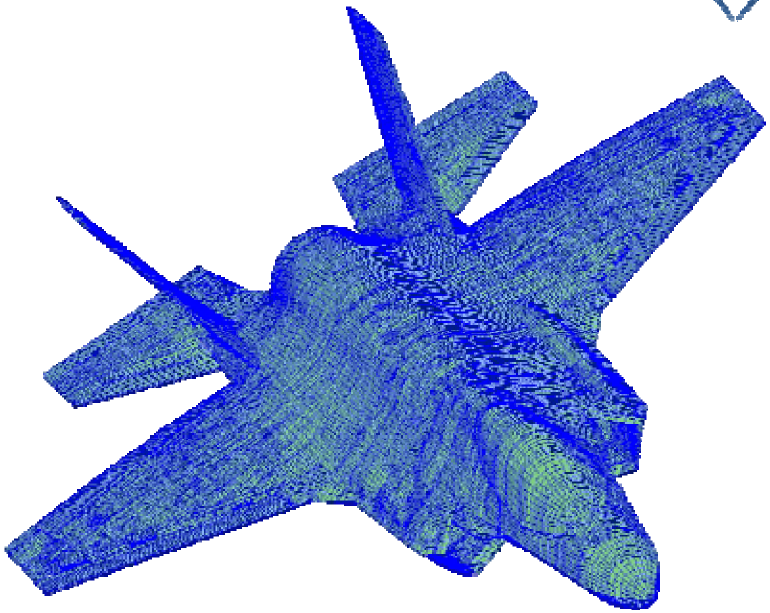
Detailed STOVL Airframe Representation

CTOL Air Frame Finite Element Model

- **CTOL aircraft structure is solved in numerous configurations based on parameters specified for any given load condition:**
  - ***LEF Angle***
  - ***Flaperon Angle***
  - ***Rudder Angle***
  - ***Horizontal Tail Angle***
  - ***Weapon Bay Door Position (4 per ship)***
  - ***Landing Gear Door Position (6 per ship)***
  - ***Landing Gears– Up/Down (3 per ship)***
  - ***Engines (1 per ship, 2 total)***
  - ***Weapon Carriage Adapters (8 per ship)***
  - ***Panel Effectivities (2 Levels)***

- **Rotatable control surfaces and in-flight-opening doors, can be solved at any angle through coordinate system parameter inputs but are solved in ± 2.5° degree buckets to reduce the number of solutions.**

- **Removable panels analyzed with overlapping assumptions validated through test.**



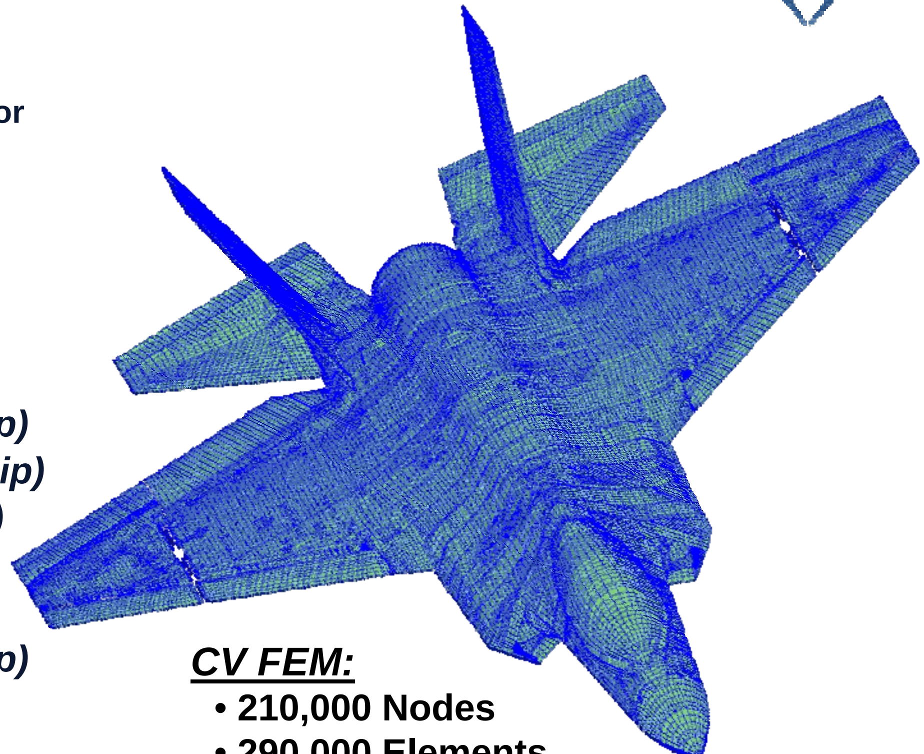
CTOL FEM:

- **190,000 Nodes**
- **270,000 Elements**
- **1,140,000 Degrees of Freedom**
- **14,845 Load Conditions**
- **1500 configurations of control surface, door and gear positions.**

Detailed CTOL Airframe Representation

CV Air Frame Finite Element Model

- **CV aircraft structure is solved in numerous configurations based on parameters specified for any given load condition:**
  - ***I/O LEF Angle***
  - ***Flap Angle***
  - ***Aileron Angle***
  - ***Rudder Angle***
  - ***Horizontal Tail Angle***
  - ***Weapon Bay Door Position (4 per ship)***
  - ***Landing Gear Door Position (6 per ship)***
  - ***Landing Gears– Up/Down (3 per ship)***
  - ***Wing Fold – Up/Down (2 per ship)***
  - ***Engines (1 per ship, 2 total)***
  - ***Weapon Carriage Adapters (8 per ship)***
  - ***Panel Effectivities (2 Levels)***
- **Rotatable control surfaces and in-flight-opening doors, can be solved at any angle through coordinate system parameter inputs but are solved in ± 2.5° degree buckets to reduce the number of solutions.**
- **Removable panels analyzed with overlapping assumptions validated through test.**



CV FEM:

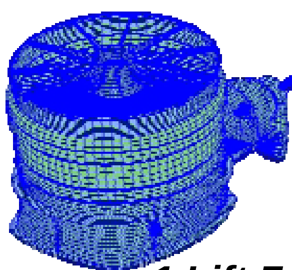
- **210,000 Nodes**
- **290,000 Elements**
- **1,260,000 Degrees of Freedom**
- **25,363 Load Conditions**
- **2000 configurations of control surface, door and gear positions.**

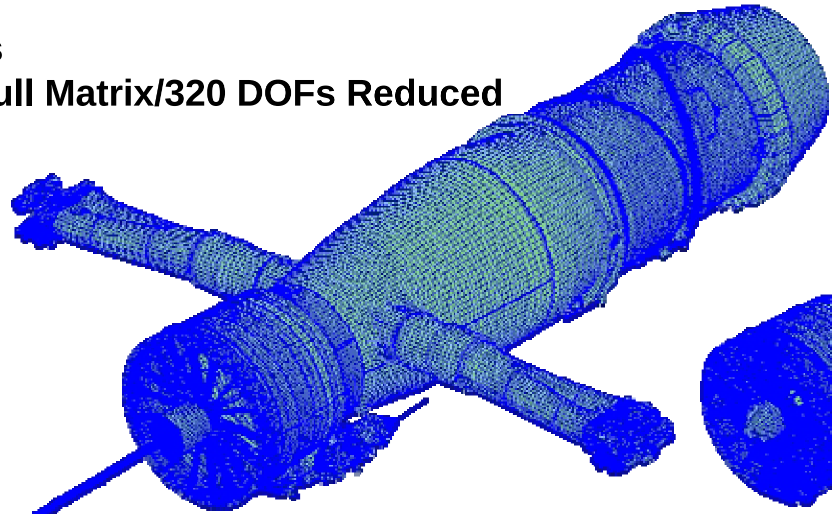
Detailed CV Airframe Representation

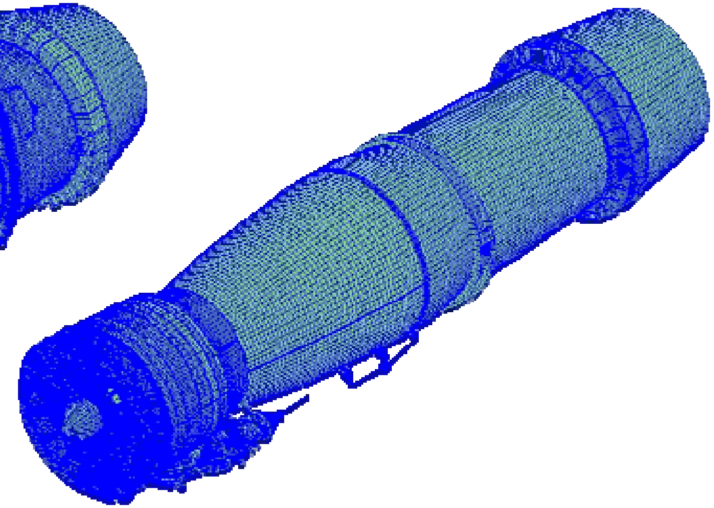
Detailed Propulsion Supplied FEA

2 Roll Posts (STOVL):

- **570K Nodes**
- **300K Elements**
- **3414K DOFs Full Matrix/320 DOFs Reduced**







Engine plus Nozzle (F135/F136: All Variants):

- **330K Nodes**
- **292K Elements**
- **1980K DOFs Full Matrix / 168 DOFs Reduced**

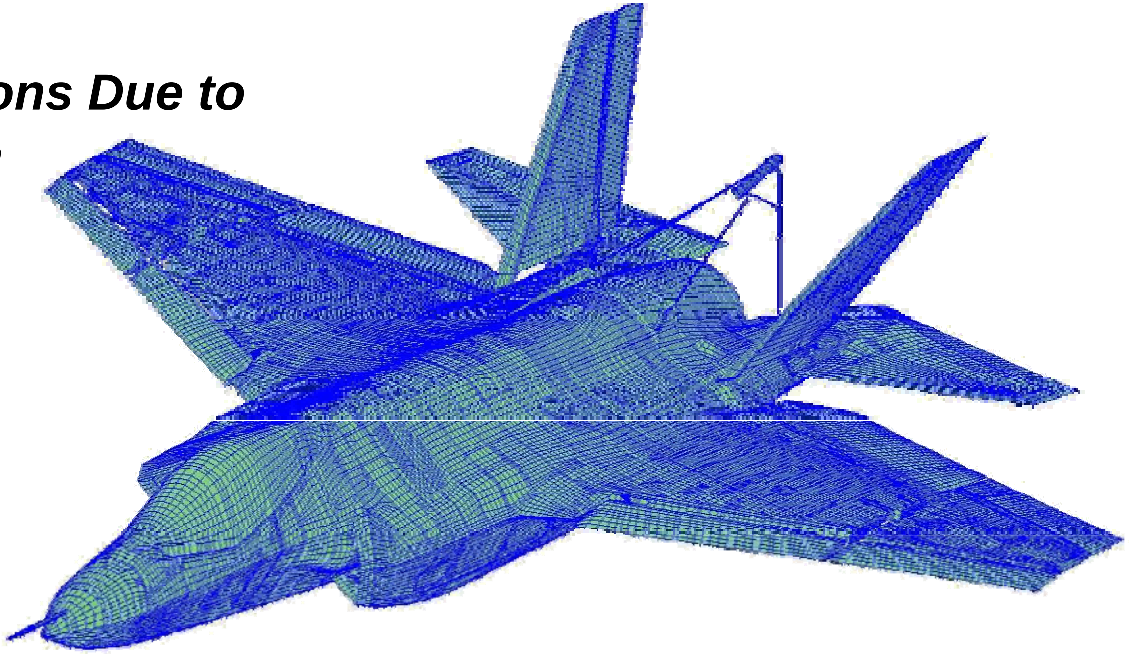
1 Lift Fan plus Drive Shaft (STOVL):

- **43K Nodes**
- **47K Elements**
- **256K DOFs Full Matrix / 114 DOFs Reduced**

High Quality Stiffness Matrices for A/V Solutions

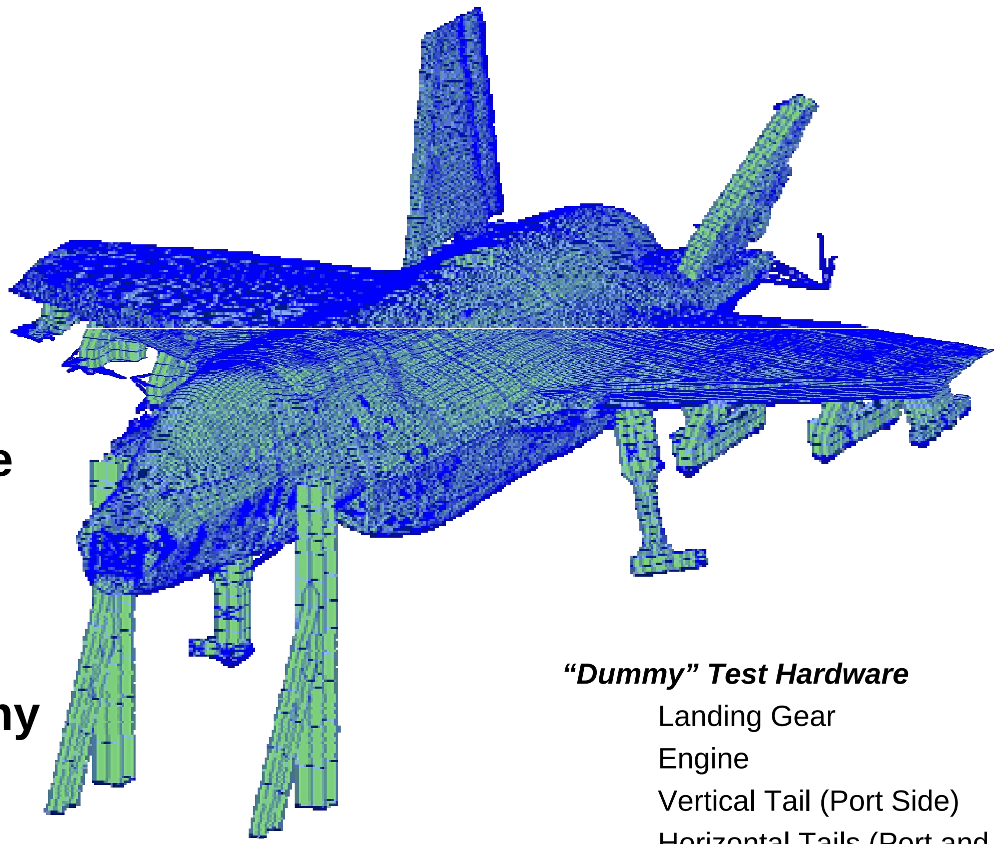
Flight Test Configurations

- **Special Flight Test configurations modeled and evaluated to determine Flight Test Operating Restrictions:**
  - ***Spin Chute***
  - ***Nose Boom***
  - ***Mass Distributions Due to Instrumentation***



Ground Test Configurations

- **Special Ground Test configurations modeled and evaluated to determine Test Adequacy, Safety of the Test Article, and Strain Gage Predictions.**
- **All structure not installed for ground test removed from the simulation and ground test loading hardware added.**
- **Loading attained through discrete load points on dummy hardware and fittings as well as distributed loads representing load pads**



"Dummy" Test Hardware

- Landing Gear
- Engine
- Vertical Tail (Port Side)
- Horizontal Tails (Port and Starboard**)**
- Pylons
- Plugs for Inlet Pressurization
- Discrete Load Fittings

F-35 Model Development: Positioned for the Future (ASIP Pillar V)

Positioned for the Future

- At the conclusion of the F-35 System Development and Demonstration program, the intent and ultimate goal of the F-35 FEA effort is to have a highly representative model of the F-35 airframe which has been validated by measured ground and flight test data.
- A representative validated Finite Element Model provides a necessary basis for any follow-on aircraft work.
- The current level of detail in the F-35 Finite Element Models provide a highly representative structural simulation which, once validated by test, will provide an excellent framework for structural analysis activities related to envelope expansion, manufacturing and ASIP Pillar V.


QUESTIONS?
F-35 LIGHTNING II
F-35

The Lightning Aircraft (U.S.)

- **Specifications: (P-38L)**
  Span: 52’ (15.85 m)
  Length: 37’ 10” (11.53 m)
  Height: 12’ 10” (3.91 m)
  Empty Weight: 12,000 lb (5,806 kg)
  Max Speed: 414 mph
  Range: 2,600 miles

- **Specifications: (F-35A)**
  Span: 35’ (10.7 m)
  Length: 51.5’ (15.7 m)
  Height: 14.2’ (4.6 m)
  Empty Weight: 25,600 lb (12,020 kg)
  Max Speed: ~1200 mph
  Range: 1,200 nm