

# ASIP 2017 T-38 Finite Element Model (FEM)

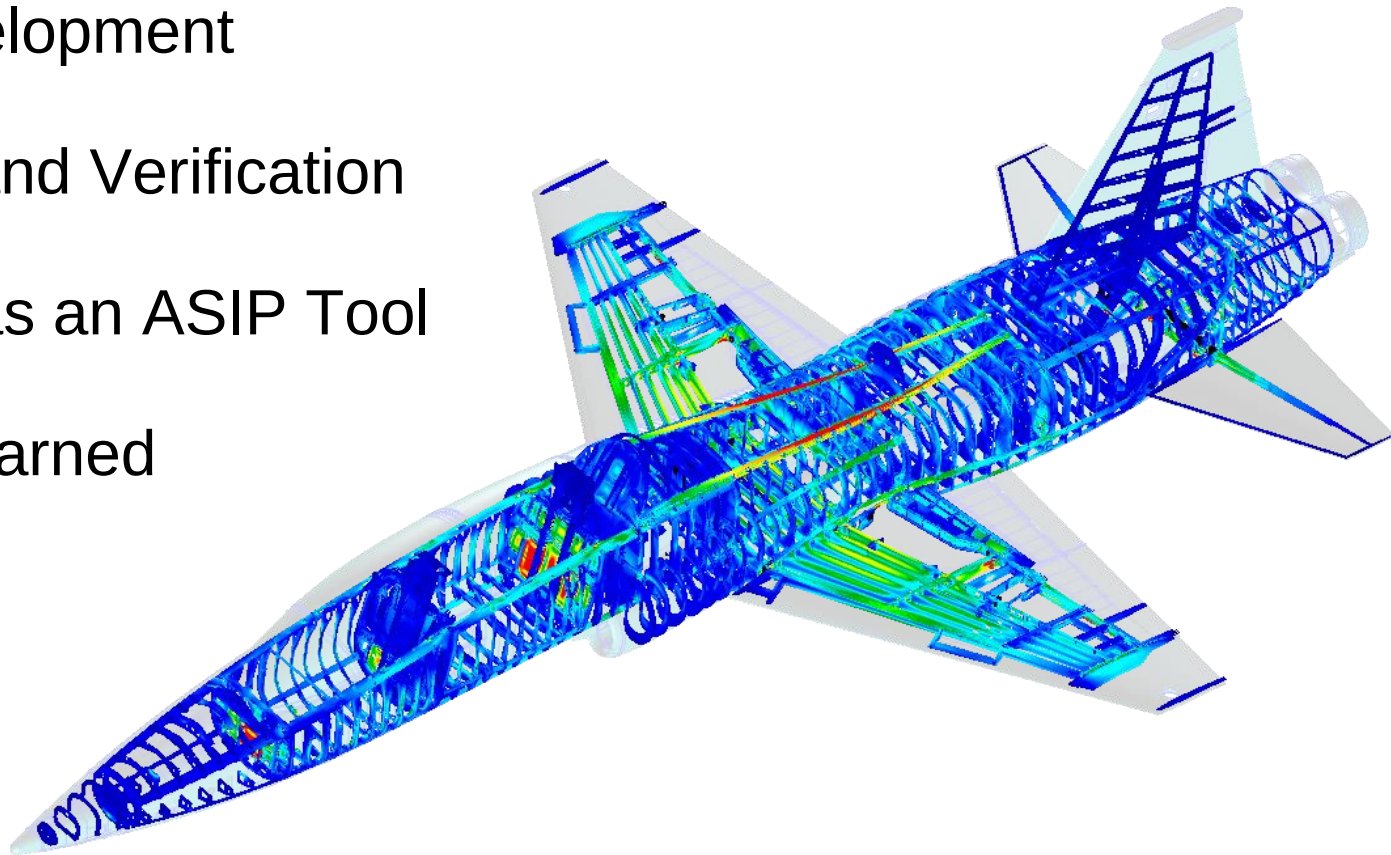
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## Overview, Correlation, and Usage

Nov. 29, 2017

John Taylor  
Aerospace Engineer

- Background
- Model Development
- Validation and Verification
- T-38 FEM as an ASIP Tool
- Lessons Learned



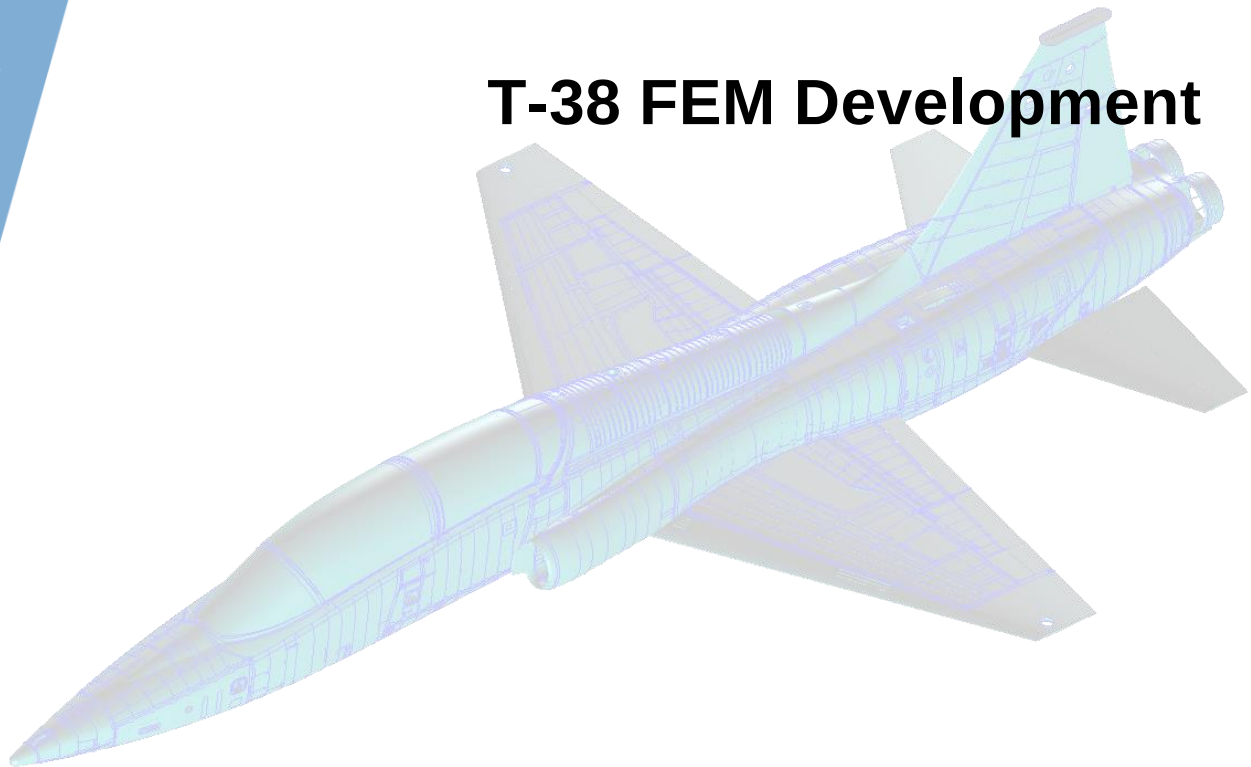
# T-38 Talon – Supersonic Trainer

- World's first supersonic trainer, Mach 1.3 flight, >7G maneuvers
- 1187 produced from 1961-72
- About half are still in service today
- ~75,000 pilots trained in the T-38
  - Nearly every USAF pilot since 1961
- Average T-38 has flown 15,000 hours
- Fleet flight hours: Over 13,000,000

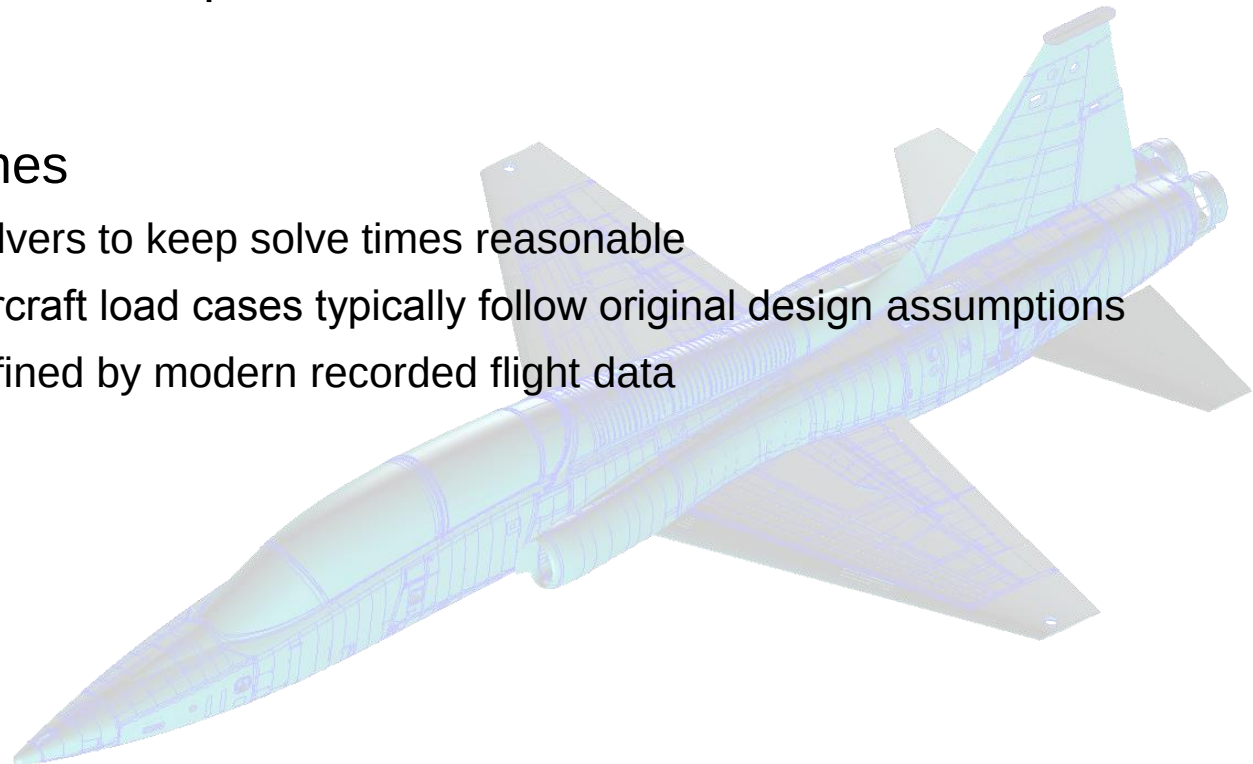


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# T-38 FEM Development

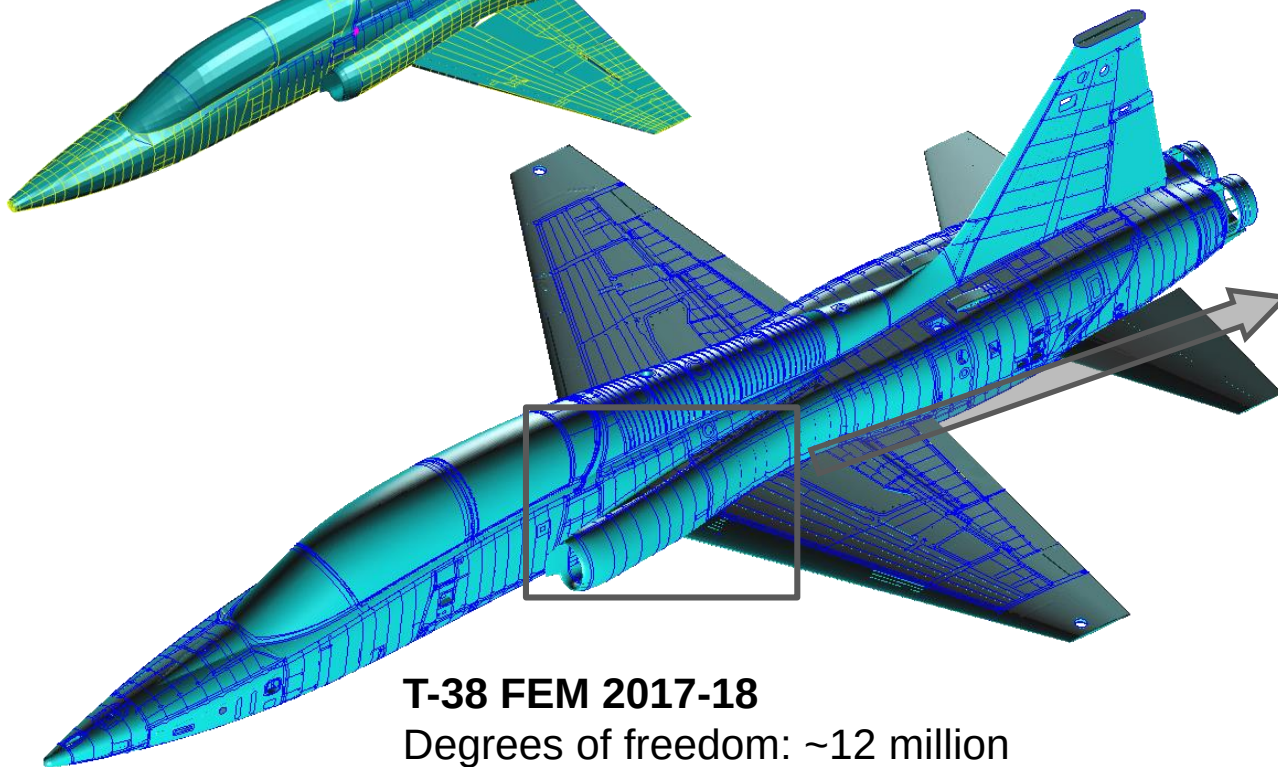
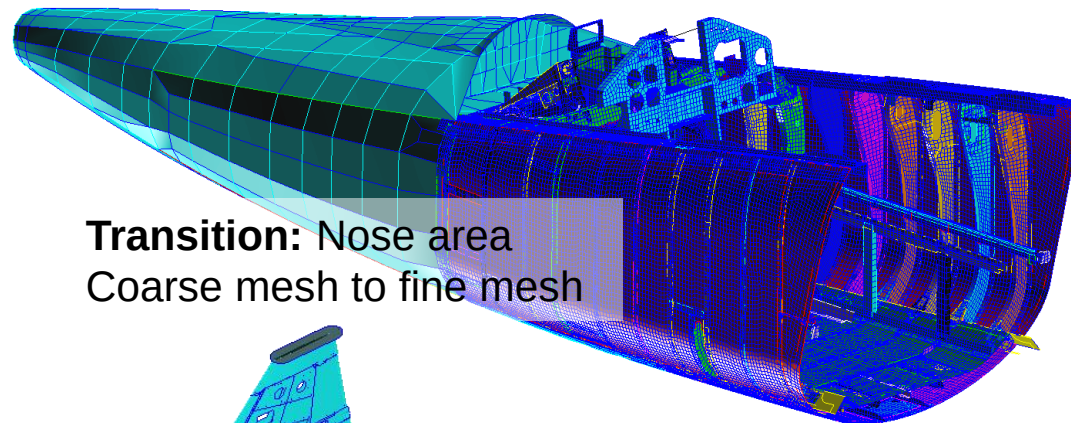
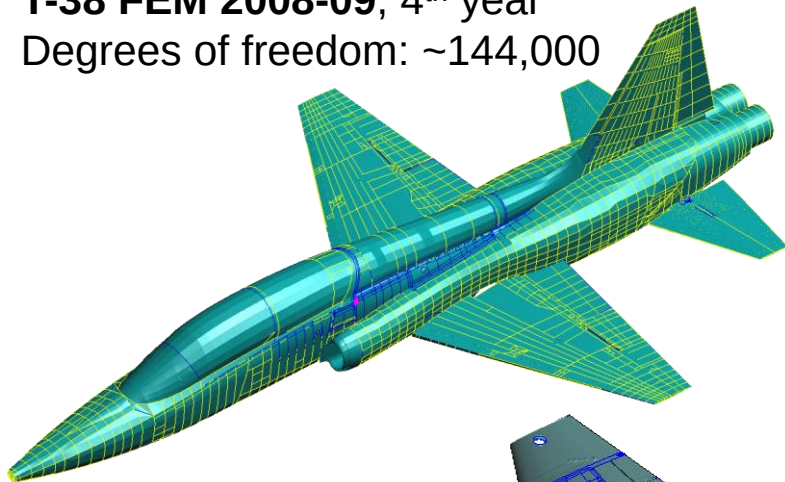


- The T-38 FEM is a tool used to aid the USAF in complying with ASIP requirements such as JSSG-2006, MIL-STD-1530D, MIL-HDBK-516C, and the T-38 ASIP Master Plan.
- Primary usage to output local part loads for ASIP structural components
- Development guidelines
  - Uses linear elastic solvers to keep solve times reasonable
  - Static “worst case” aircraft load cases typically follow original design assumptions
  - Fatigue cases are defined by modern recorded flight data

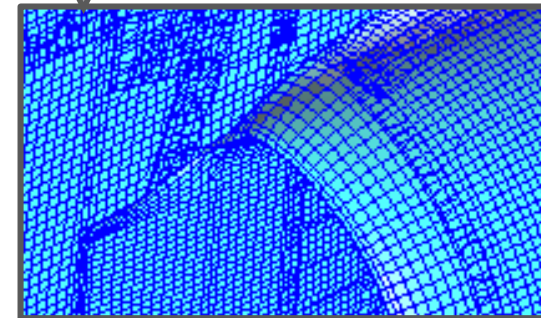
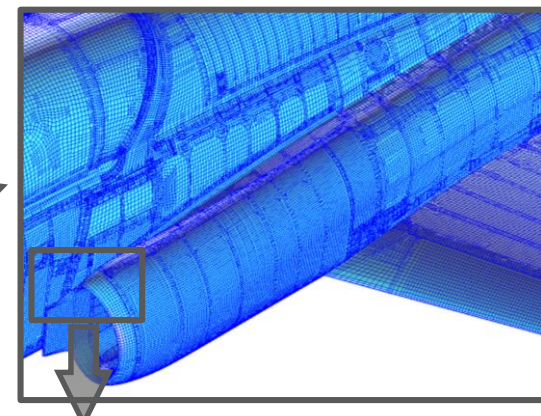


# T-38 Finite Element Model Evolution

**T-38 FEM 2008-09, 4<sup>th</sup> year**  
Degrees of freedom: ~144,000

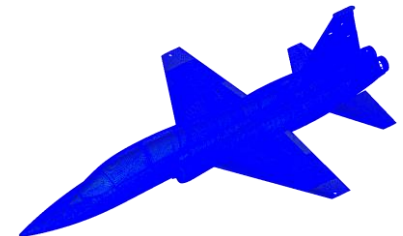
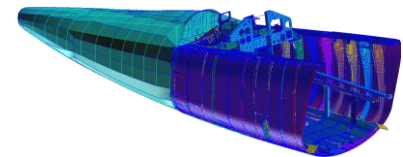
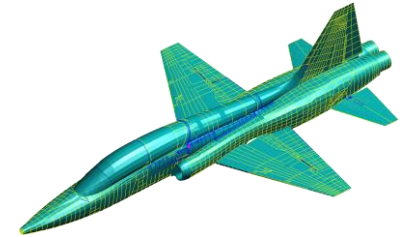


**T-38 FEM 2017-18**  
Degrees of freedom: ~12 million  
62 static cases: >50 GB output

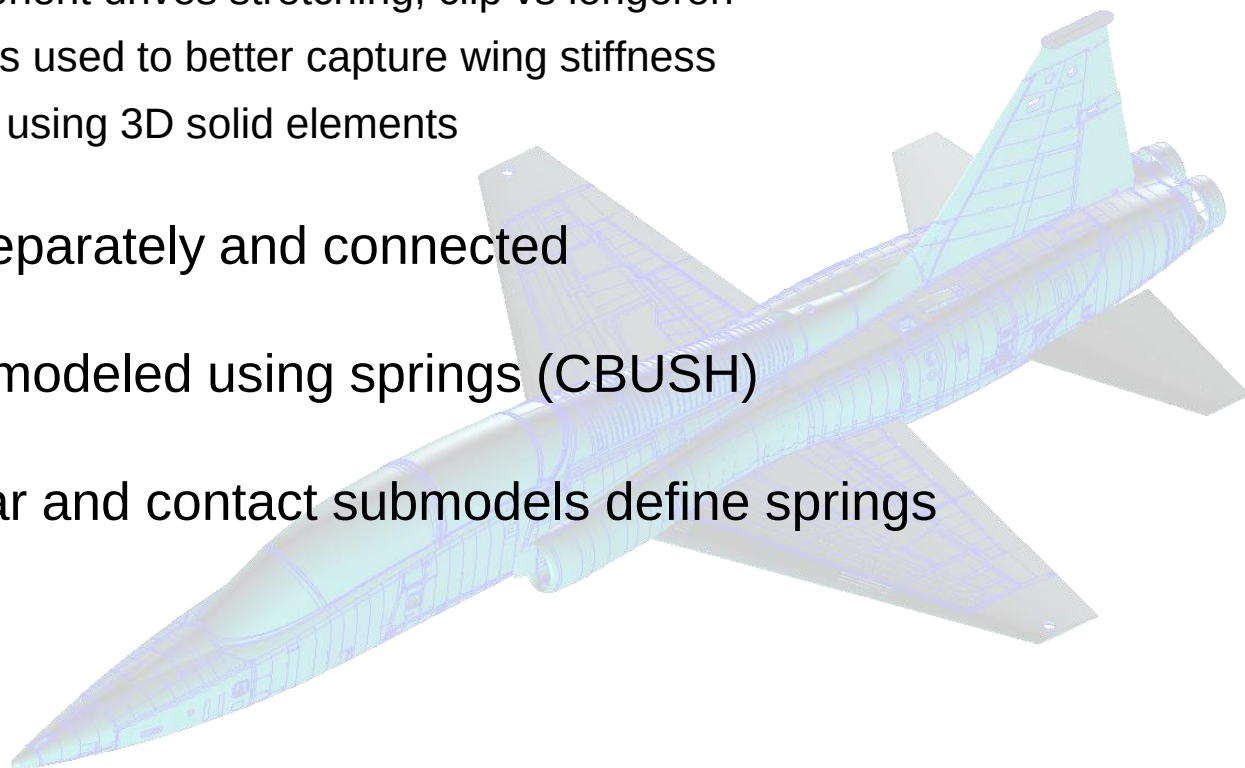


# T-38 Finite Element Model Evolution

- Early stages – Build full aircraft FEM
  - Initially created 6” nominal grid size bar/shell model
  - Resolution limited, some key structure blended by necessity
  - Using FEM requires time, experienced staff
  - Some local refinements in areas of special interest (FCLs)
- Transition – Enhance model resolution, separated parts
  - Sections of aircraft recreated at high resolution, zone by zone
    - Sections such as the nose, cabin, forward fuselage, or wing
  - Refine mesh and separately define each part
- Today – Resolution no longer limiting factor
  - Nominal shell element size of 0.5 inch
  - Each part modeled separately and connected
  - Fastener stiffnesses modeled using springs (CBUSH)

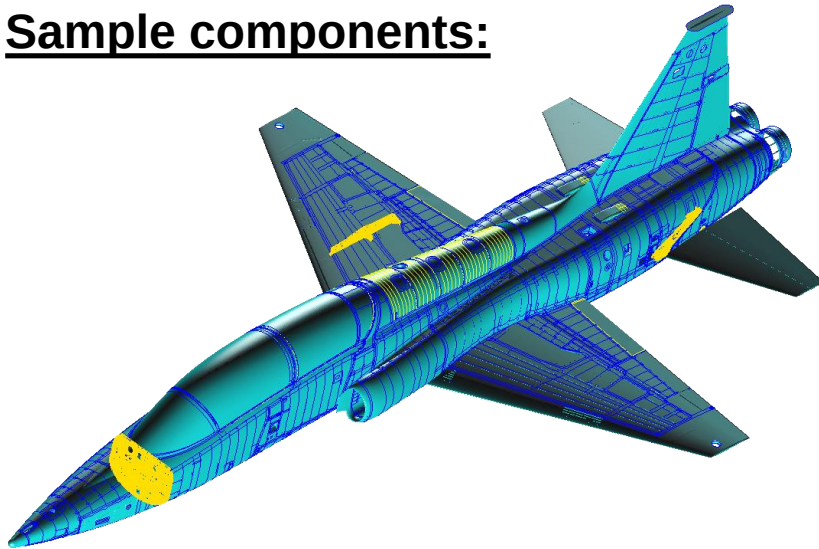


- Built primarily out of shell elements, Nastran first order QUAD4
  - Nominal shell element size of 0.5 inch
- Components stretched to the OML or reference station to attach
  - Significance of component drives stretching, clip vs longeron
  - Numerical shell offsets used to better capture wing stiffness
  - Honeycomb modeled using 3D solid elements
- Each part modeled separately and connected
- Fastener stiffnesses modeled using springs (CBUSH)
- Major joints: Nonlinear and contact submodels define springs (CBUSH, MPCs)

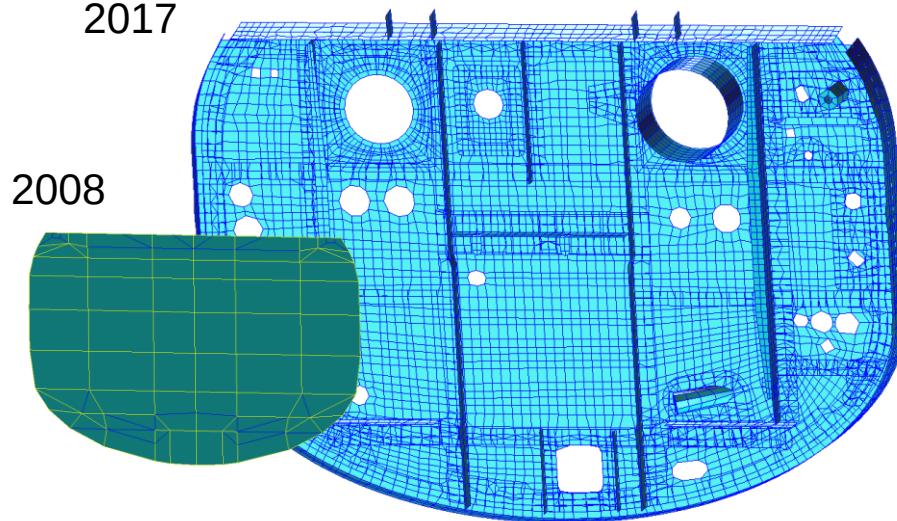


# T-38 FEM Sample Components

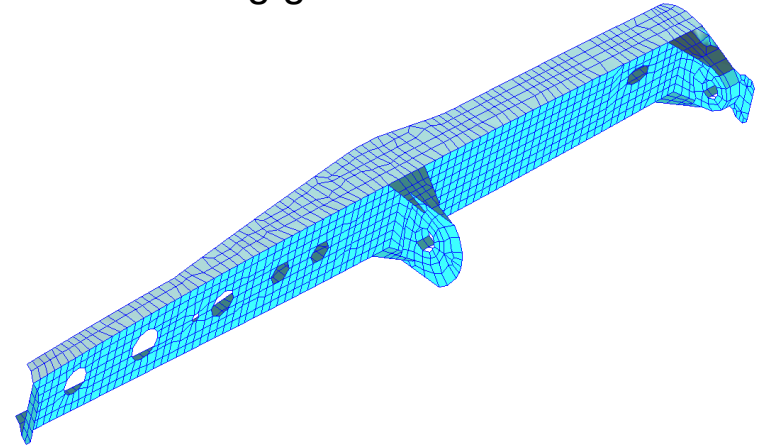
## Sample components:



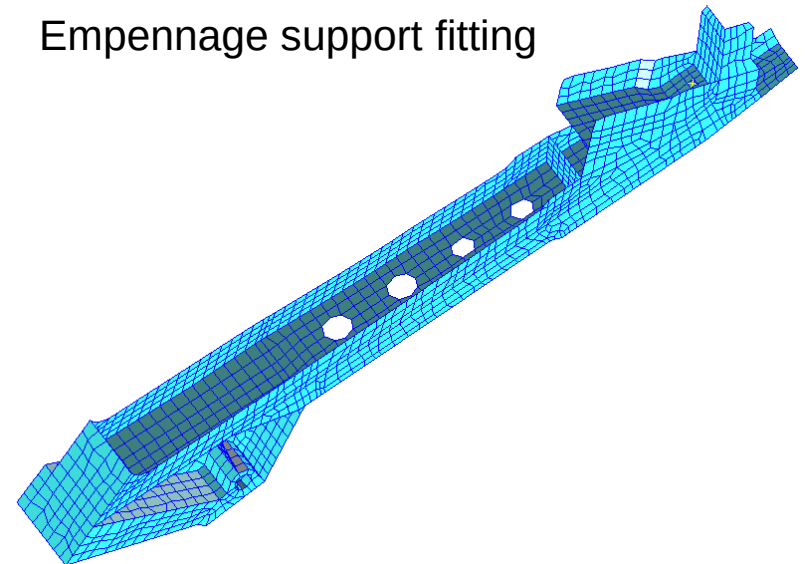
Forward bulkhead assembly  
2017



Main landing gear attachment rib

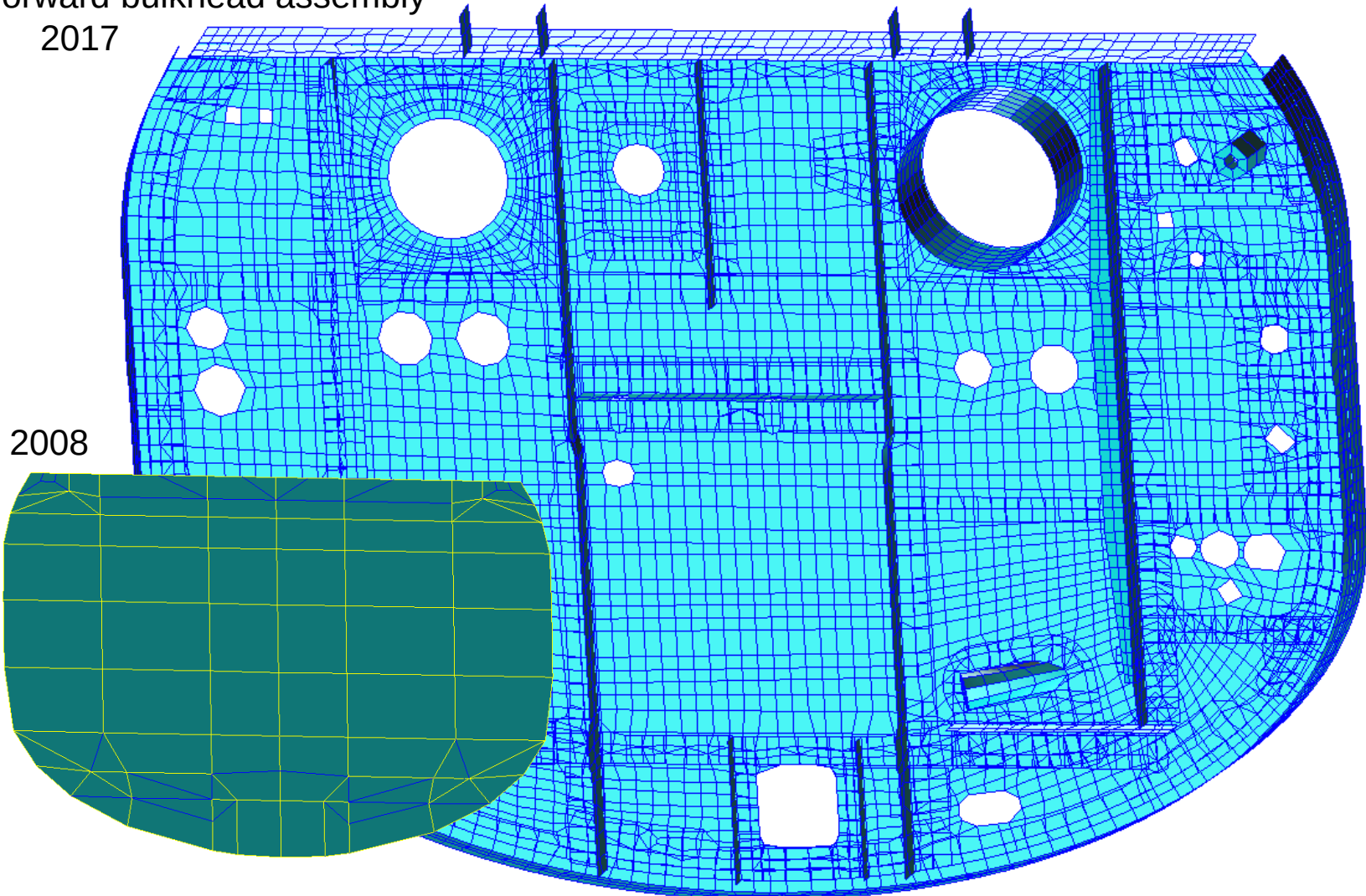


Empennage support fitting



# T-38 FEM Sample Components

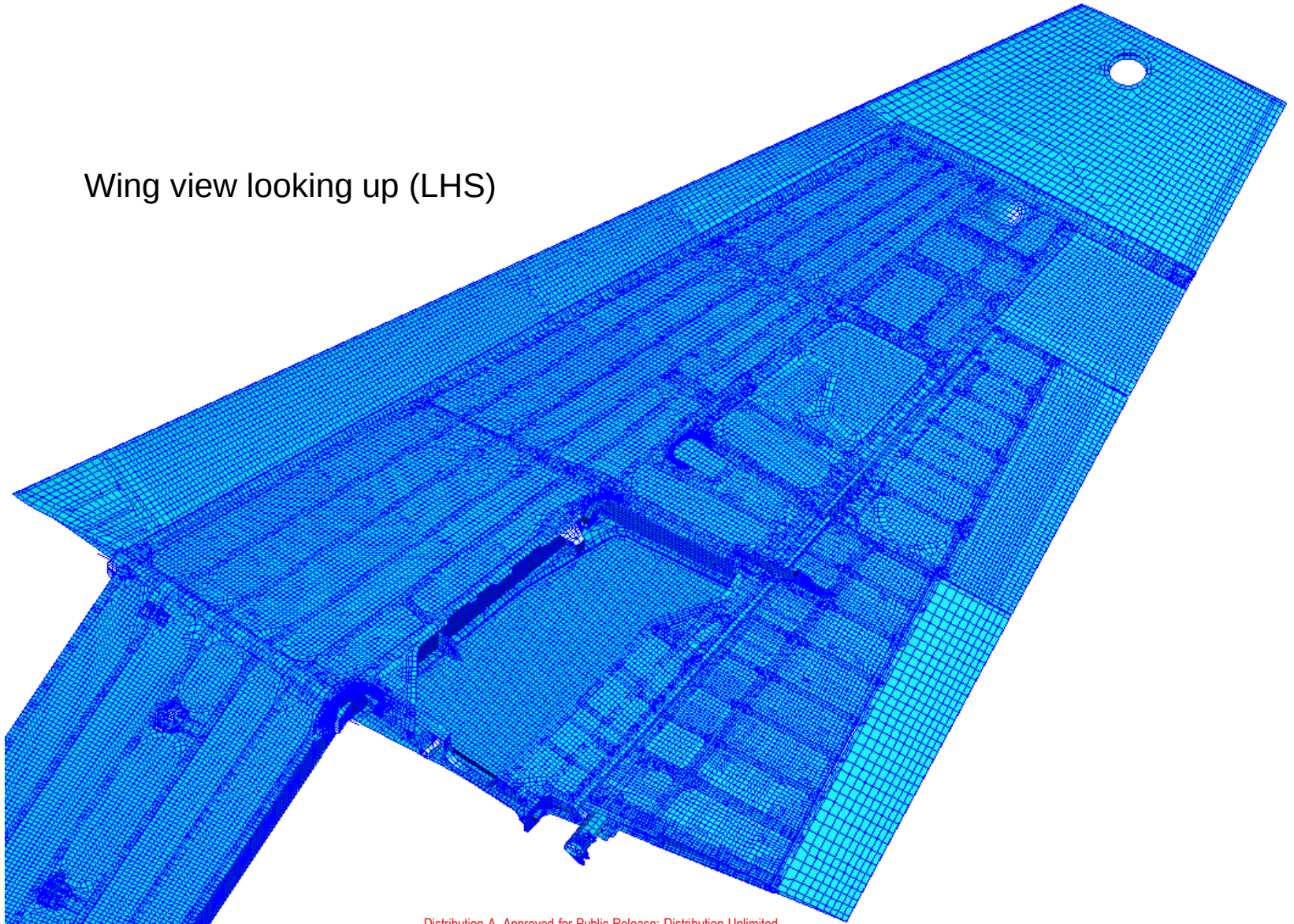
Forward bulkhead assembly  
2017



2008

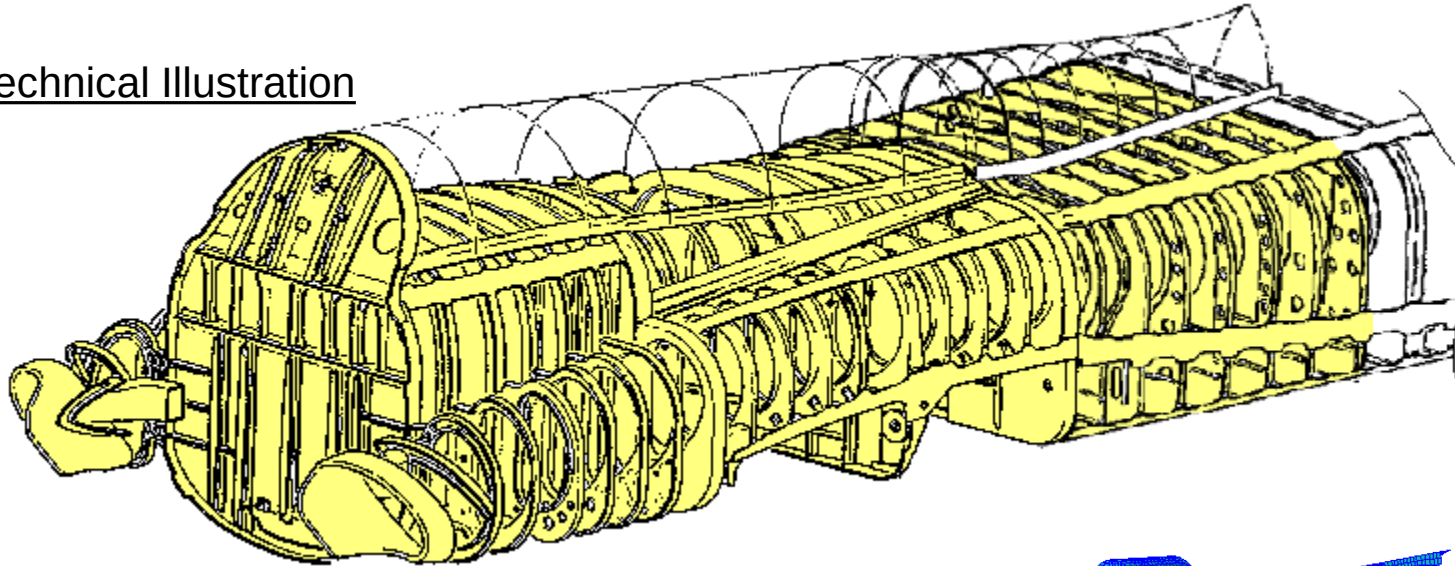
# T-38 FEM Sample Mesh – Wing

Wing view looking up (LHS)

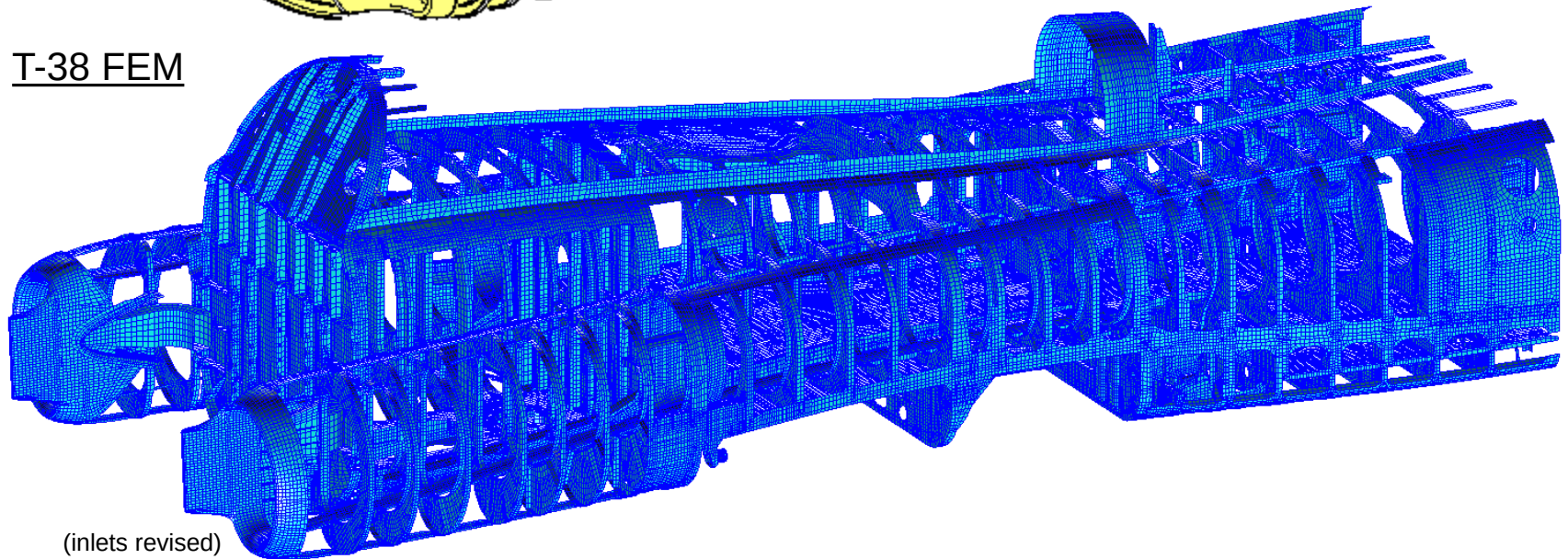


# T-38 FEM Sample Mesh – Center Fuselage

Technical Illustration



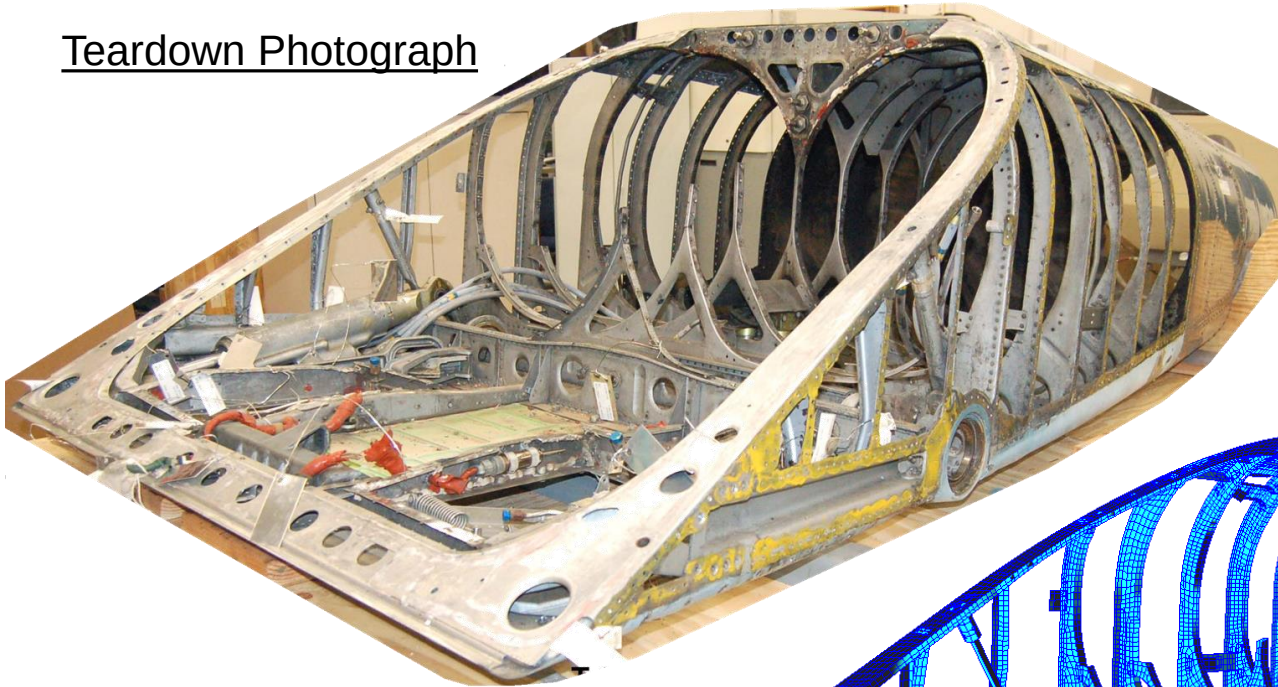
T-38 FEM



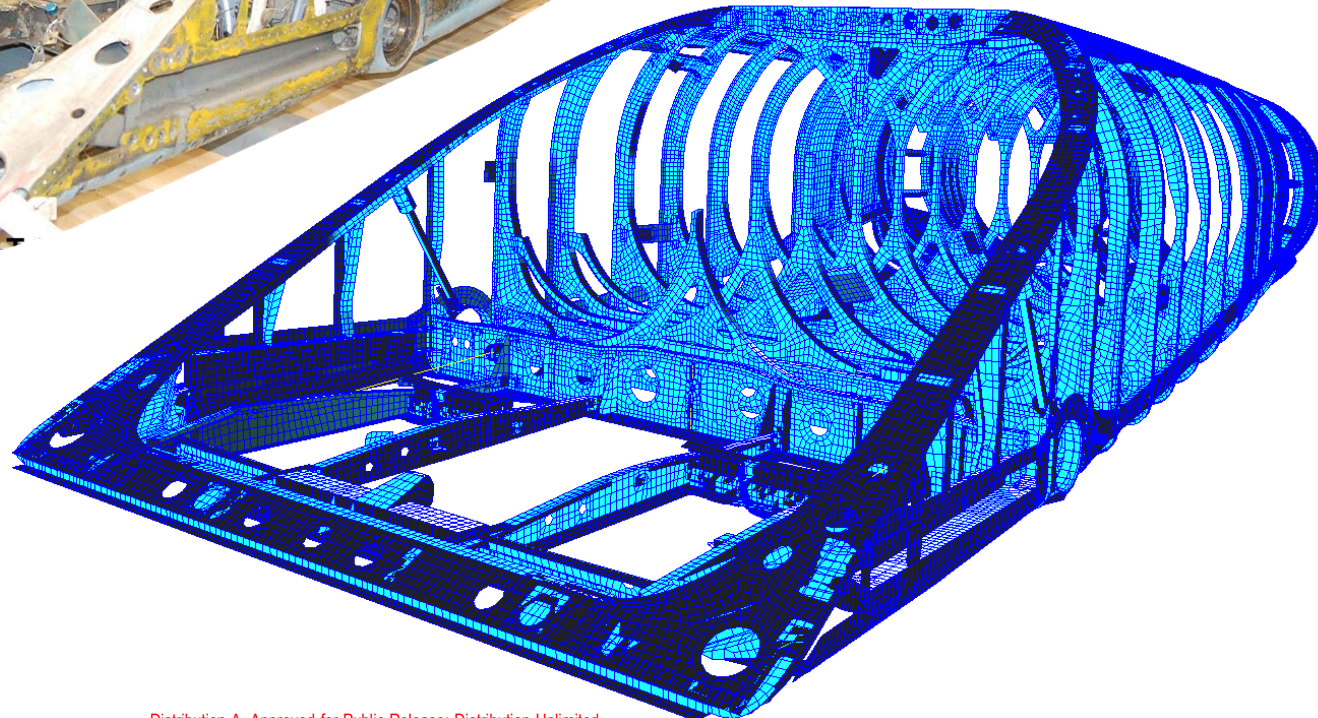
(inlets revised)

# T-38 FEM Sample Mesh – Empennage

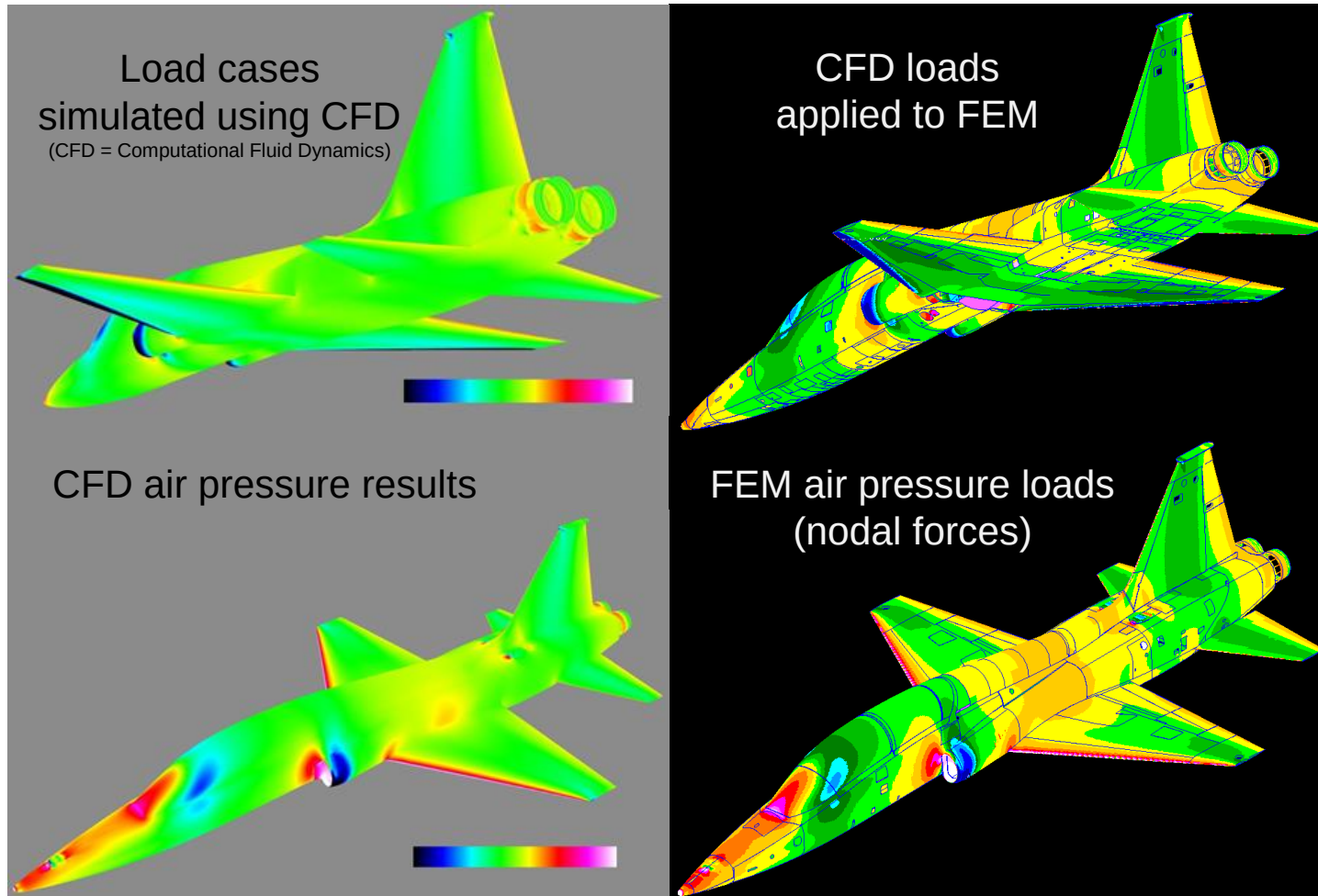
Teardown Photograph



T-38 FEM



# FEM Loads – Recreated Using Modern Tools



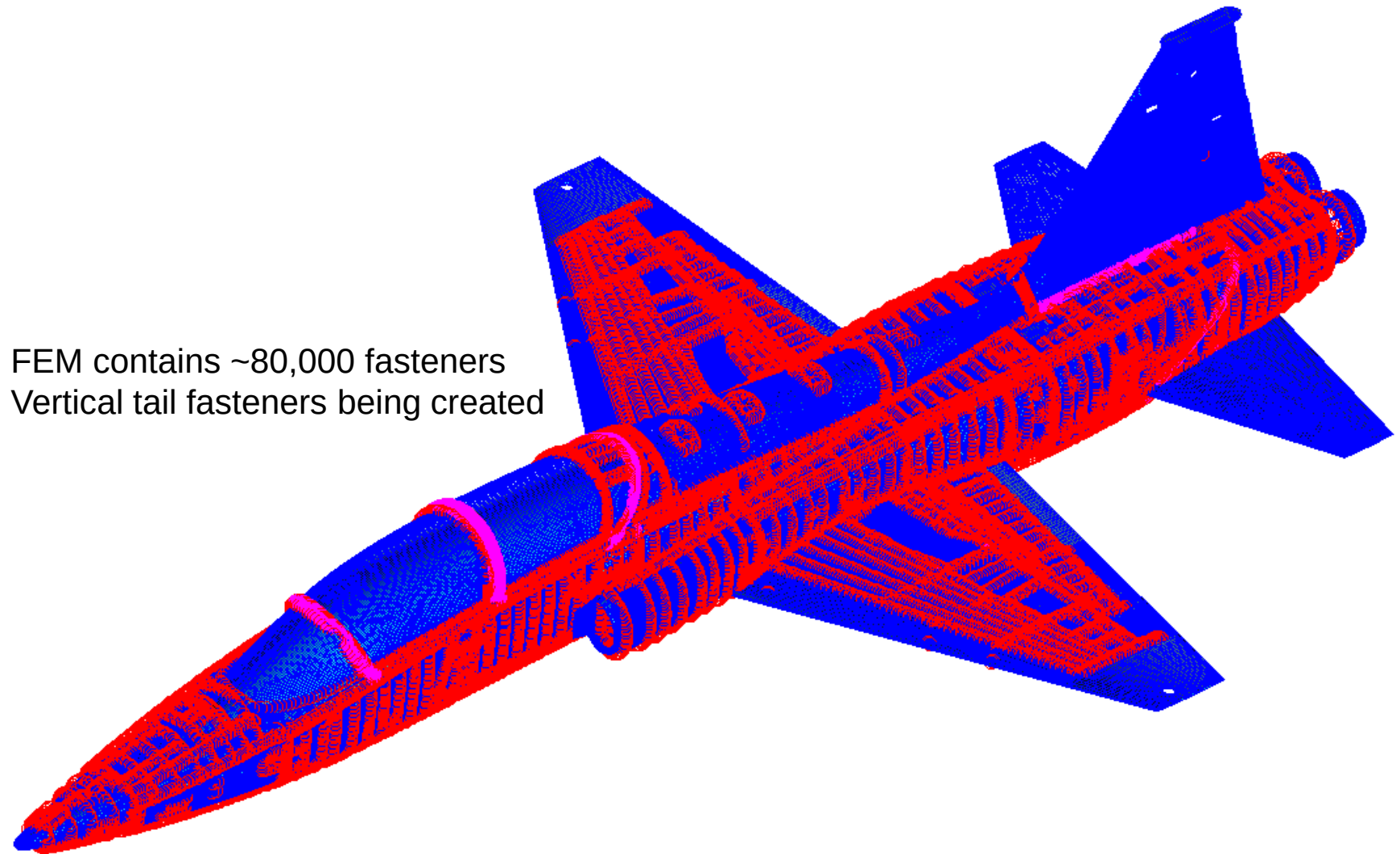
Notes: Consistent scales used for all plots. FEM pressure plots show banding but actual FEM loading varies continuously.

Air Loads Recreated Using CFD, Mapped to FEM

- Parts-separated transitional FEM fastener modeling
  - Initially used merged/shared nodes to represent fasteners
  - This simulates rigid load transfer between parts; structure drives loads
  - Good design selects fasteners that are well-suited to structure
- Springs added to represent fasteners
  - Fasteners are modeled as springs using CBUSH elements
    - Equations approximate fastener axial & shear stiffness
    - Essentially curve fits to NGC fastener test databases
  - Fastener generation heavily automated
  - Global results similar, local load distribution typically improved
  - Now possible: Automated preliminary margins of safety at every fastener

Fastener Stiffness Improves Local Load Distribution

# T-38 FEM External Fastener Entities



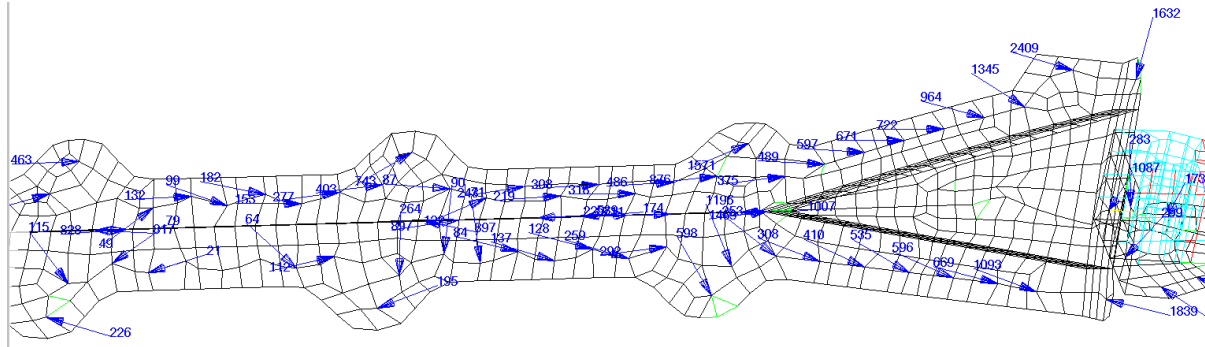
FEM contains ~80,000 fasteners  
Vertical tail fasteners being created

- Wing stiffness uses shell offsets to correct spar/rib flange locations
  - Web stiffness is overstated with shells placed on wing skins
- Global: External fuselage skins typically knife-edged at fasteners
  - External fuselage skins use reduced modulus of  $E_{\text{fuse\_skin}} = 70\% * E$
  - This reduction introduces global calibration “tuning” effects
  - Knife-edged fastener CBUSH stiffness knockdown will replace modulus reduction
- Local: Modeled doors use reduced stiffness
  - Door panel stiffness is rarely simple or linear
    - Some preload, some nutplate and quick release fastener types
  - Stiffness knockdown uses curve fit based on geometric parameters
  - This reduction also introduces global calibration “tuning” effects
  - Door fastener CBUSH stiffness knockdown will replace modulus reduction

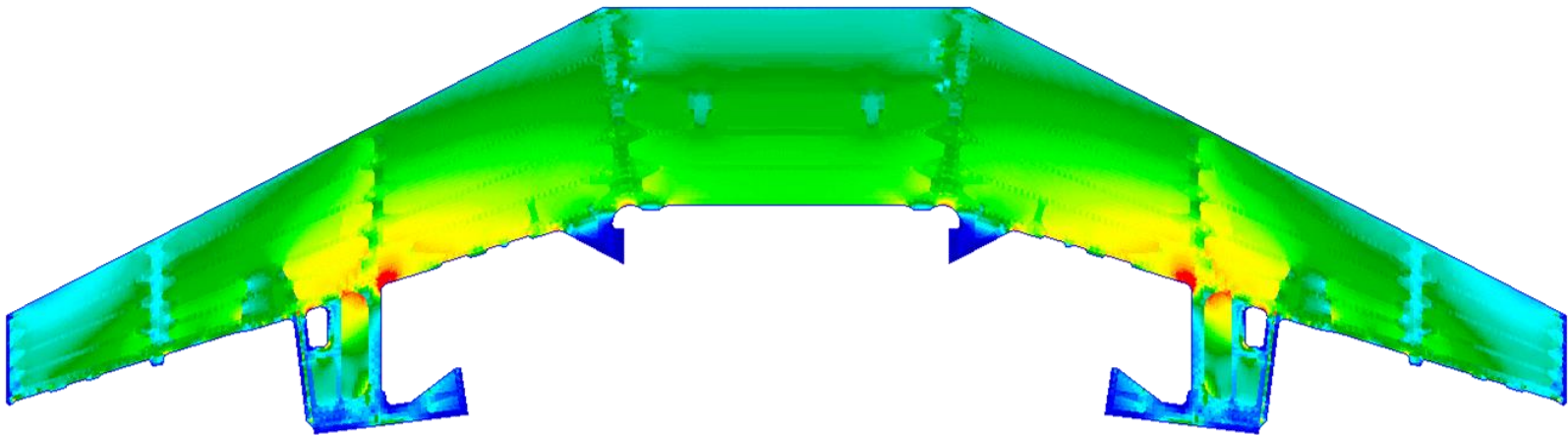
- Local: Additional known and intuitive sources of FEM stiffness error
  - Examples include latches, doors, hinges, attachment lugs, contact load transfer areas
  - Local stiffness/nonlinear modeling is an area of current work, tech fellows involved
- Effective connection stiffness can be approximated for linear FEM
  - Create nonlinear submodel capturing behavior of interest
  - Solve submodel for all FEM load cases and export results
  - Apply results to global linear FEM
    - Create element connection using appropriate elements (typically MPC/CBUSH)
    - Translate submodel results to define unique connection stiffness for each load case
- Stiffness is reasonable for the submodeled case and small deviations
  - Stiffness essentially follows the slope line ( $d/dx$ ) of the nonlinear stiffness curve
  - Requires mature FEM as significant deviations will invalidate the stiffness results

# T-38 Finite Element Model Sample Outputs

Typical loads output: Fastener loads along longeron segment, connected skin and former



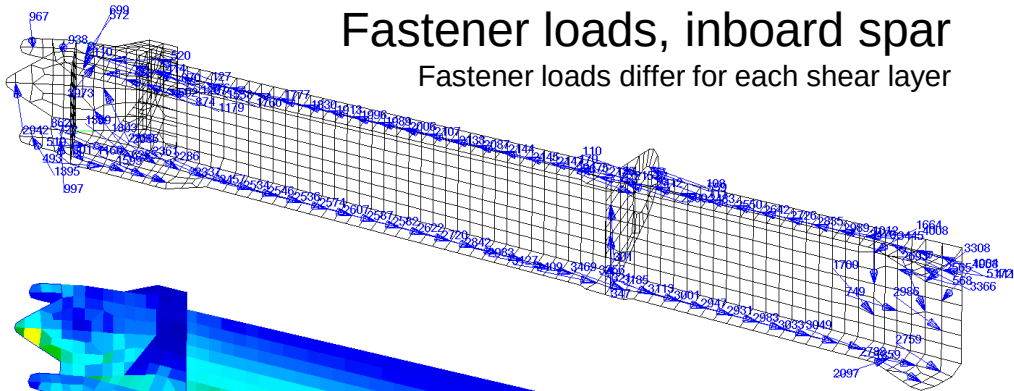
Typical stress output: Top view of lower wing skin in a high-G pull up scenario



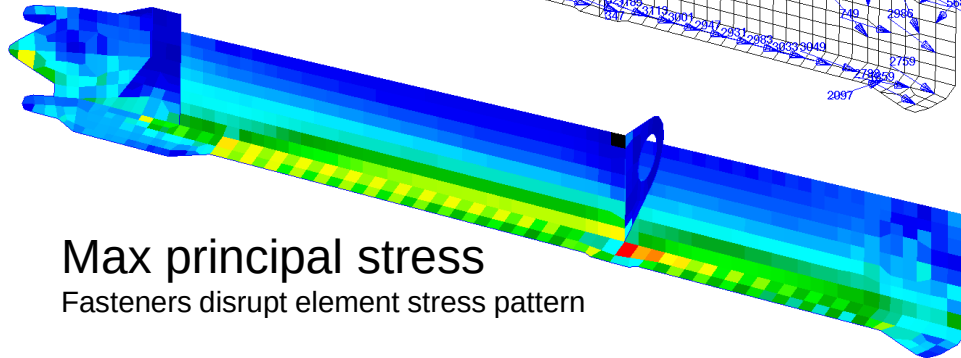
Aircraft FEM Produces High Fidelity Loads

# T-38 Finite Element Model Sample Outputs

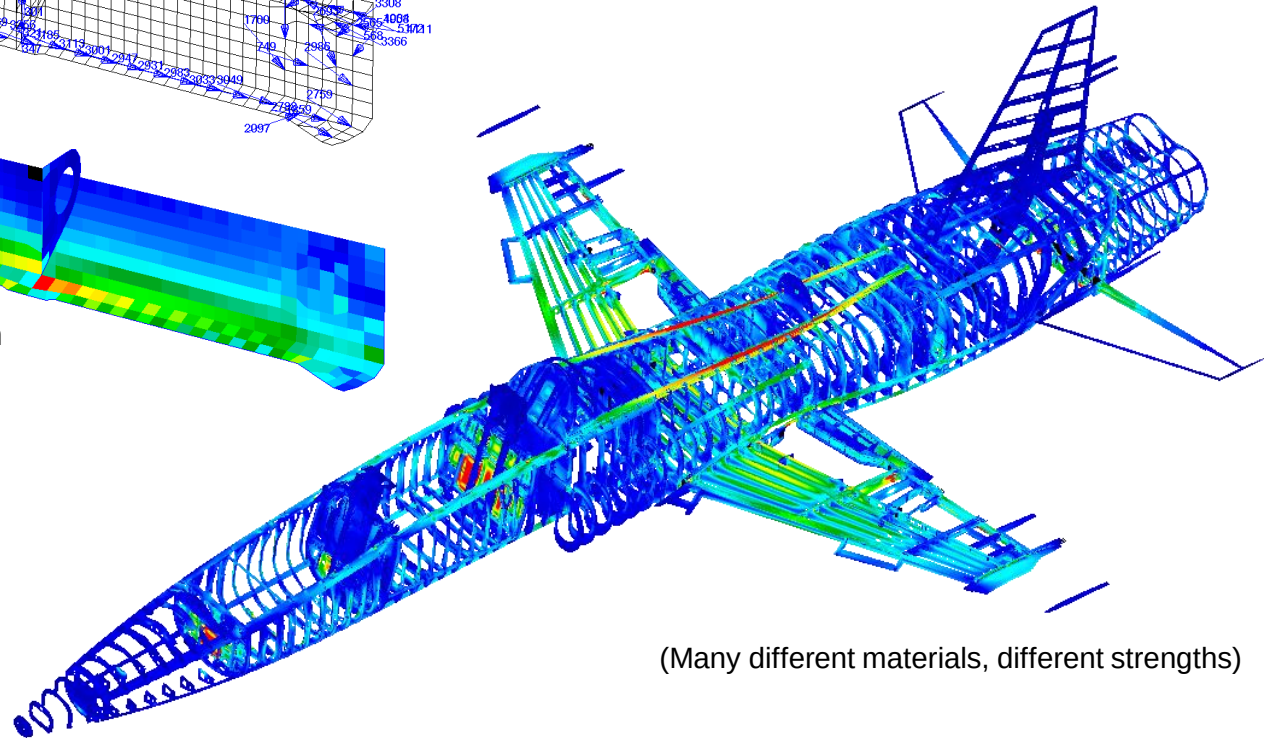
**Fastener loads, inboard spar**  
Fastener loads differ for each shear layer



**Max principal stress**  
Fasteners disrupt element stress pattern



**Aircraft von Mises stress overview**



(Many different materials, different strengths)

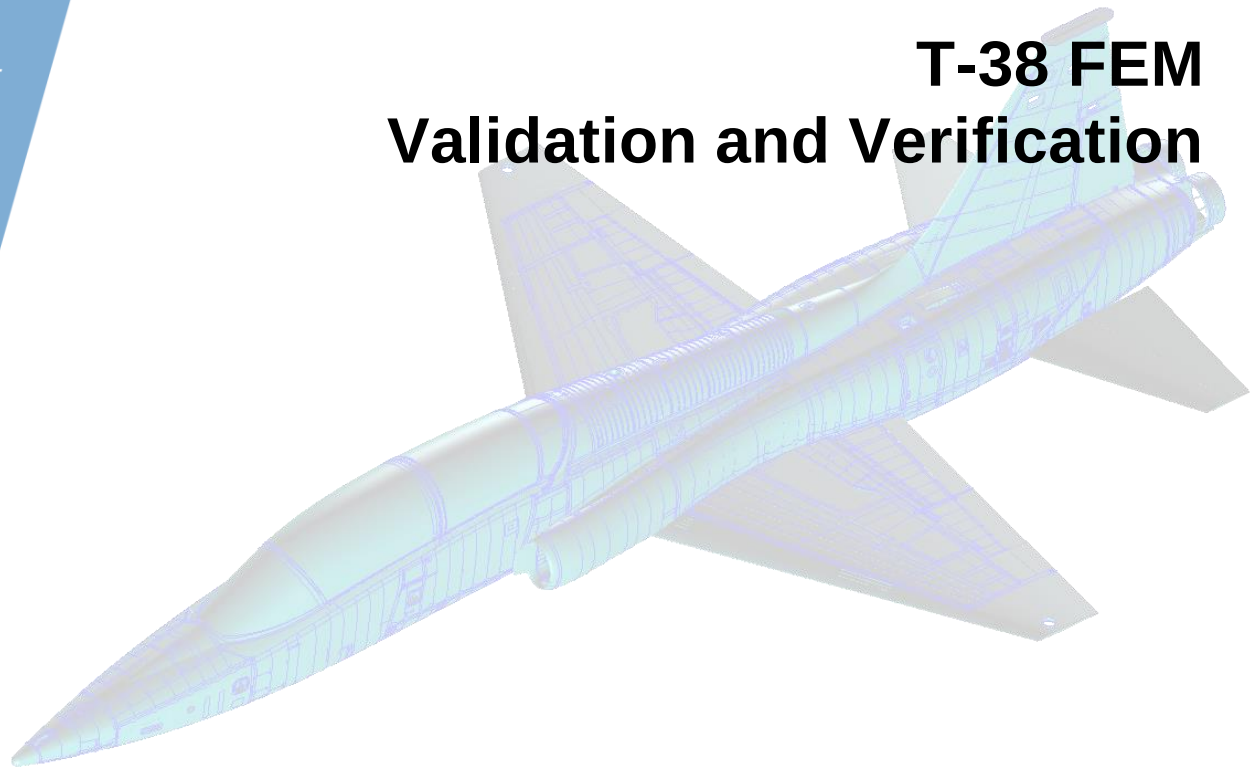
**Aircraft FEM Produces High Fidelity Loads**

- Fastener loads often used directly in screening and analysis
  - Spreadsheet can compare all individual fastener loads to their allowables
  - For highly loaded parts, load distribution/averaging must be considered
    - Many analytical methods use the average fastener load, not peak
- Loads through beam sections frequently requested and used
  - Parts separation makes this very intuitive and straightforward
- Stresses are good as reference, some are well developed
  - Stress plots are frequently used to verify hand calculations
  - Very useful when interpreting loads, screening load cases and failure modes
  - Mesh not converged at stress concentrations, fastener loads disrupt plots

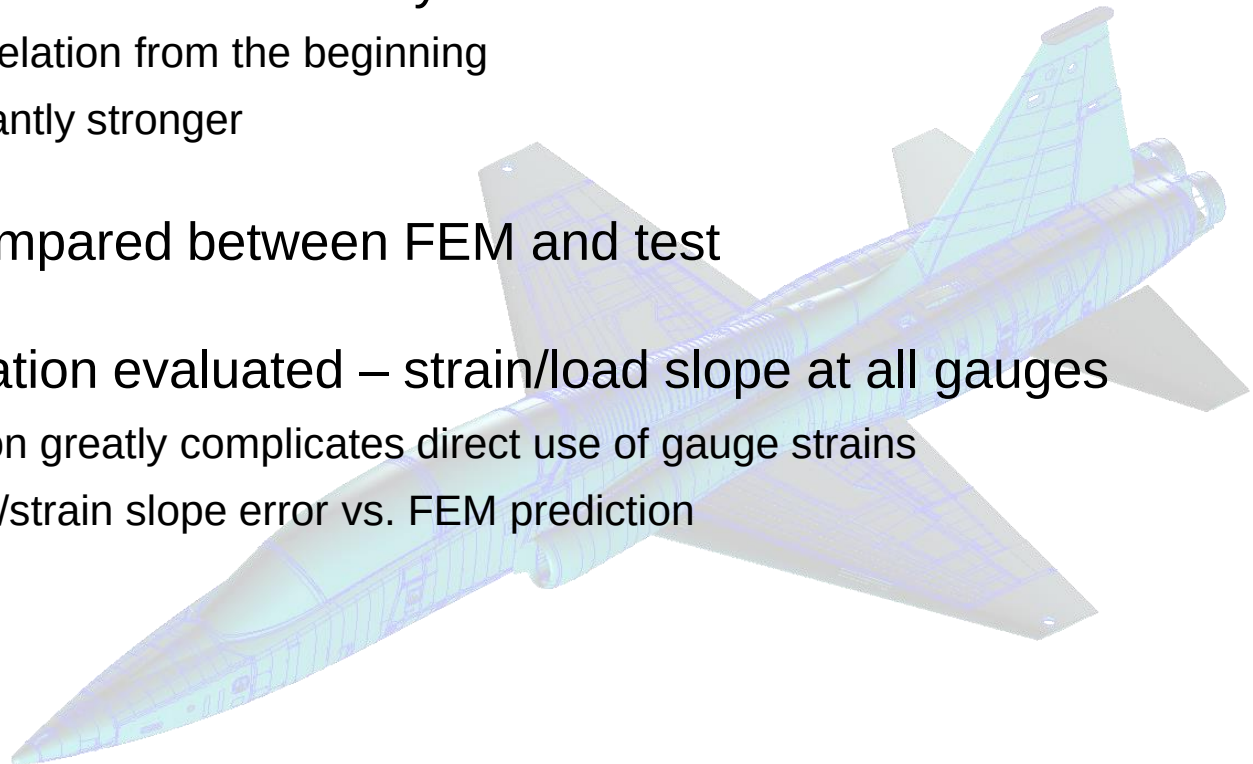
Aircraft FEM Produces High Fidelity Loads

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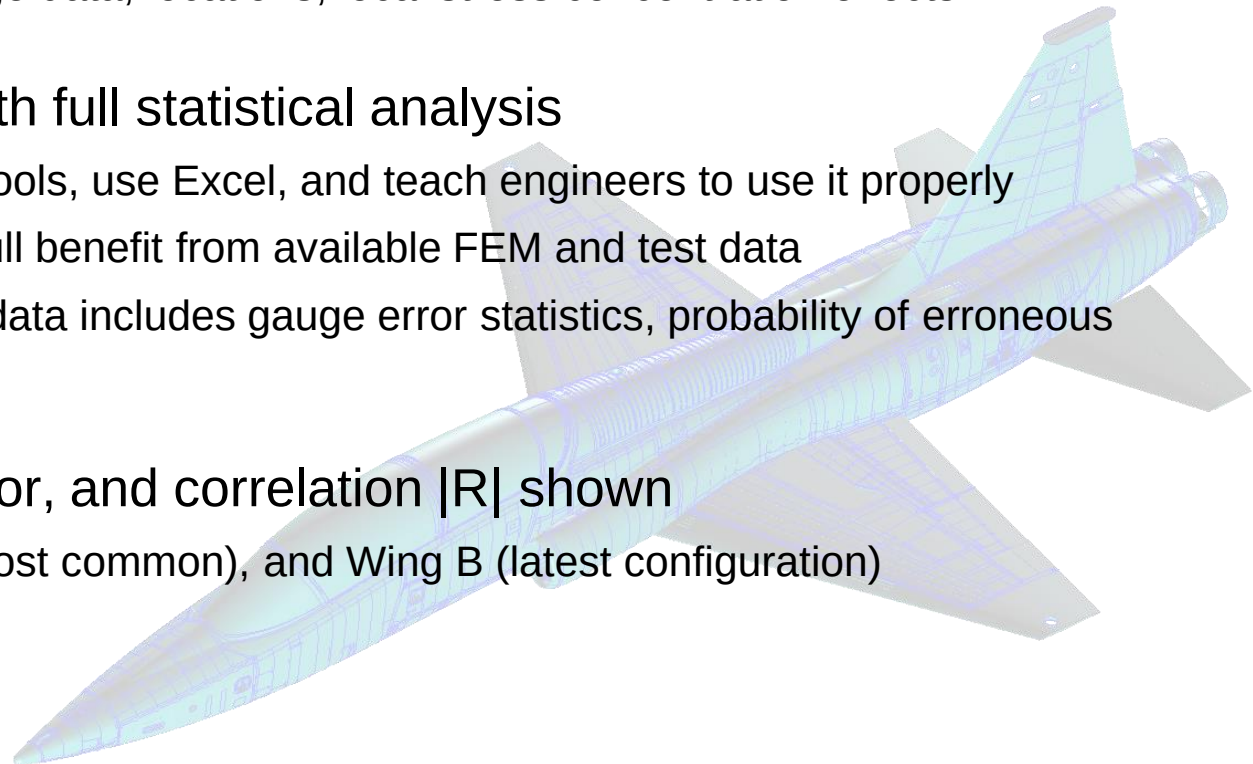
# T-38 FEM Validation and Verification



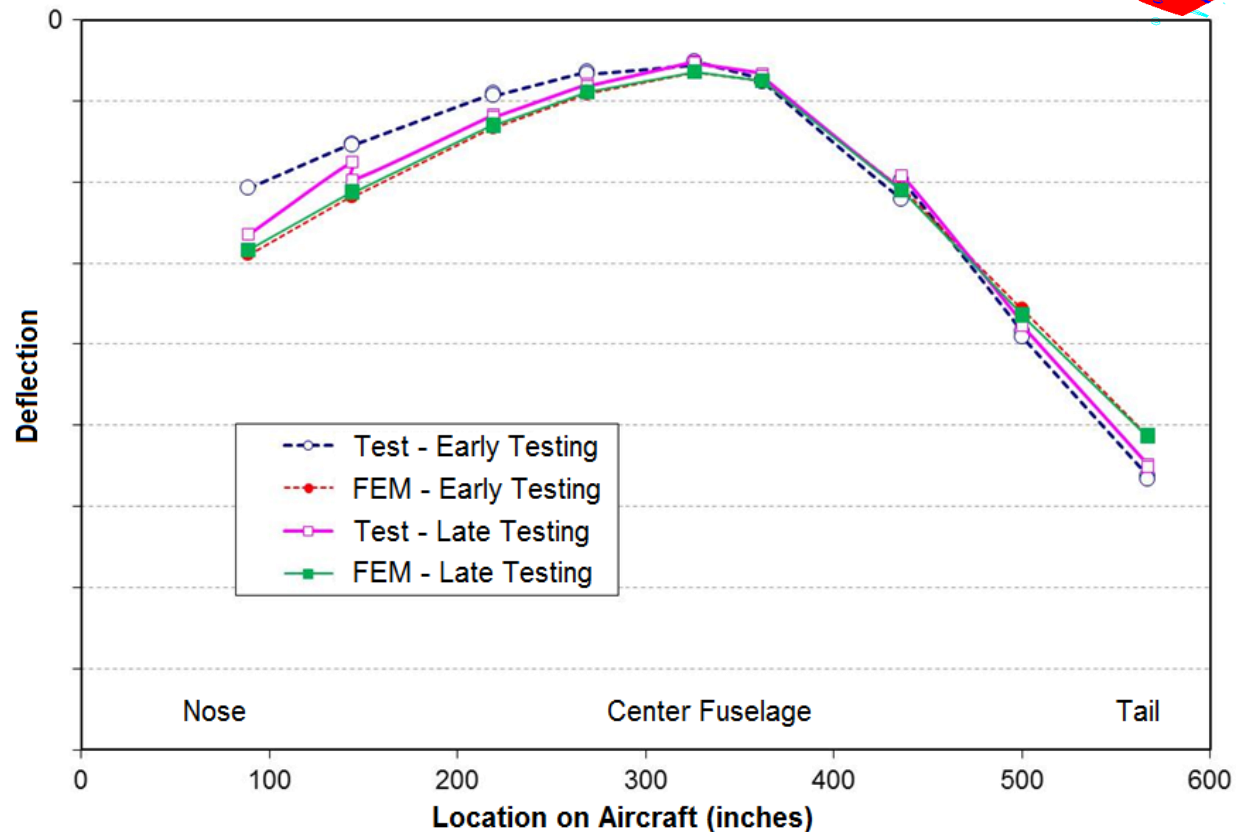
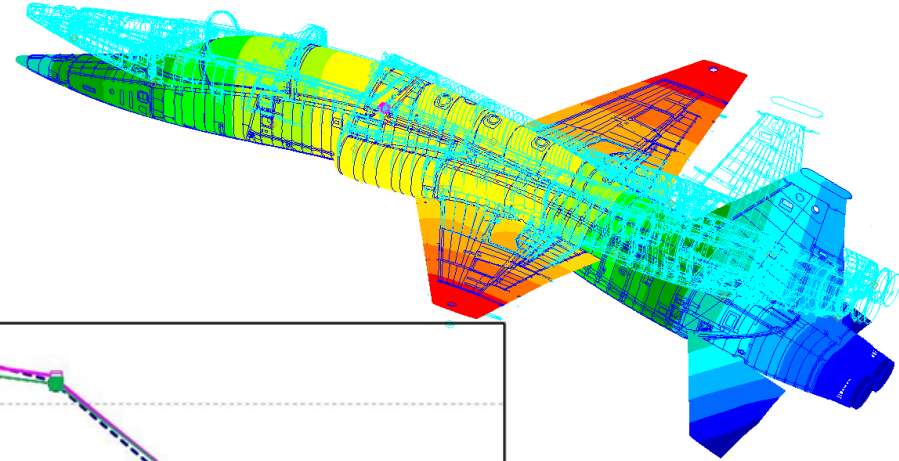
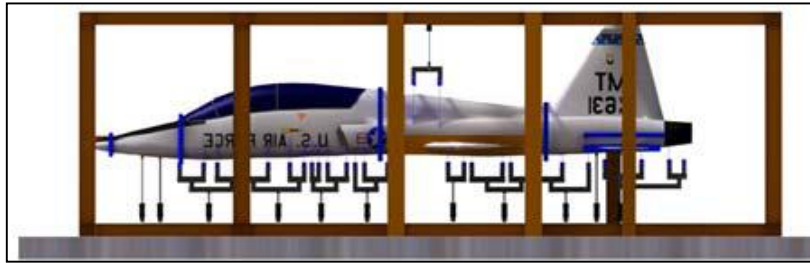
- As FEM began, fuselage fatigue test underway
  - Fuselage strain gauges located for fatigue testing and damage tolerance analysis
  - FEM correlation considered as an afterthought
- Wing tests performed after FEM already established
  - Considered FEM correlation from the beginning
  - Correlation is significantly stronger
- Global deflections compared between FEM and test
- Coarse FEM: Association evaluated – strain/load slope at all gauges
  - Coarse FEM resolution greatly complicates direct use of gauge strains
  - Check for gauge load/strain slope error vs. FEM prediction



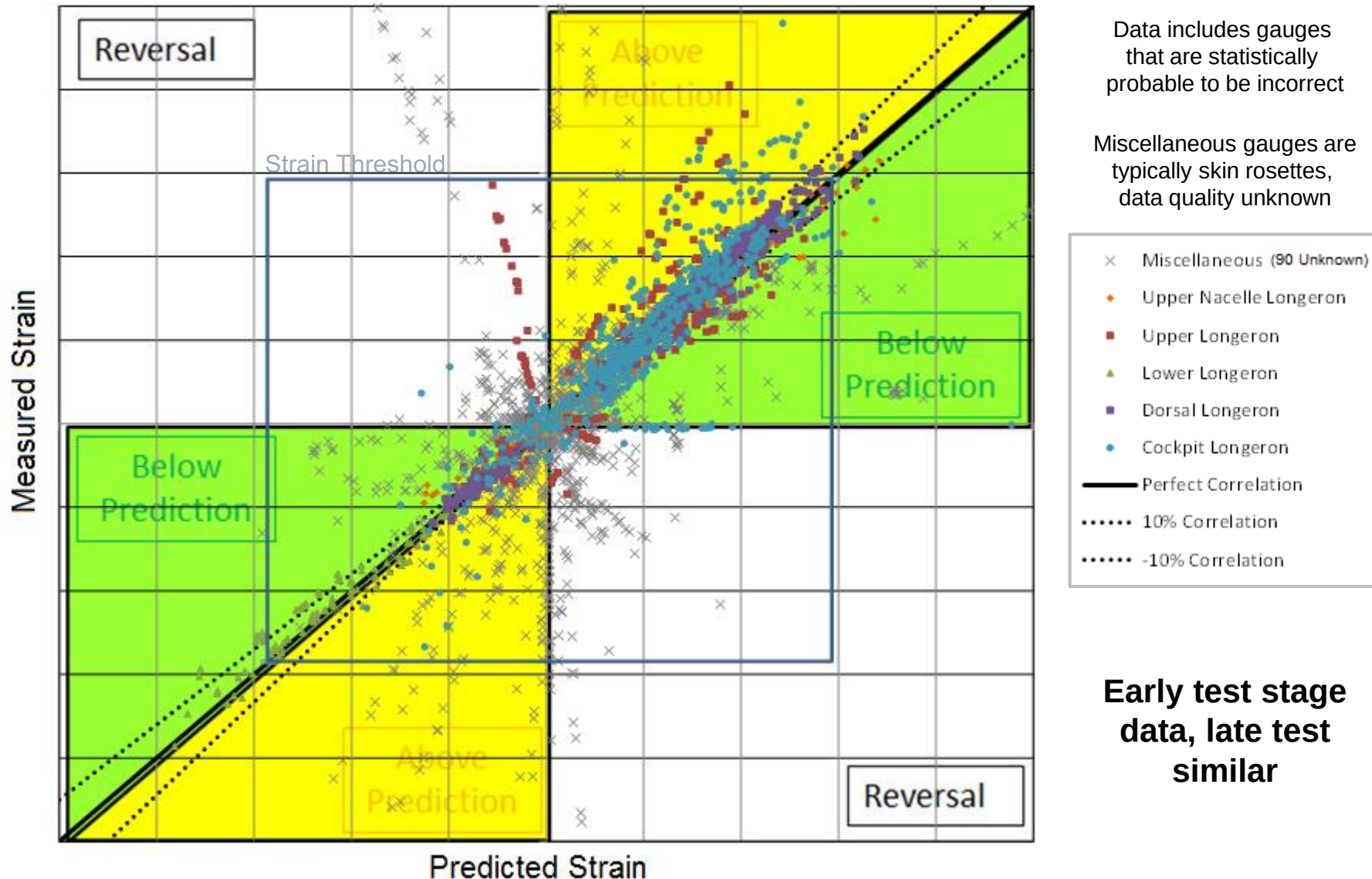
- Fine FEM resolution allows error to be directly evaluated
- “Deep dive” task to better understand, match FEM and test data
  - Accuracy of FEM “gauge” entity locations and angles
  - Accuracy of test gauge data, locations, local stress concentration effects
- Statistician tasked with full statistical analysis
  - Build new statistical tools, use Excel, and teach engineers to use it properly
  - Goal to capture the full benefit from available FEM and test data
  - Enhanced statistical data includes gauge error statistics, probability of erroneous gauge reading, more
- Deflection, gauge error, and correlation  $|R|$  shown
  - Fuselage, Wing A (most common), and Wing B (latest configuration)



# FEM Correlation – Fuselage Deflection



# FEM Correlation – Fuselage Gauge Data

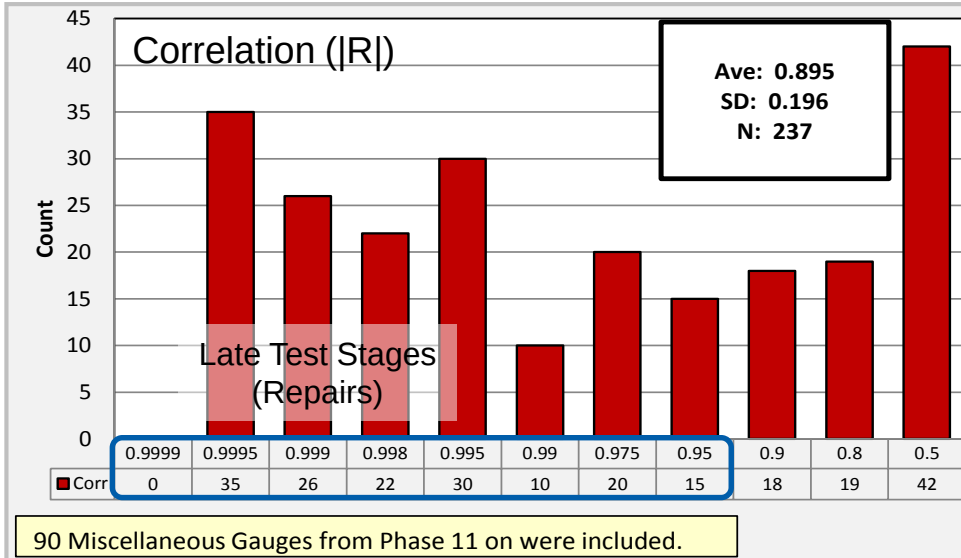
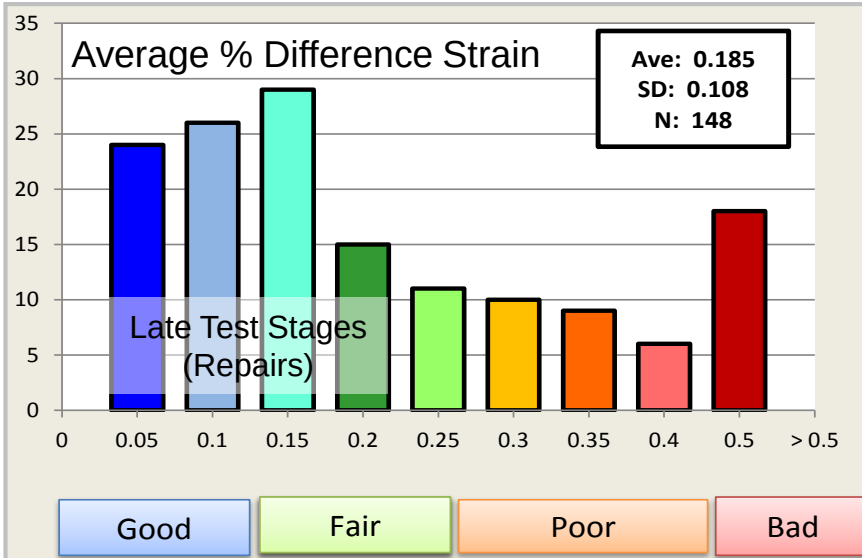
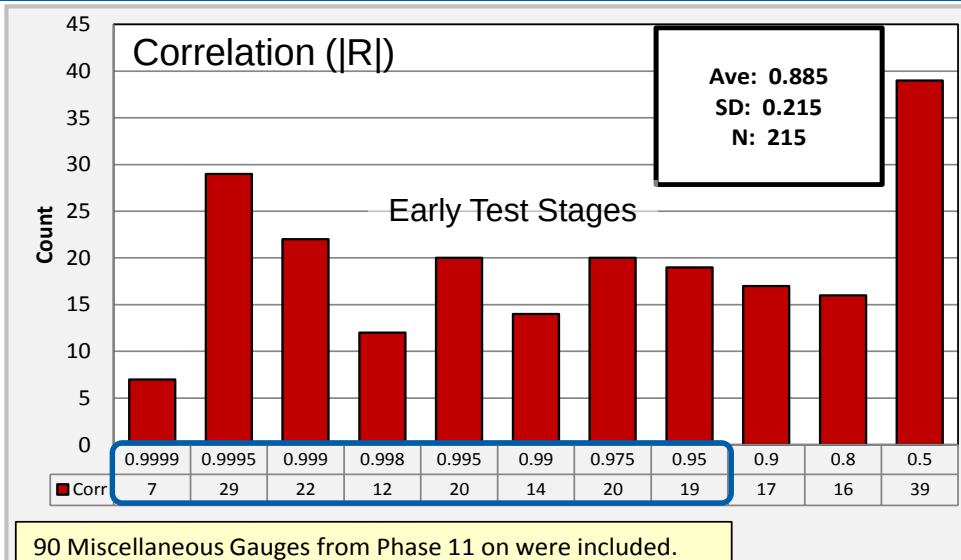
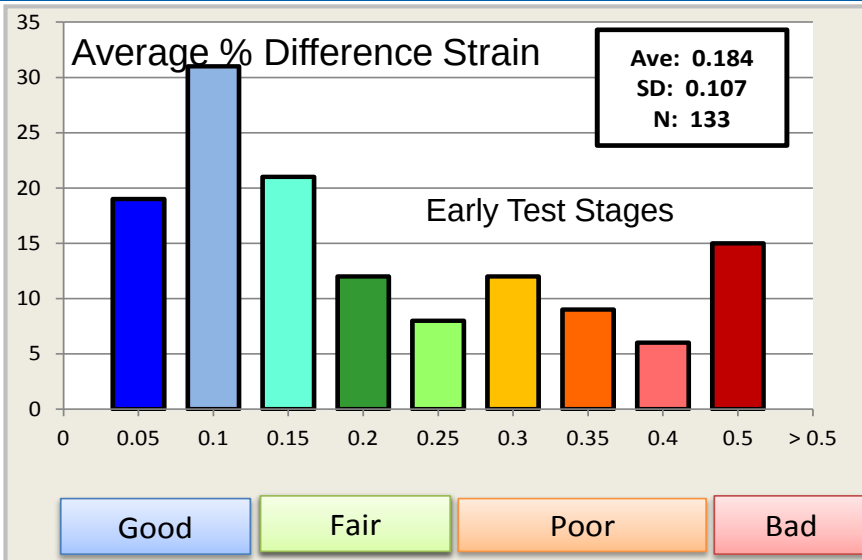


Data includes gauges that are statistically probable to be incorrect

Miscellaneous gauges are typically skin rosettes, data quality unknown

**Early test stage data, late test similar**

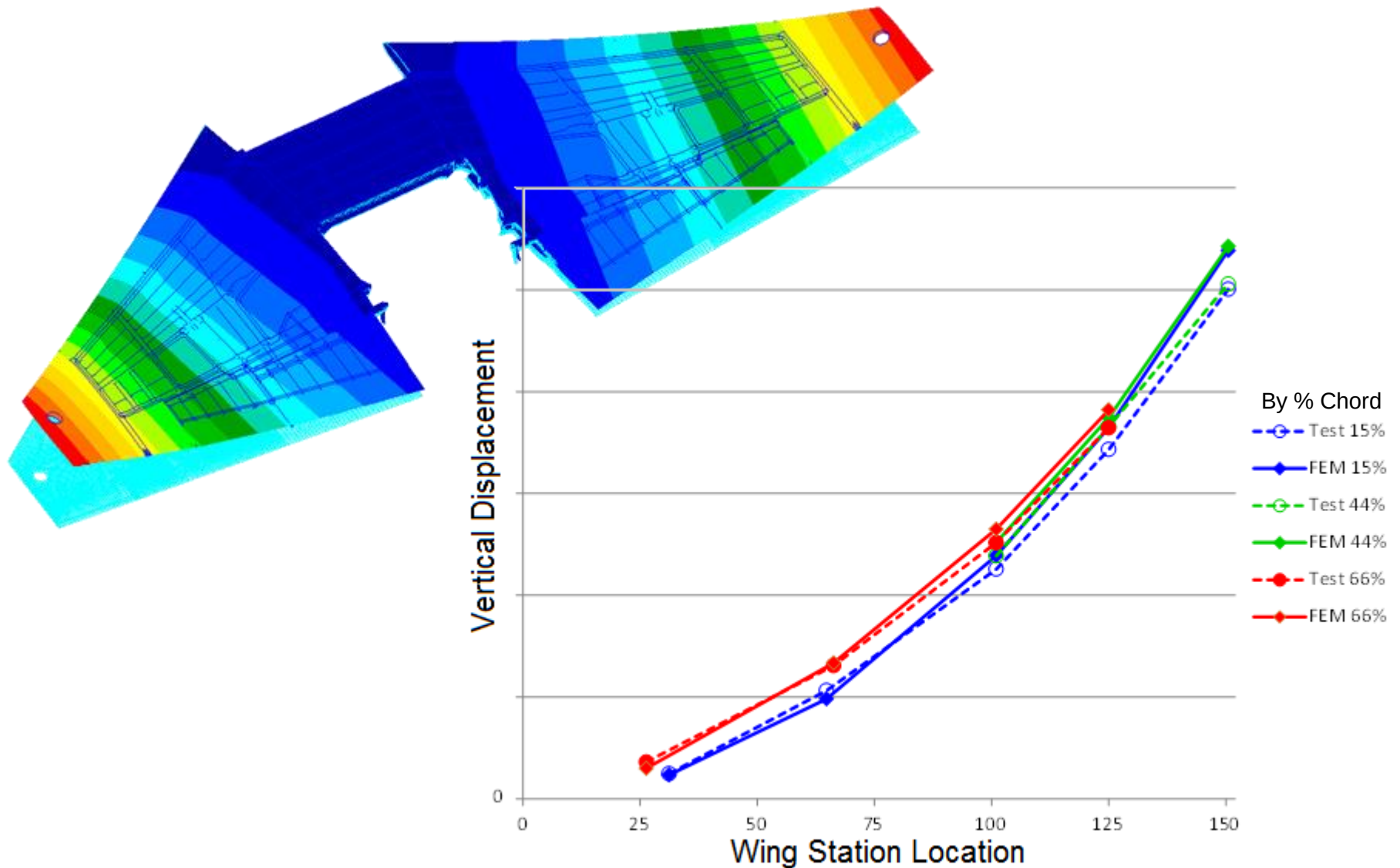
# FEM Correlation – Fuselage Gauge Data



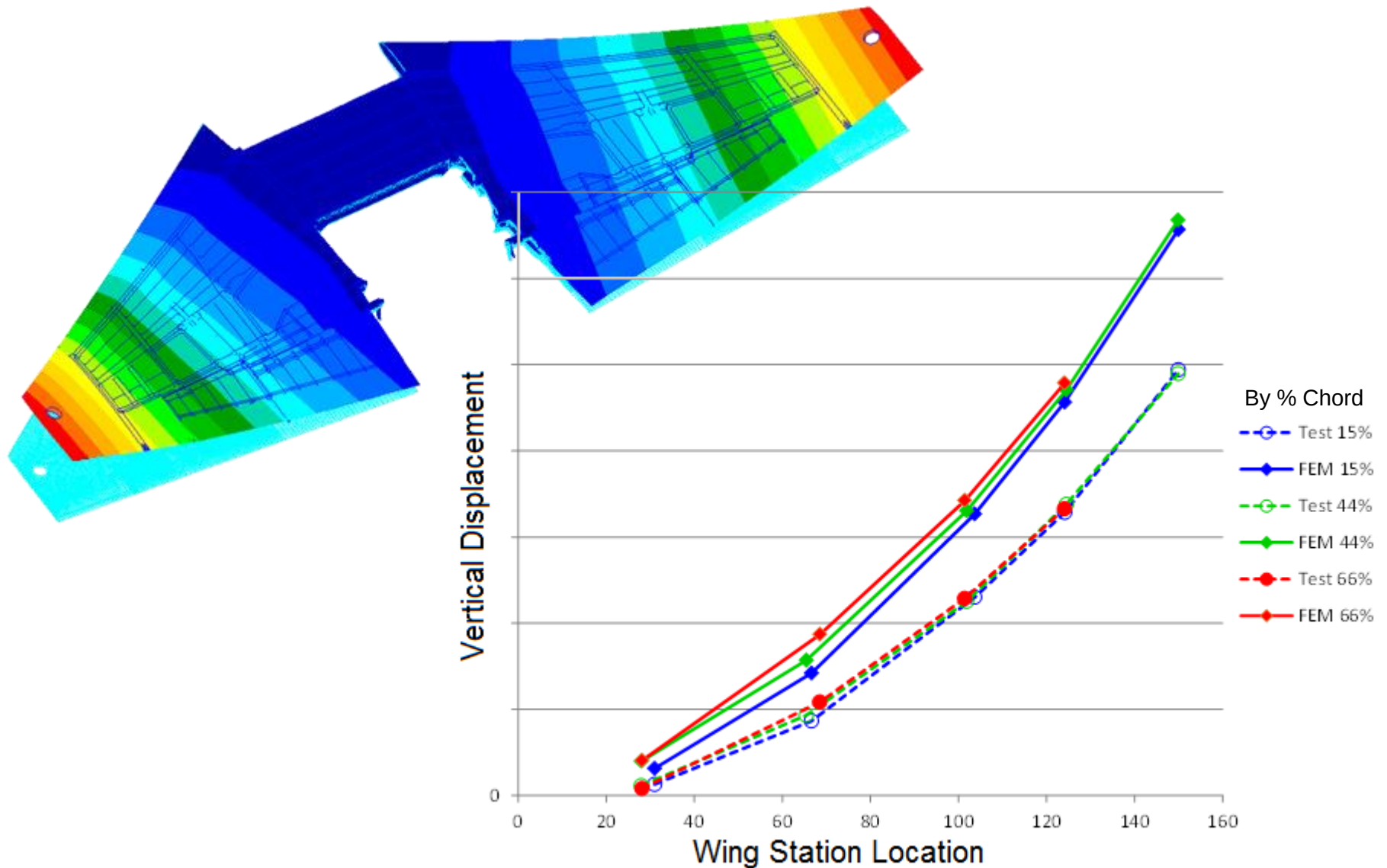
- For later wing tests, FEM correlation was a consideration
  - Very good contractor collaboration orchestrated by USAF to maximize benefit
  - Being involved and able to provide input makes a huge difference
  - Wing test process benefitted FEM correlation as much as practical
- Much better understanding of conditions of wing test and how to replicate them for FEM correlation
  - Mylar wing drawings taken to the test site and marked to locate gauges
  - Additional gauge locations chosen from FEM specifically for correlation
  - Contractor collaboration was strong; multiple contractors use T-38 FEM
- Two tests of Wing A, one test of Wing B available for correlation

Wing Deflection and Local Gauge Error Correlated  
USAF Arranged Strong Contractor Collaboration, Great Outcome

# FEM Correlation – Wing A Deflection



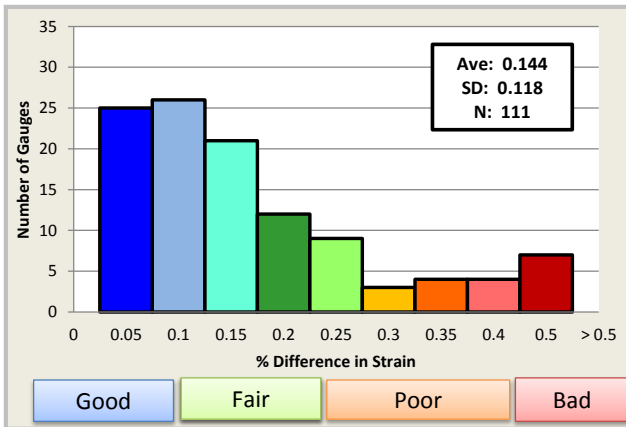
# FEM Correlation – Wing B Deflection



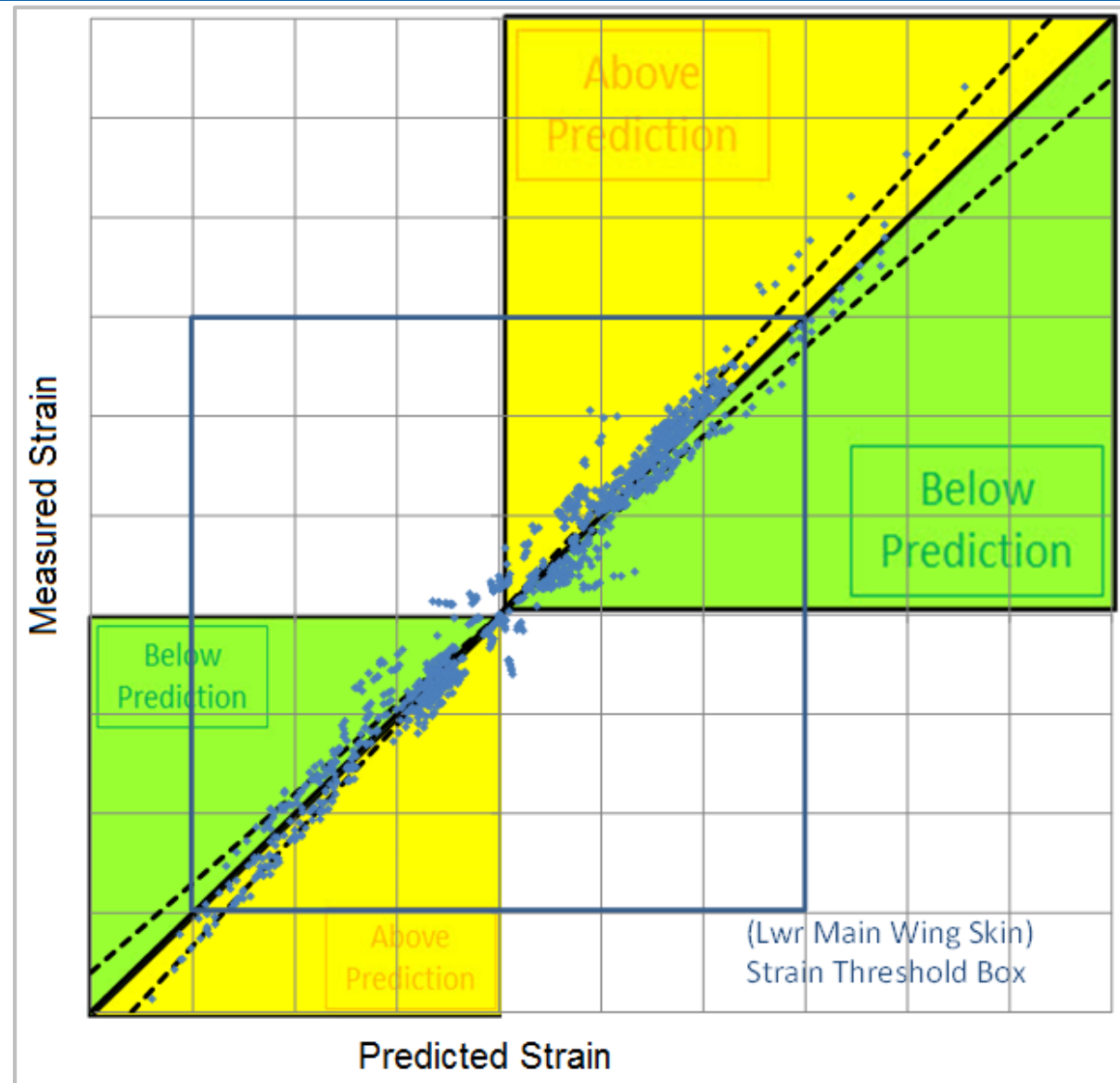
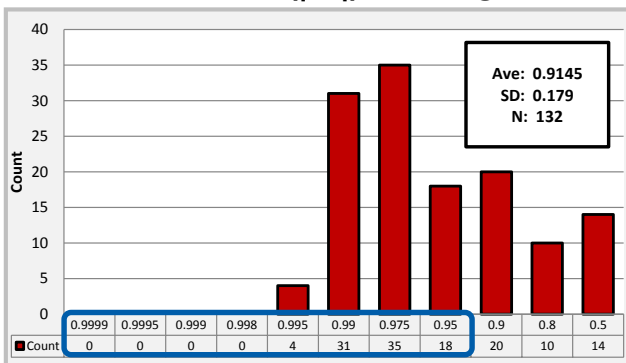
# FEM Correlation – Wing A Gauge Data

Data includes all  
known bad gauges

## % Difference Histogram



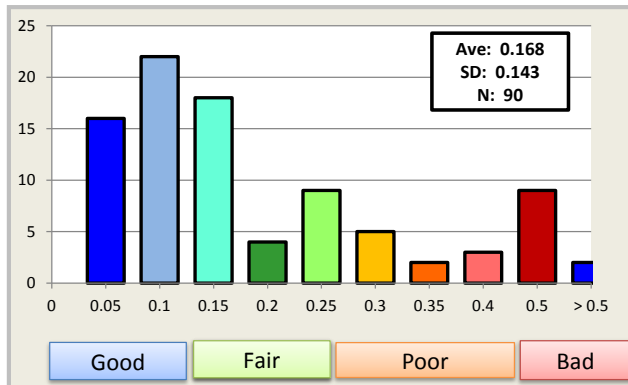
## Correlation (|R|) Histogram



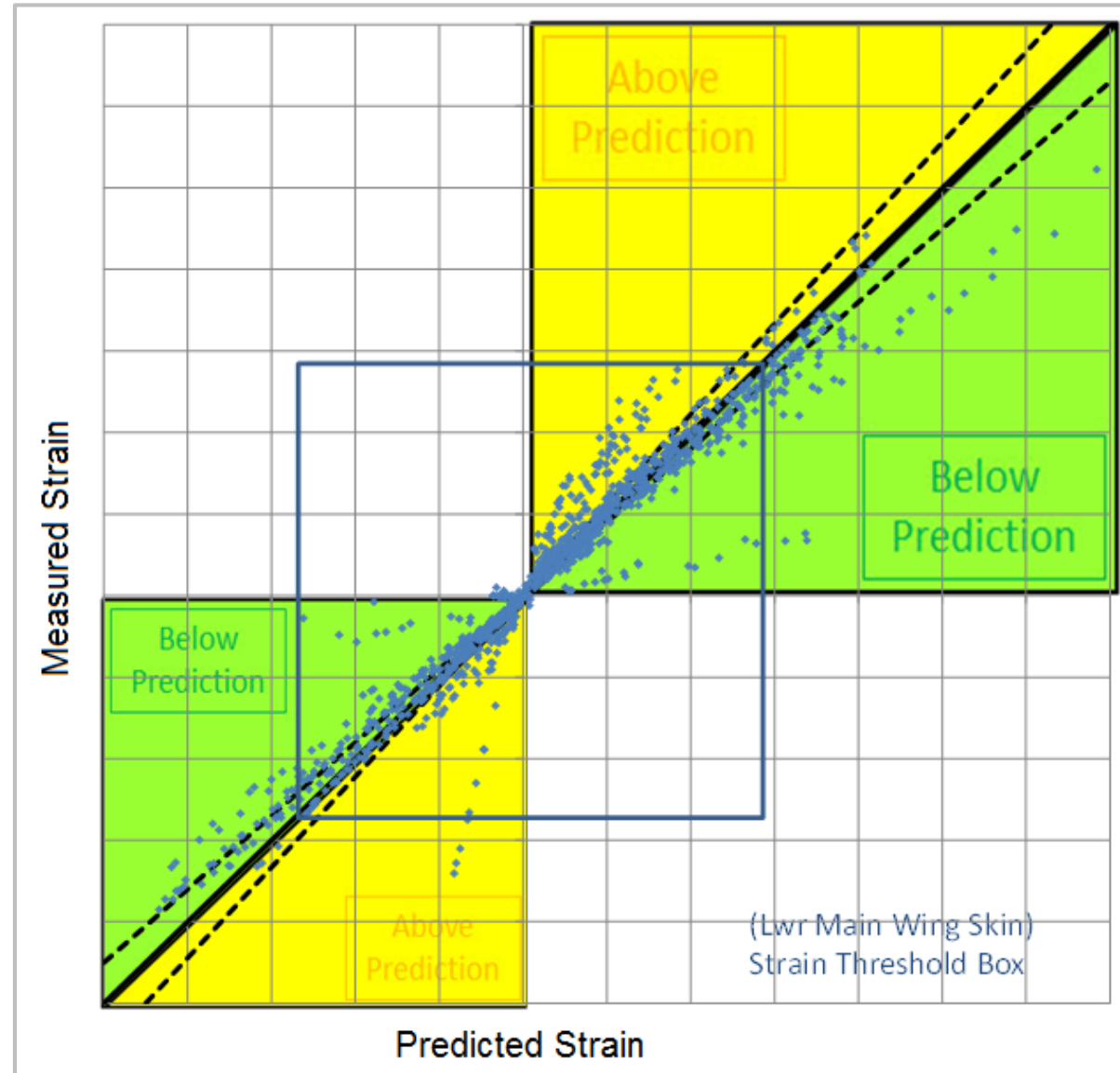
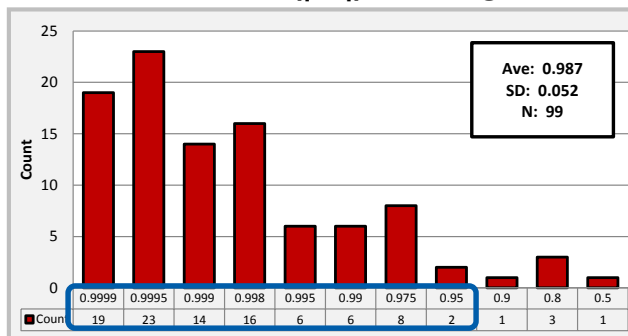
# FEM Correlation – Wing B Gauge Data

Data includes all  
known bad gauges

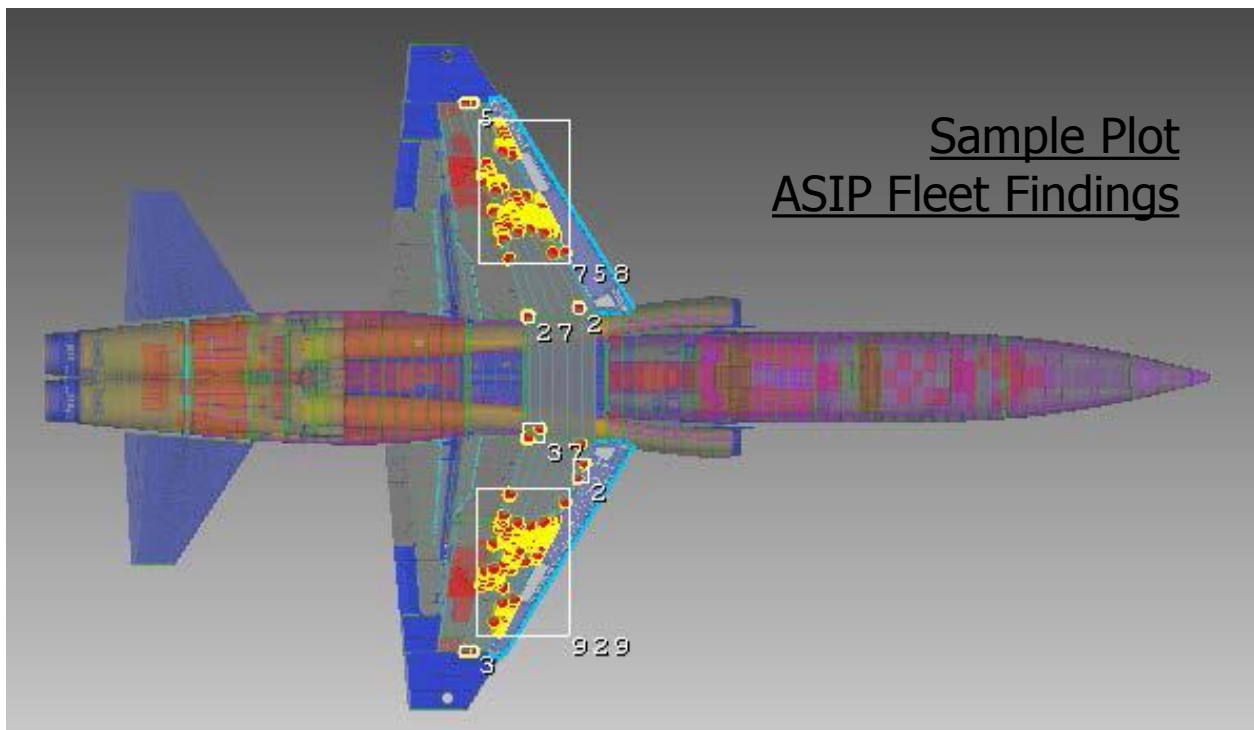
## % Difference Histogram



## Correlation (|R|) Histogram

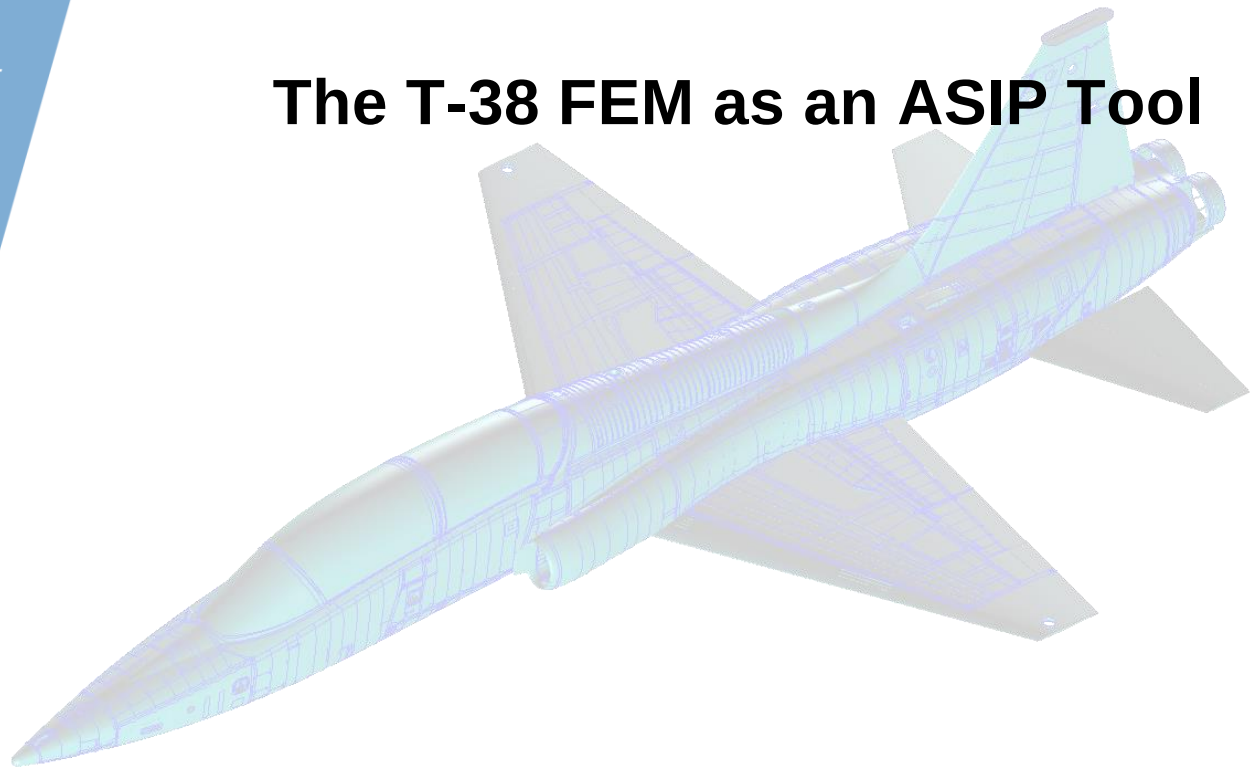


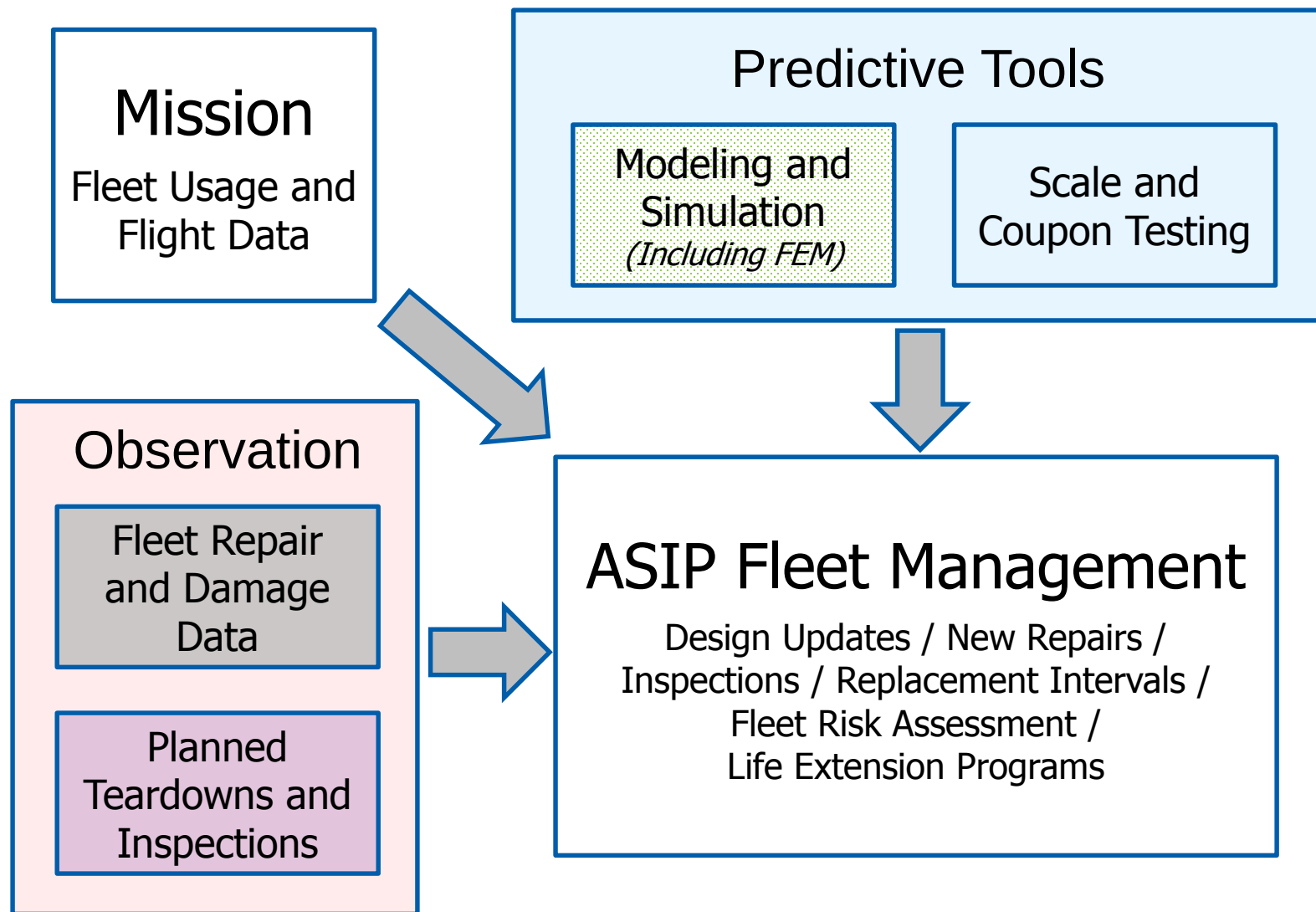
- Most ASIP data can be co-plotted in 3D coordinates
  - NLign 3D Tool in early deployment, all ASIP data being incorporated
    - Data such as field findings, teardown results, analyses, etc.
    - Correlation data and statistics also viewed in this manner
  - Allows FEM correlation usage in ASIP decision making and FEM development



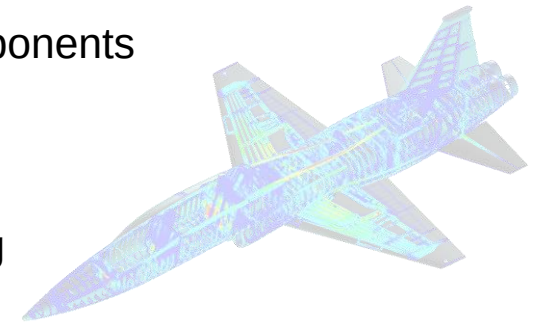
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# The T-38 FEM as an ASIP Tool





- The T-38 FEM is a tool used to aid the USAF in complying with ASIP Requirements such as JSSG-2006, MIL-STD-1530D, MIL-HDBK-516C, and the T-38 ASIP Master Plan.
- Examples of T-38 FEM usage
  - Static cases: Updating stress analysis for modern configuration
  - Fatigue cases: Input to damage tolerance analysis models
    - Determine life and inspection intervals for critical components
  - Specialty use: Design, modernization, and management
    - Assess component design changes, deviations
    - Assist in aircraft modification program decision making
    - Consult while addressing field requests
      - Evaluate repair concepts, decide if replacement is warranted
      - Criticality evaluation, USAF one time flight requests



T-38 FEM Used in Fleet Management

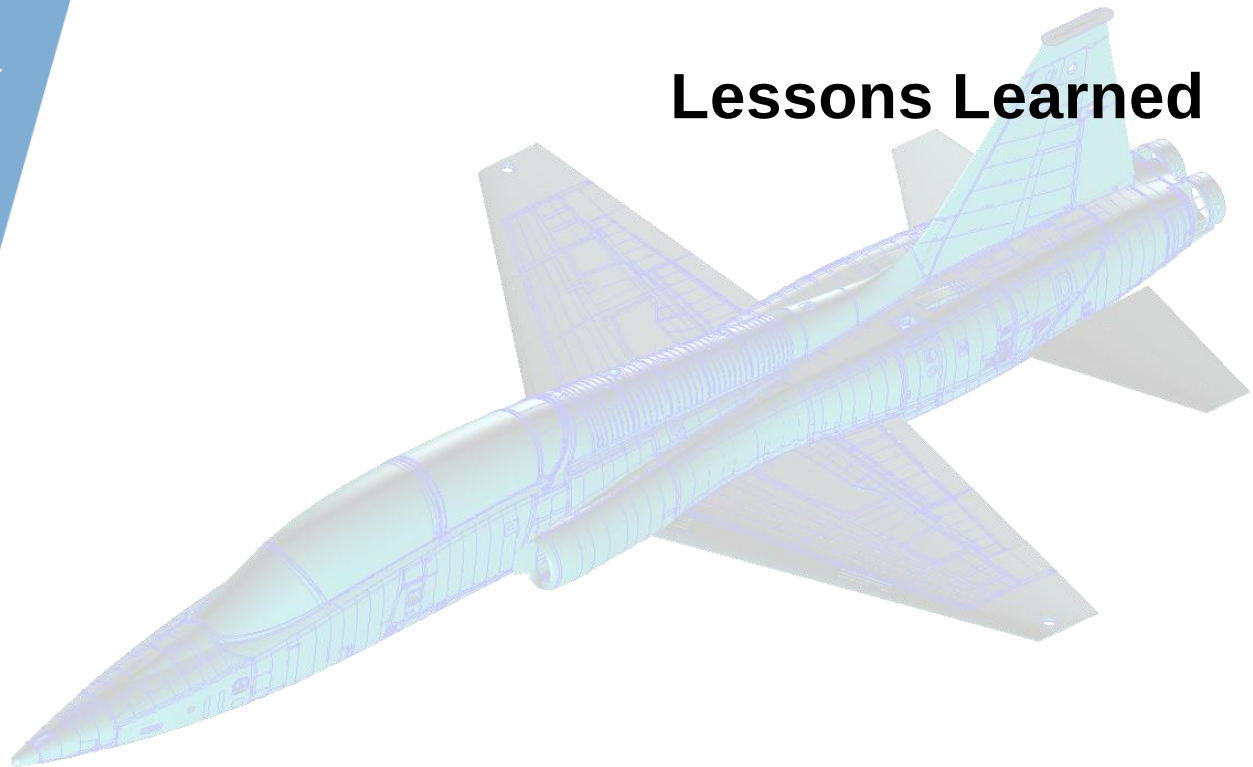
# T-38 FEM – Example of ASIP Impact

- Example: Attach angle, vertical tail to fuselage
  - Preliminary analysis using T-38 FEM identified negative fastener margins of safety
  - Follow on FEM analyses with greater detail and fidelity confirmed findings
  - USAF reviewed damage database, confirmed cracking in fleet
- USAF ASIP team revised part management plan
  - New scheduled inspection was added, repair/replace as required

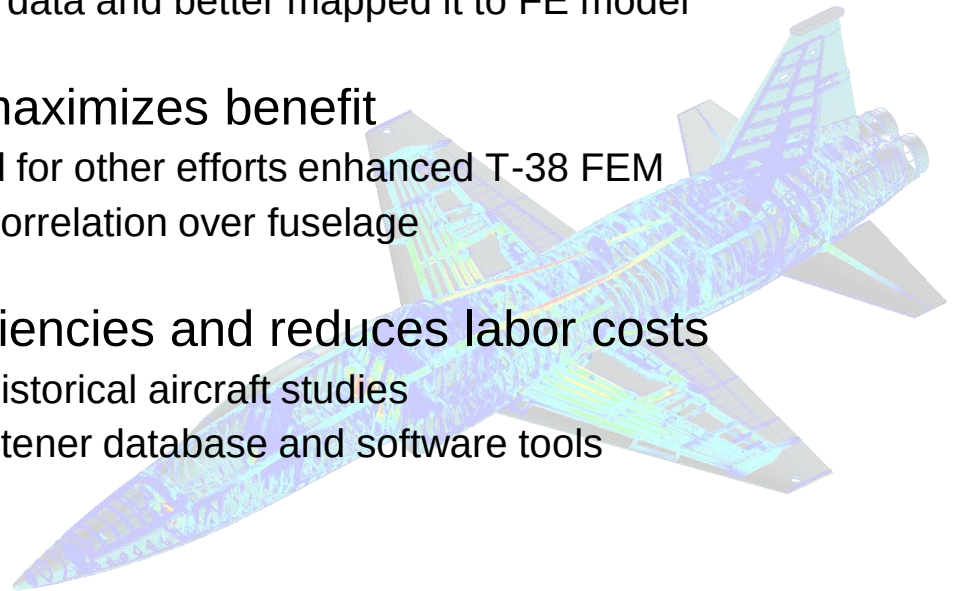


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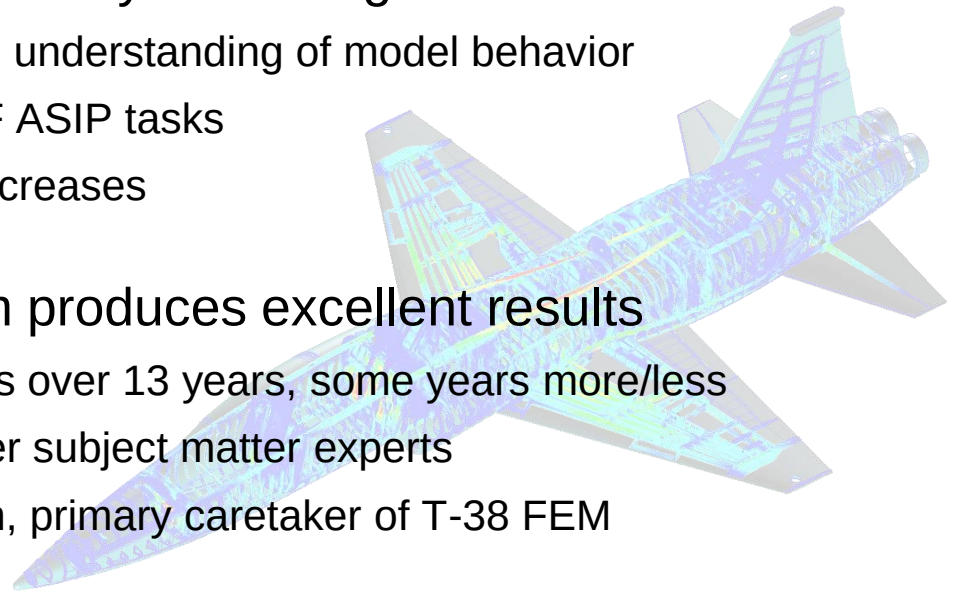
# Lessons Learned



- Detailed parts-separated loads FEM can produce good correlation to deflection and strain gauge test results
  - Capturing contact and stiffness details at attachment points is very important
- Precise test gauge locations and orientations strongly impact FEM correlation
  - Prudent planning goes a long way if an opportunity is anticipated
  - Due to this we were able to use fuselage fatigue test data in the first place
  - Post-test effort enhanced fuselage test data and better mapped it to FE model
- Collaboration on technical efforts maximizes benefit
  - Fuselage test, CFD analysis performed for other efforts enhanced T-38 FEM
  - Wing tests offer much improved FEM correlation over fuselage
- Access to legacy data creates efficiencies and reduces labor costs
  - Fleet data, design and data archives, historical aircraft studies
  - Examples: USAF fuselage test, NG fastener database and software tools



- FEM usage improves utility (enhancements) and quality (bug reports)
  - NGC stress update task requires heavy FEM use and understanding of loads
  - FEM studies and improvements require close examination of model, results
  - SwRI usage of FEM for activities such as damage tolerance analysis input
  - USAF usage for analyzing repairs
- Improved FEM resolution and accuracy have fringe benefits
  - Improves confidence in FEM results, understanding of model behavior
  - Fewer submodels required for USAF ASIP tasks
  - FEM more user friendly, so usage increases
- Small steady effort over long term produces excellent results
  - Typically 2-3 full time NGC engineers over 13 years, some years more/less
  - On call: Statistician, tech fellow, other subject matter experts
  - Special thanks to Joseph Henderson, primary caretaker of T-38 FEM



# T-38 FEM: Questions?

