



# Evaluation of the Hinge Moment and Normal Force Aerodynamic Loads from a Seamless Adaptive Compliant Trailing Edge Flap in Flight



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# Outline

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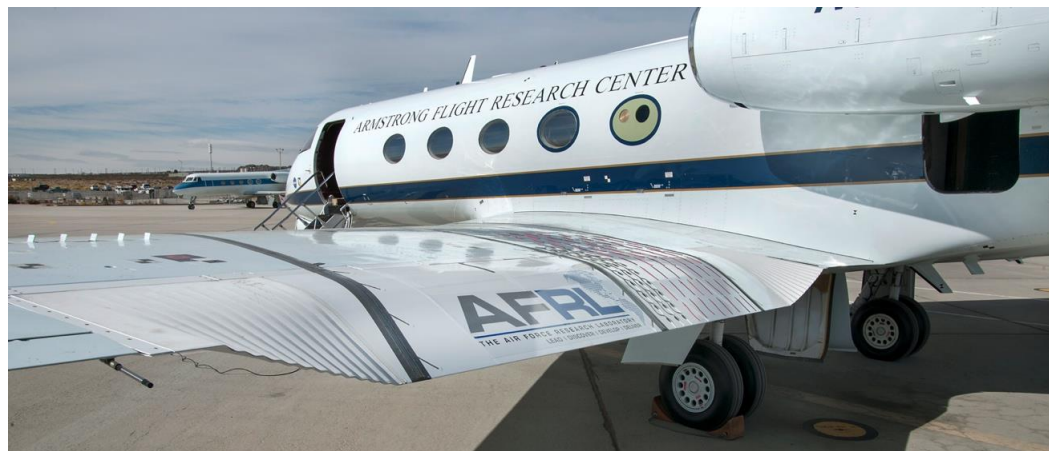
- **Project overview and motivation**
- **Historical perspective AFTI/F-111 MAW**
- **Compliant mechanisms overview**
- **Structural composition**
- **Strain gage instrumentation**
- **Load calibration methodology**
- **Flight test conditions**
- **Computational tools**
- **Hinge moment load comparisons**
- **Normal force load comparisons**
- **Pressure sensor measured loads**
- **Conclusions**



# ACTE Project Overview

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- **Project objective: Flight demonstrate a compliant structure that replaces a large control surface**
- **Partnership between: NASA, AFRL, and FlexSys Inc.**
- **ACTE potential performance benefits:**
  - Cruise drag reduction, wing weight reduction through structural load alleviation, and noise reduction during approach & landing
- **Status:**
  - Phase 1 complete: -2 to 30 deg deflection; flight envelope to 0.75, 40kft, 340 KCAS, 2g load factor
  - Phase 2 test planning: Mach expansion to 0.85; Flap twist for load/cruise performance tailoring; Drag characterization; Noise characterization



Armstrong Flight Research Center



# Motivation

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- **Opportunity to investigate aerodynamic flight loads on a trailing edge flap and compare to analysis predictions**
- **Instrumentation systems**
  - Strain gages located on flap attachment interface fittings
  - Static pressure sensors located on flap surface
- **Analysis tools**
  - Cmarc panel code
  - TRANAIR
  - STARCCM+
  - NASTRAN FEM

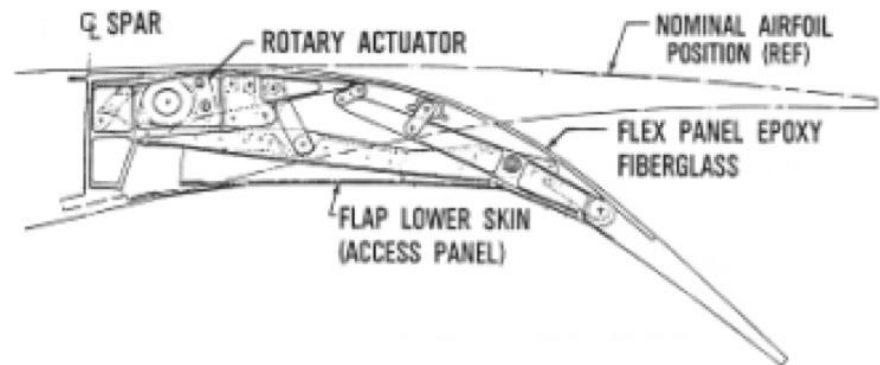




# Historical Perspective - AFTI/F-111 Mission

## Adaptive Wing

- Mission Adaptive Wing was a joint USAF/NASA/Boeing demonstration program
- Variable camber leading and trailing edge surfaces were installed on a F-111 testbed using mechanical rigid linkages
- The AFTI/F-111 MAW system had 59 flights from 1985 through 1988
- The flight test data showed a drag reduction of around 7 percent at the wing design cruise point to over 20 percent at an off-design condition
- Mechanical actuation system weight penalties and system complexity hindered the acceptance of the technology







# Compliant Mechanisms Overview

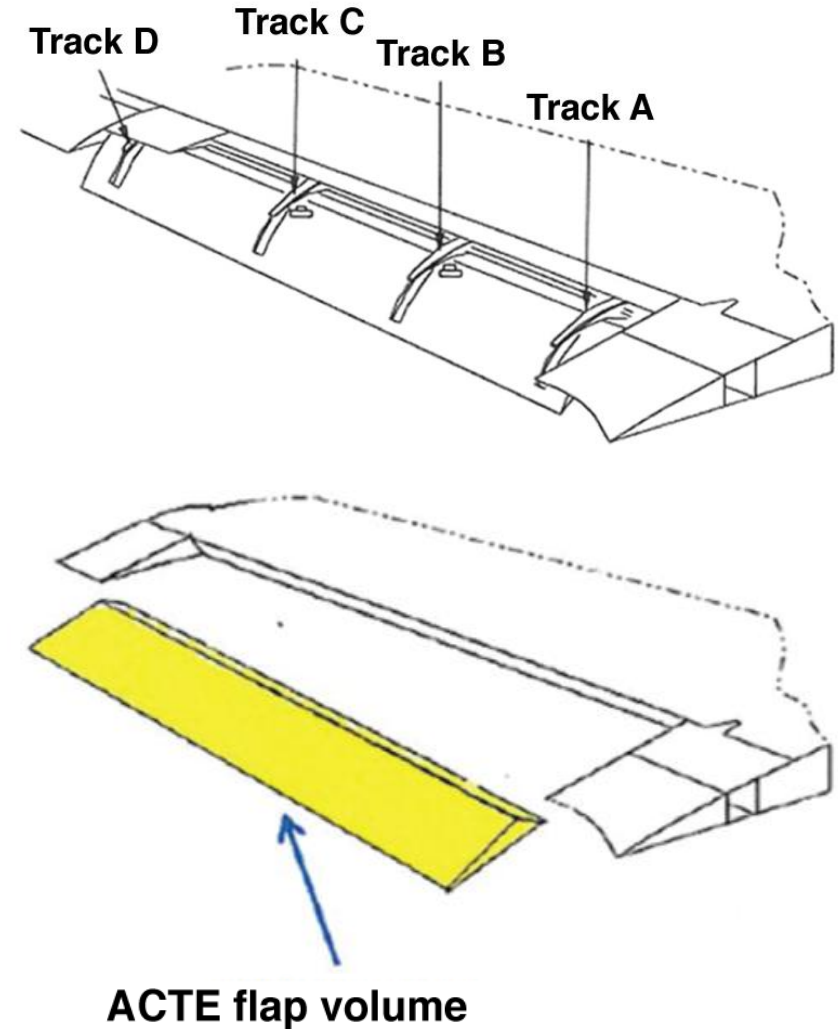
- **Compliant design embraces elasticity, rather than avoiding it, to create one-piece kinematic machines, or joint-less mechanisms, that are strong and flexible (for shape adaptation)**
- **Large deformations can be achieved by subjecting every section of the material to contribute equally to the (shape morphing) objective while all components share the loads**
- **Every section of the material undergoes small linear elastic strain with very low stress and hence the structure can undergo large deformations with high fatigue life**





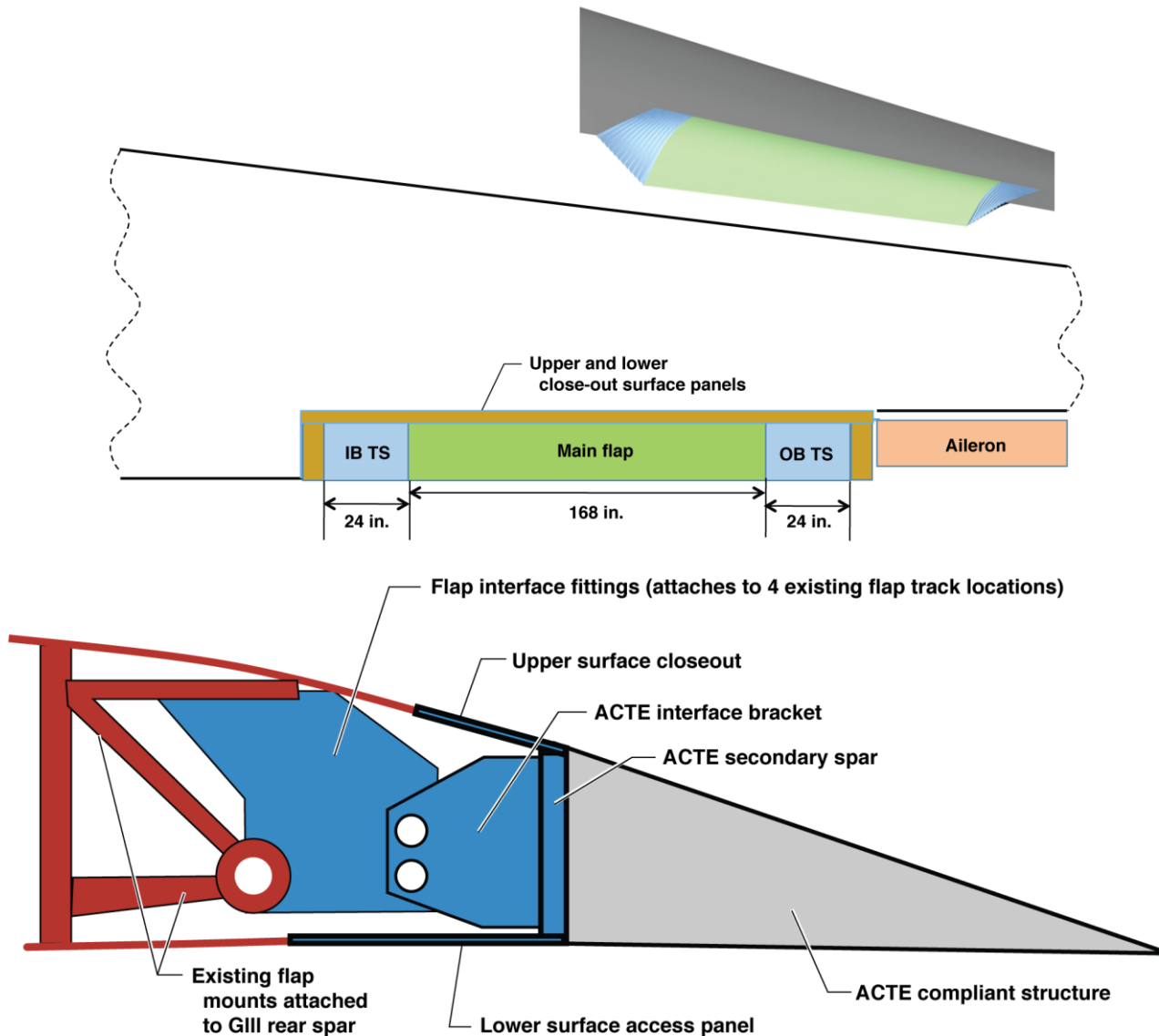
# Interface Geometry Definition

- **The goal of the ACTE integration was to**
  - Match the shape of the existing Fowler flap in its zero-degree flap deflection fully retracted state
  - Integrate the ACTE onto the GIII with as little modification to the GIII as possible
- **The integration of the ACTE on to the GIII required removal of the Fowler flap, flap tracks, flap actuators and flight and ground spoilers**
- **The ACTE was attached to the rear spar using existing Fowler flap track fitting attachment points**
- **The lateral loads on the original Fowler flap were reacted out at track D which is adjacent to the aileron**





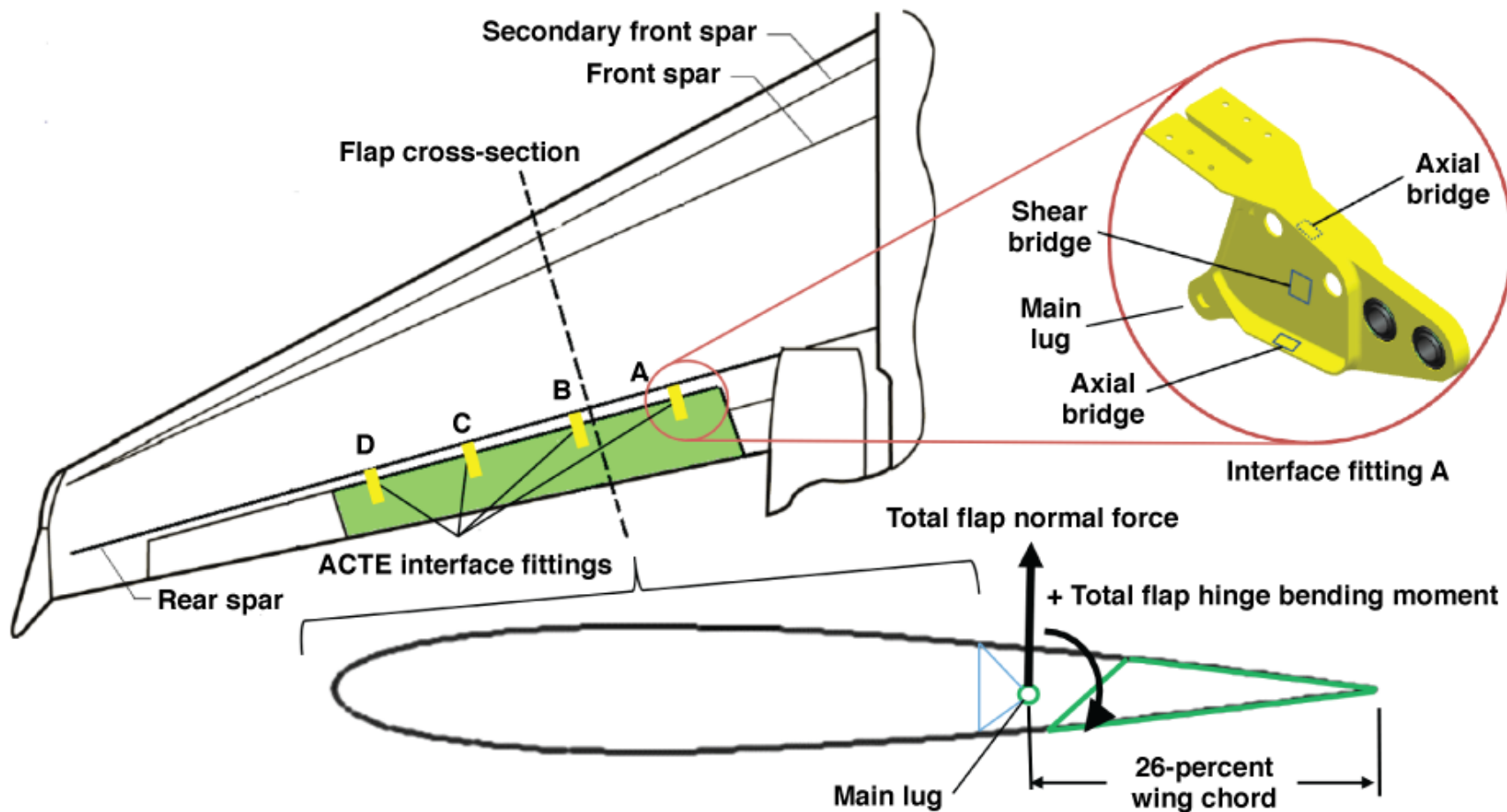
# ACTE Structure Definition







# Flap Load Geometry





# Strain Gage Instrumentation

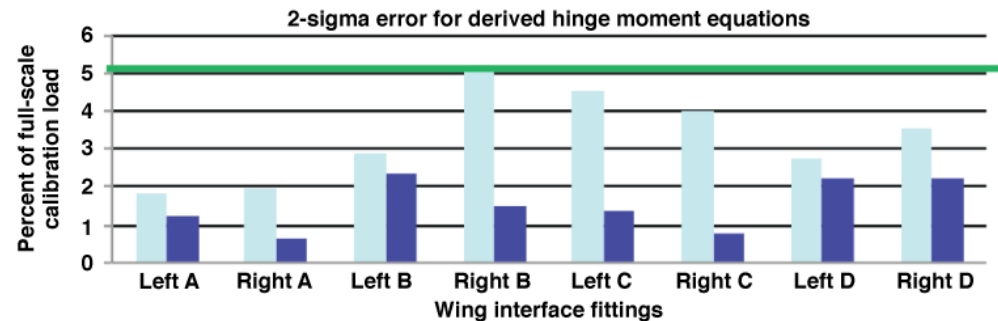
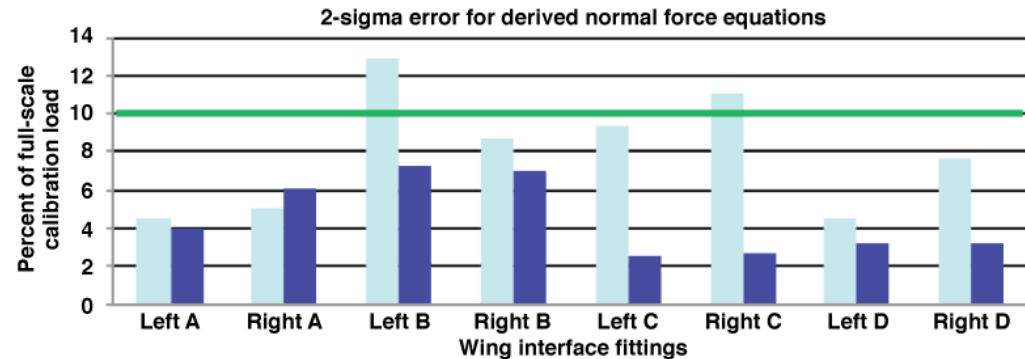
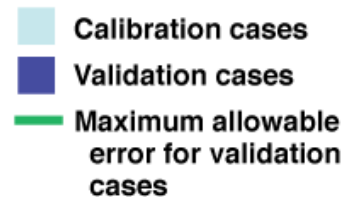
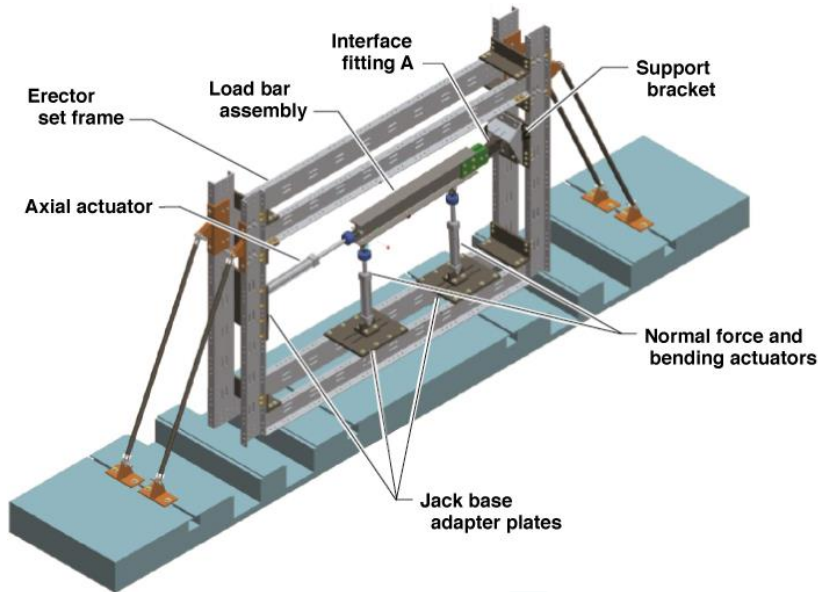
- Shear, bending, and axial full bridge strain gages were installed on the interface fittings for monitoring hinge moment and normal force loads
- The orientation and locations of the strain gages were determined based on finite element method (FEM) strain predictions in the interface fittings in order to give an adequate calibration result





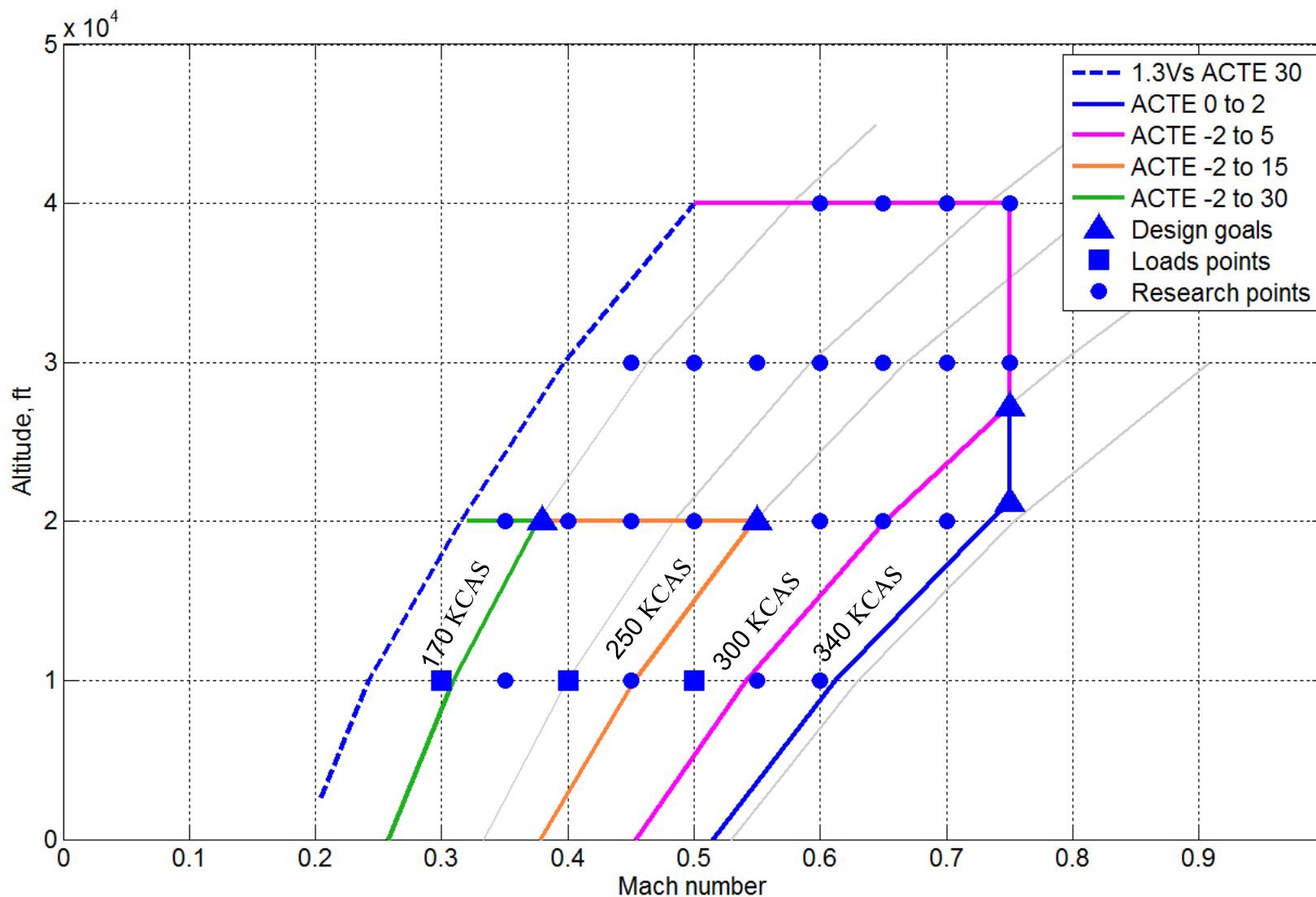
# Load Calibration Methodology

- Support hardware was designed to accommodate all four unique interface fittings as they are installed on the aircraft
- The primary load equations were selected based on multiple calibration metrics
- An independent set of validation cases were used to validate each derived equation
- The largest validation case 2-sigma residual errors were
  - Hinge moment: 2.4 percent,
  - Normal force: 7.3 percent





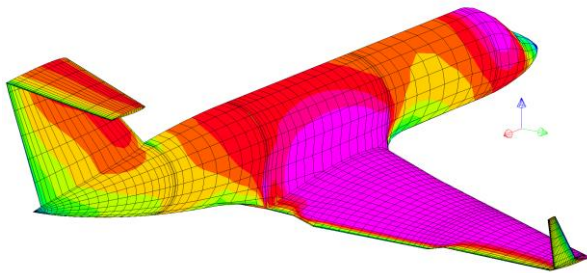
# Flight Test Envelope



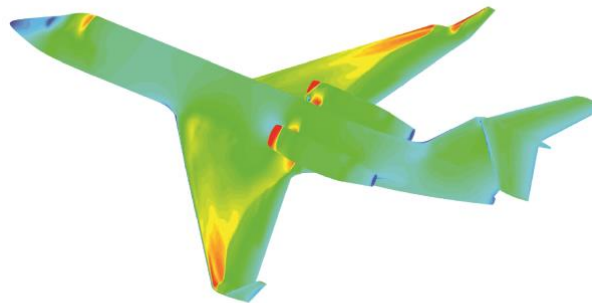


# Computational Tools

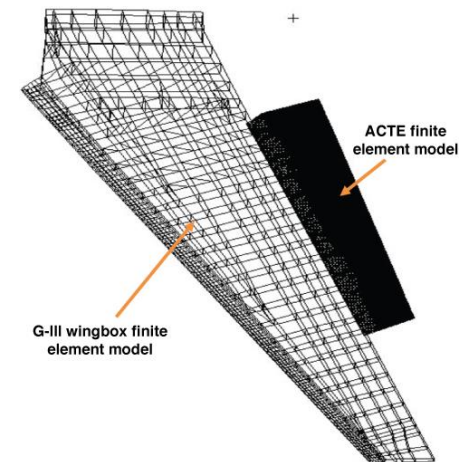
- **Cmarc**: lower-level inviscid panel code, useful tool for assessing loads on subsonic aircraft
- **TRANAIR**: models minor flow separation and can vary the trim angle to match a specified lift coefficient; TRANAIR uses a structured grid
- **STARCCM+**: full Navier-Stokes CFD code that uses an unstructured grid.
- **NASTRAN**: Finite element model of G-III wing and ACTE flap for calculating loads on the individual interface fittings



Cmarc



TRANAIR

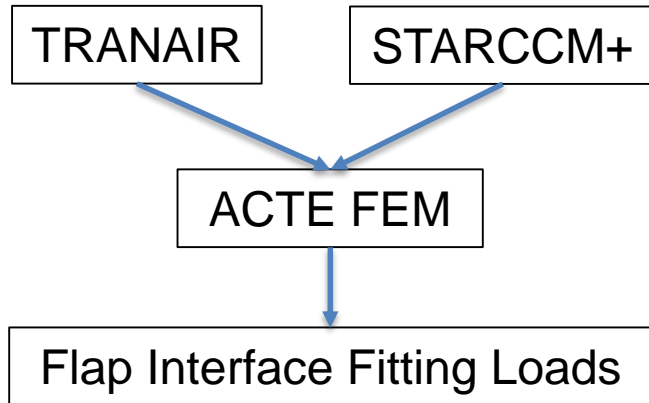


NASTRAN



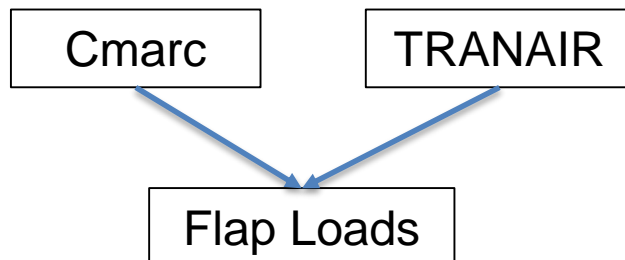
# Analysis Conditions

## Preflight Analysis



| Flap position | Analysis method               | Flight condition             |
|---------------|-------------------------------|------------------------------|
| 0             | TRANAIR to FEM                | Mach 0.40 altitude 10,000 ft |
| 2             | TRANAIR to FEM                | Mach 0.40 altitude 10,000 ft |
| 5             | TRANAIR to FEM                | Mach 0.40 altitude 10,000 ft |
| 10            | TRANAIR to FEM                | Mach 0.40 altitude 10,000 ft |
| 15            | TRANAIR to FEM                | Mach 0.40 altitude 10,000 ft |
| 15            | STAR-CCM+ <sup>®</sup> to FEM | Mach 0.40 altitude 10,000 ft |
| 20            | STAR-CCM+ <sup>®</sup> to FEM | Mach 0.30 altitude 10,000 ft |
| 25            | STAR-CCM+ <sup>®</sup> to FEM | Mach 0.30 altitude 10,000 ft |
| 30            | STAR-CCM+ <sup>®</sup> to FEM | Mach 0.30 altitude 10,000 ft |

## Post Flight Analysis



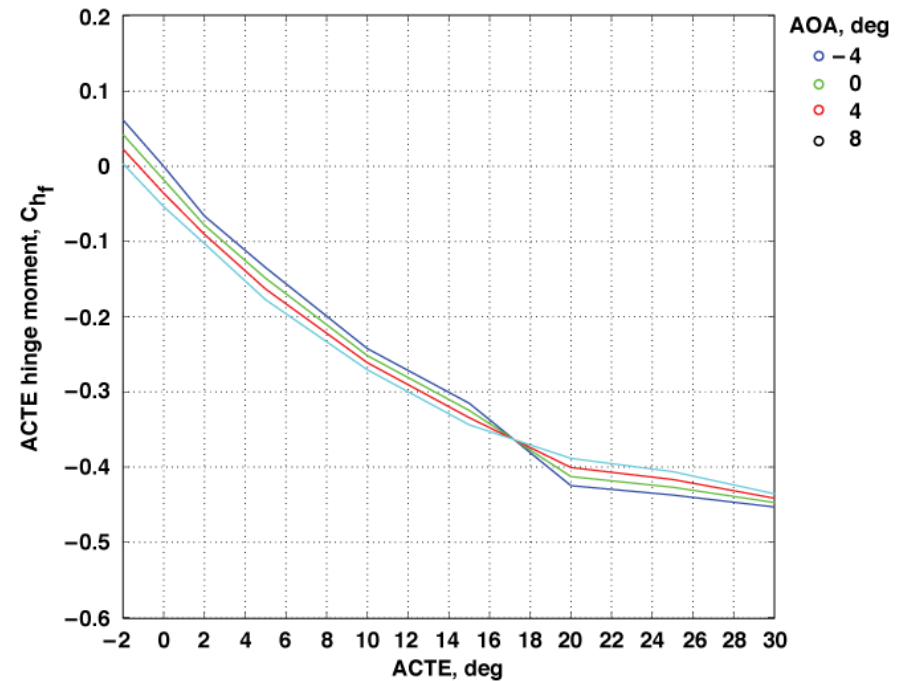
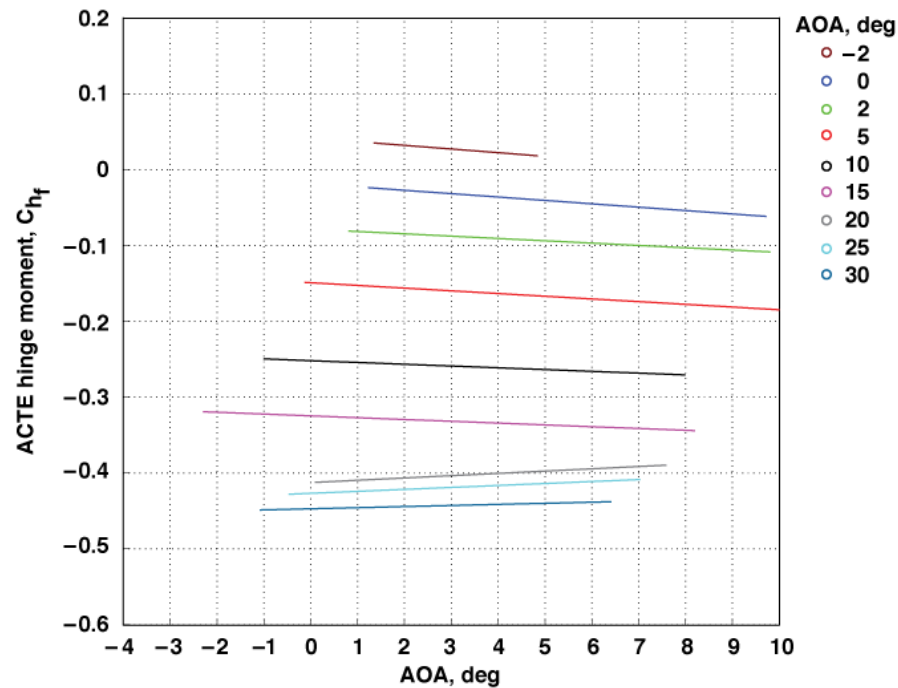
| Flap position | Analysis code     | Flight condition             |
|---------------|-------------------|------------------------------|
| 0             | TRANAIR and Cmarc | Mach 0.30 altitude 10,000 ft |
| 0             | TRANAIR and Cmarc | Mach 0.40 altitude 10,000 ft |
| 0             | TRANAIR and Cmarc | Mach 0.50 altitude 10,000 ft |
| 5             | TRANAIR and Cmarc | Mach 0.30 altitude 10,000 ft |
| 5             | TRANAIR and Cmarc | Mach 0.40 altitude 10,000 ft |
| 5             | TRANAIR and Cmarc | Mach 0.50 altitude 10,000 ft |
| 15            | TRANAIR and Cmarc | Mach 0.30 altitude 10,000 ft |
| 15            | TRANAIR and Cmarc | Mach 0.40 altitude 10,000 ft |
| 15            | TRANAIR and Cmarc | Mach 0.50 altitude 20,000 ft |





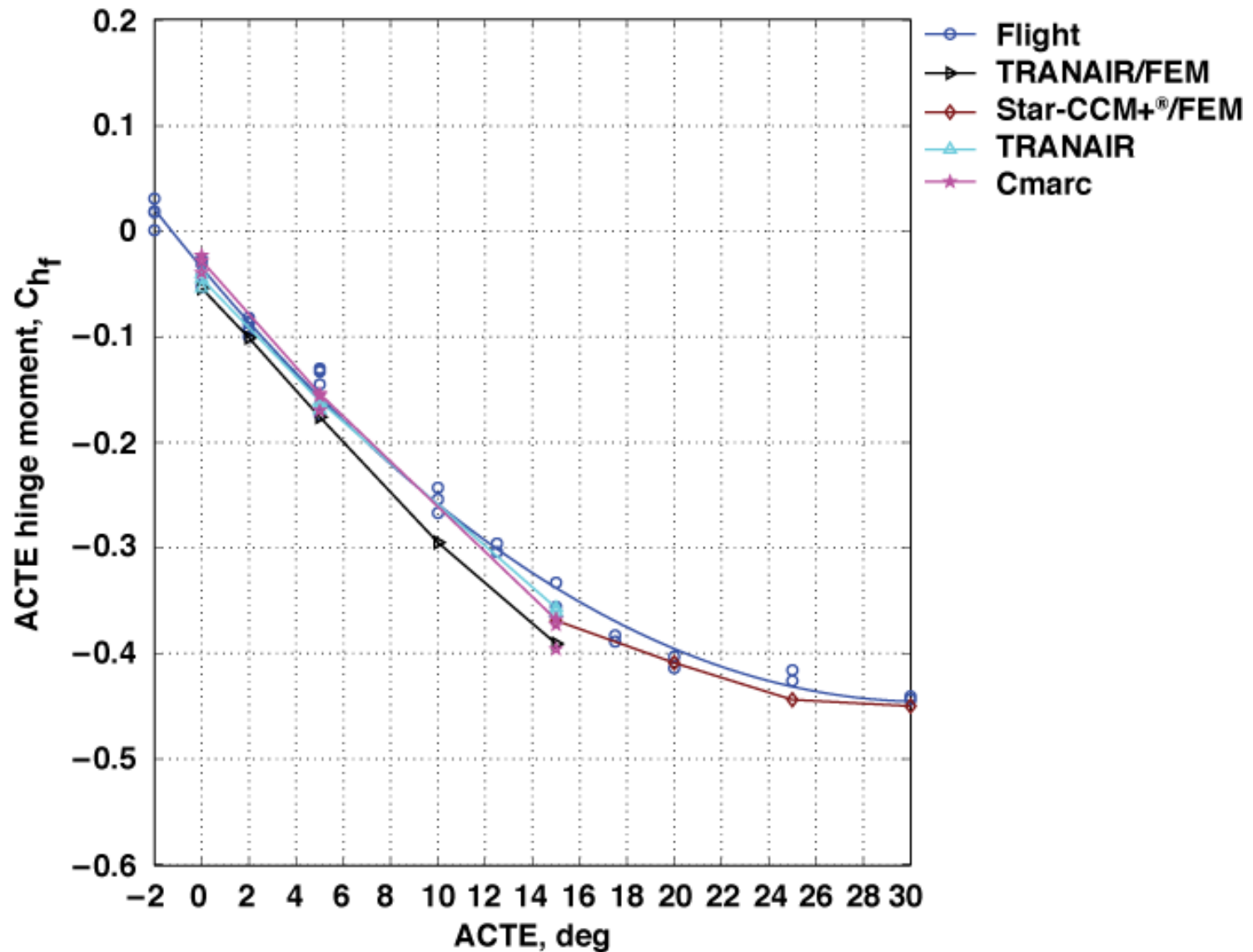
# Hinge Moment Loads Measured in Flight

Flap interface hinge moment loads versus angle of attack for WUTs and POPUs at Mach numbers 0.3 and 0.4 and an altitude of 10,000 ft.



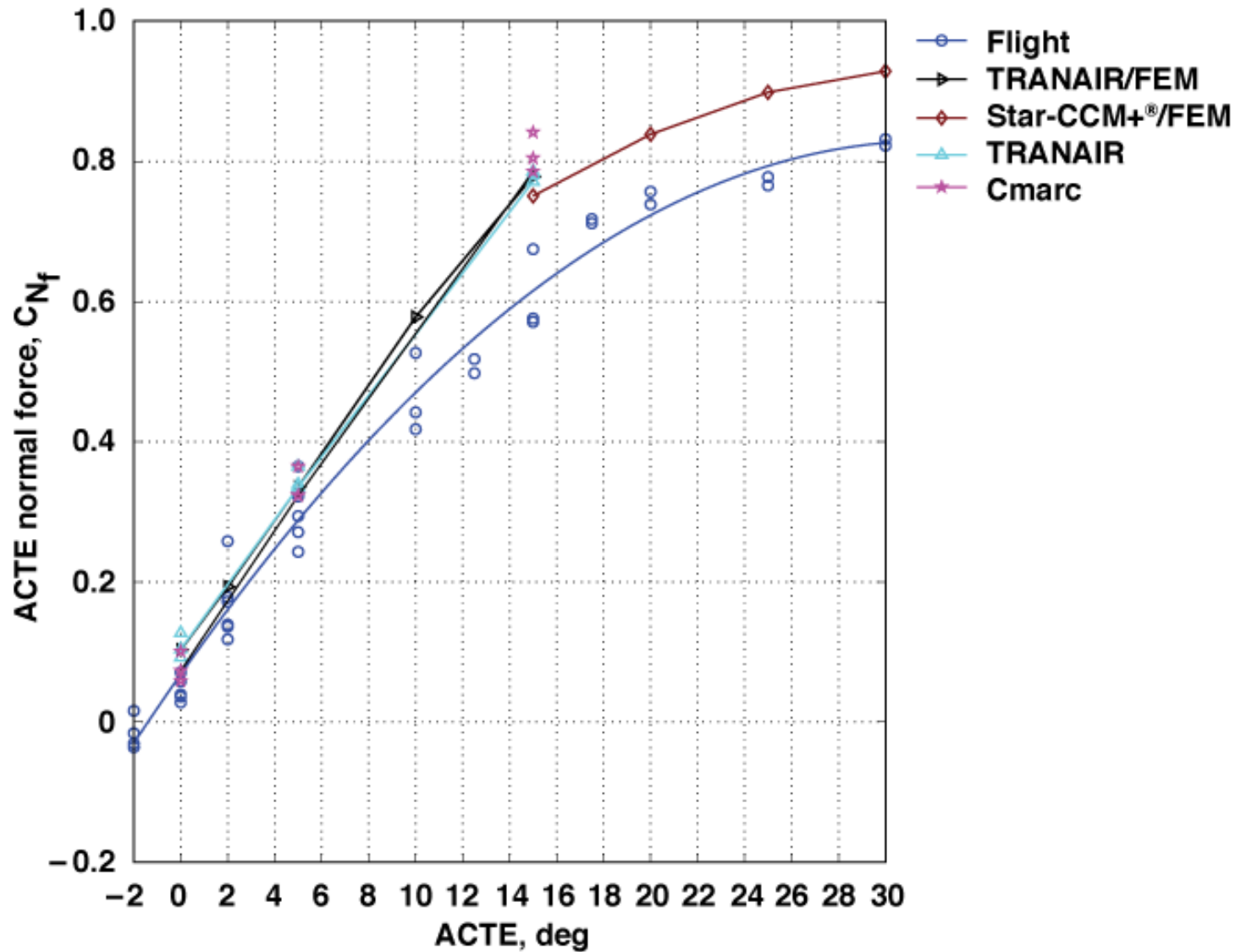


# Hinge Moment Load Comparisons





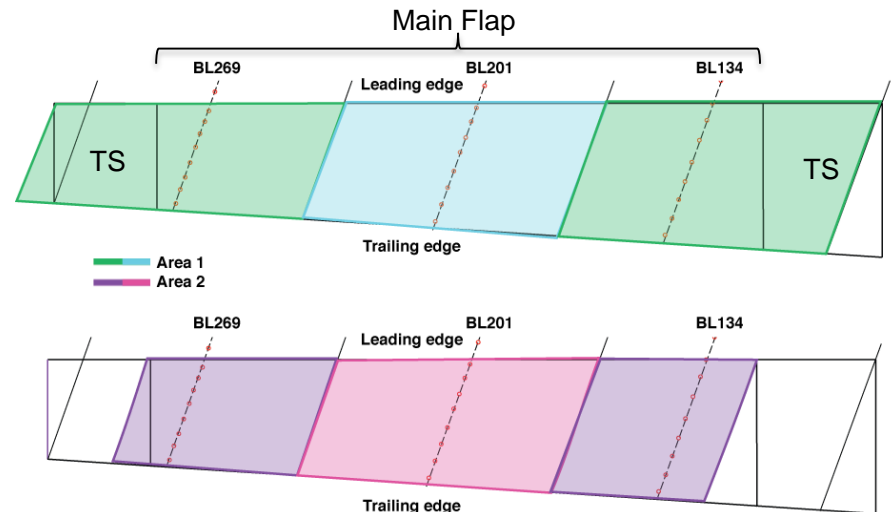
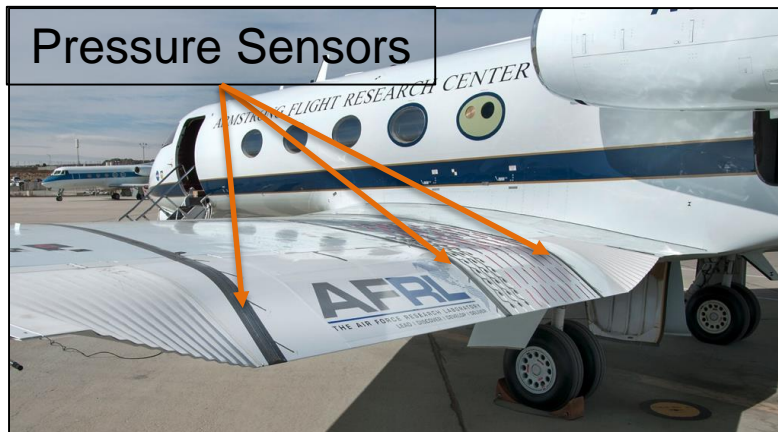
# Normal Force Load Comparisons





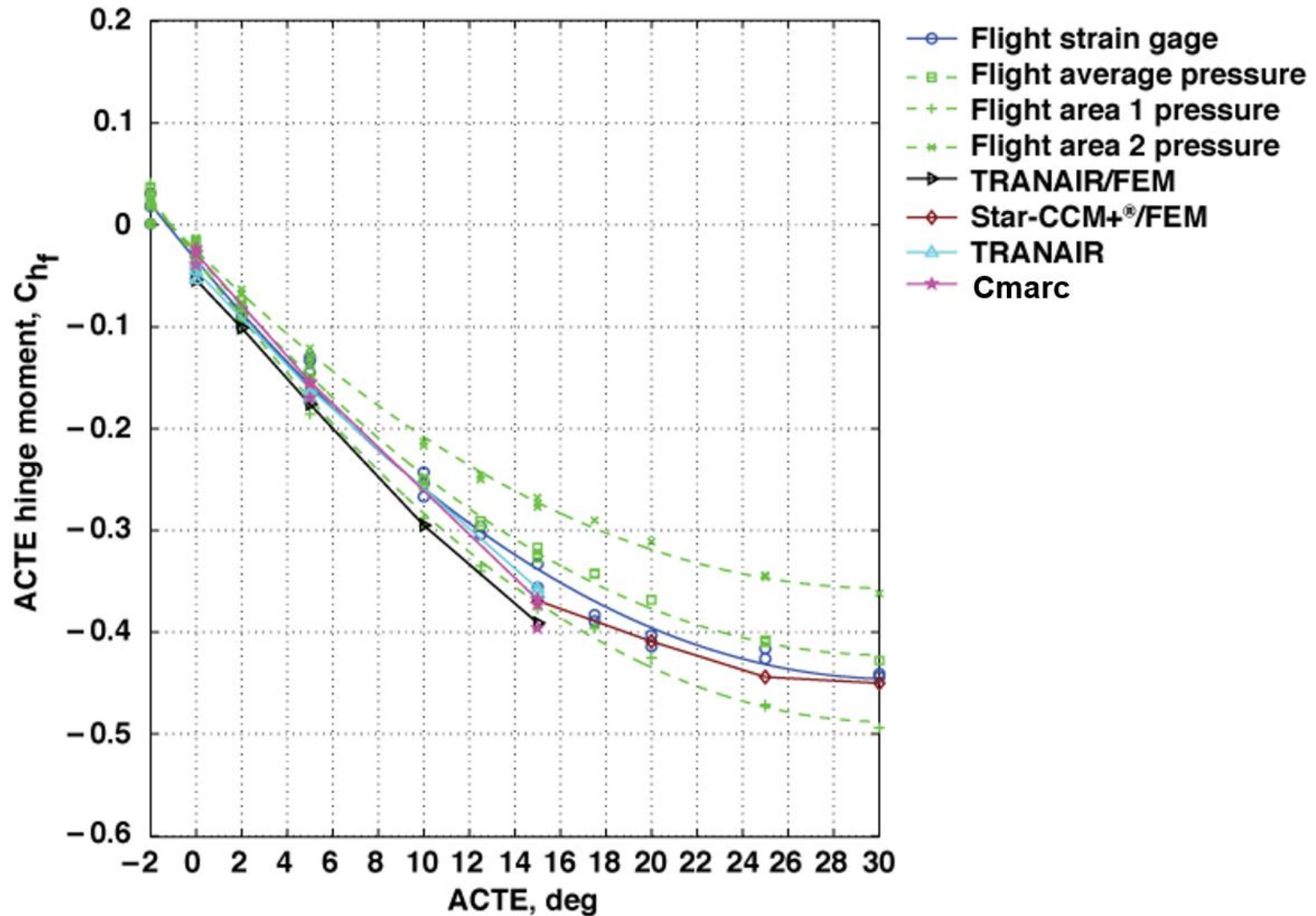
# Pressure Sensor Measured Loads

- **Static pressure sensors were installed on the upper and lower ACTE flap surface at three spanwise locations**
  - Nine pressure sensors on the lower surface
  - Eight pressure sensors on the upper surface
- **Two specific flap geometries were used to average the normal force load to account for the loss of load in the transition sections**
  - Area 1 represents the loads as if the entire flap surface (including transition surfaces) were generating a uniform pressure
  - Area 2 represents the loads as if only the main flap is generating load
- **The calculated pressure surface load was converted to coefficient form using the same values used for converting the strain-gage loads to coefficients**



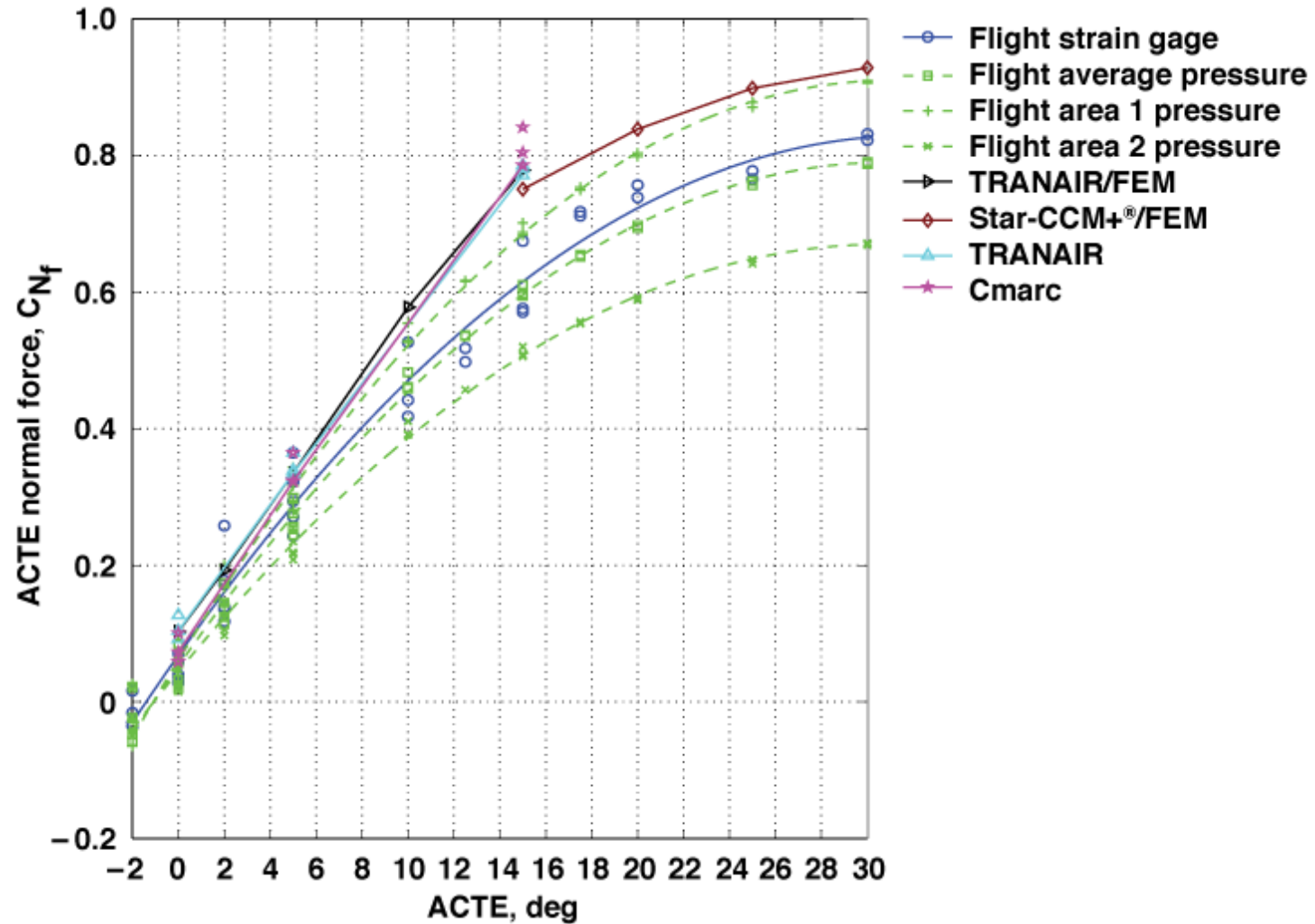


# Pressure Sensor Measured Loads





# Pressure Sensor Measured Loads







# Conclusions

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- **The ACTE technology was flight-tested on a GIII airplane for flap deflections of  $-2^{\circ}$  up and  $+30^{\circ}$  down**
- **ACTE technology is applicable to leading and trailing edge devices, high rate ailerons and high lift flaps**
- **The ACTE technology on the GIII SCRAT was not optimized for maximum aerodynamic load benefit, but future clean sheet designs will be able tailor the structure for maximum aerodynamic load advantage**
- **The hinge moment and normal force loads generated at ACTE flap positions above  $15^{\circ}$  plateaued due to flow separation and were lower than the loads generated by a typical Fowler flap that creates a gap in the structure for energizing the flow over the flap**



# Conclusions

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- **Multiple CFD codes were utilized with varying results, Cmarc is a time efficient CFD code as compared to TRANAIR, thus future work will make use of the Cmarc code more significantly for flap positions up to 15°**
- **The interface fittings in general do not lend themselves to ample bridge response given the large design factors of safety and the short, stubby nature of the flight fittings, but the resulting flight data were sufficient for flight monitoring and analysis comparisons**
- **Normal force and hinge moment loads measured from the static pressure sensors located on the flap surface compared well to the calibrated strain-gage loads and can provide additional insight into the external air loads acting on the flap**