# Symmetric Maneuver Loads Module Development & Integration within an Aircraft Tracking Environment

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Phoenix Integration Workshop

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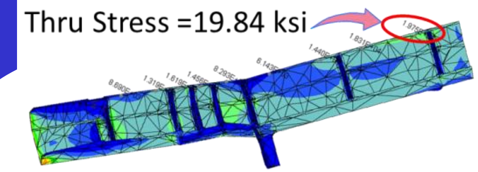
# Transition Success Story:

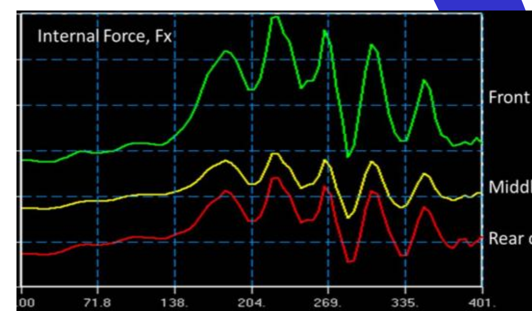
## *Stick-to-Stress Real-time Simulator (StS-RtS) Applied to F-15C/D*

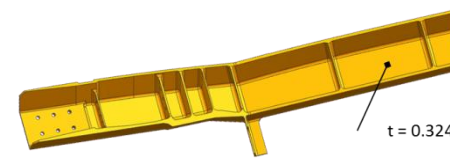
U.S. AIR FORCE

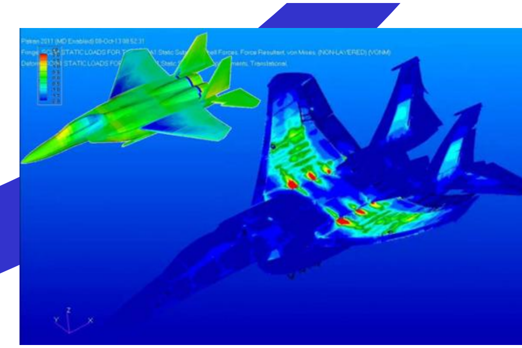
- **Background**
  - **Clearly established need for more accurate & rapid analysis tools to manage cracking in legacy aircraft**
  - **Using aircraft past their design service life leads to:**
    - **Unexpected new cracking locations**
    - **Requirement for extensive re-analysis**
    - **More frequent inspections; Longer depot visits**
    - **Mishaps, Fleet groundings**
  - **AFRL-VA-WP-TR-1999-3037: The overwhelming type of problem encountered w/ F-15 is Excessive Dynamic Load"**
- **Objectives**
  - **Deliver improved accuracy F-15C/D Simulator**
  - **Provide SPO with engineering analysis for use in assessment of a known cracking problem**
  - **Provide F-15 program with an improved tool for Crisis Management, Service Life Extension Programs & ASIP use**
- **Transitions**
  - **Small Non-Recurring Expense to build for each Fleet/Block**
  - **Delivered F-15C/D StS-RtS to AFRL's ADT Spiral I Program**
  - **Reduces risk for other platforms**

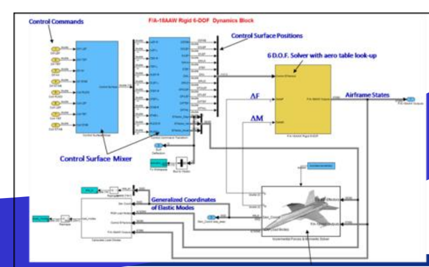
**Remaining Useful Life via Dynamic Internal Loads On Critical Components**







*Integrity - Service - Excellence*

# Motivation

- **USAF F-15C/D aircraft need to remain operational until 2025**
- **Lead the fleet aircraft have reached over 10,000 flight hours – exceeds the 8,000 FH design life**
- **Air National Guard mishap in Nov 2007 grounded the fleet**
- **The fleet was eventually cleared for flight**
- **However, concern remains regarding risks as the fleet continues to age**
- **New technology is absolutely necessary for the continued economic operation of the fleet**

# Stick-to-Stress

- What is it?
  - A Physics Preserving, Real-time 6-DOF Simulation Tool for an Aeroelastic Vehicle, from Pilot Input to Global Airframe Stress
  - Includes Sensors, Control Surface Freeplay and Gust
- Why is it here?
  - Generate Comprehensive Representative Dynamic Stress Histories
- What else is it?
  - Prototype Development, Pilot Training, CLAW Evaluation
- **Preserve Individuality, then apply Uncertainty Quantification**

# SOA vs. MODSDF-StS

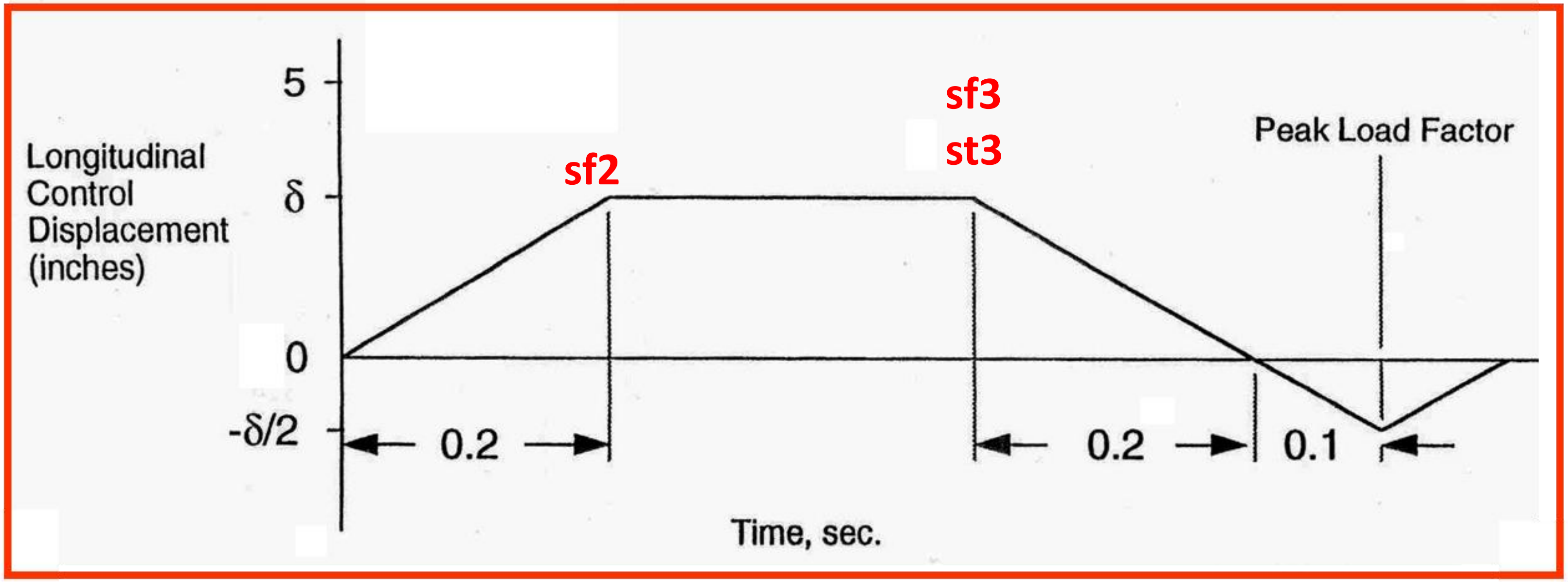
- SOA:
  - Quasi-steady, empirical, stress-transfer functions (STF)
  - Expensive to create, utilize and modify
  - New “hot spots” only from field
    - Curve-fit the curve-fit, usage severity amplification factors
- MODSDF-StS:
  - Dynamic, physics-based global stresses
  - Component Load comparison (dynamics included)
    - Quick comparison for original 16 (and re-fit) location STF
  - ID global hot-spots using direct dynamic stress
  - DADT FEM “cut-outs” of these global hot-spots

# Mil-Spec Maneuvers

## Symmetric Maneuvers

Abrupt Maneuvers (continued):

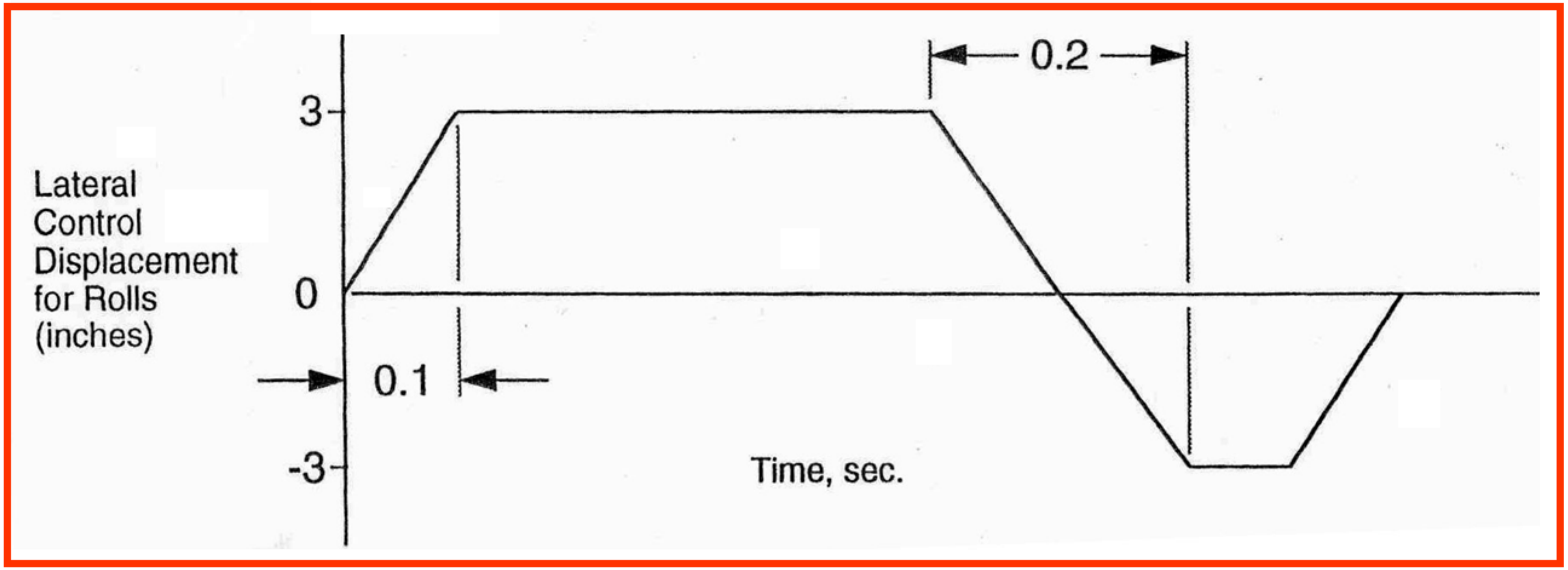
(c) By a control movement resulting in a ramp type displacement time curve as illustrated by the solid lines of the figure below. The duration of the maneuver and the control displacement δ will be just sufficient to attain the specified load factor coincidentally with the attainment of minus one-half δ .



# Mil-Spec Maneuvers

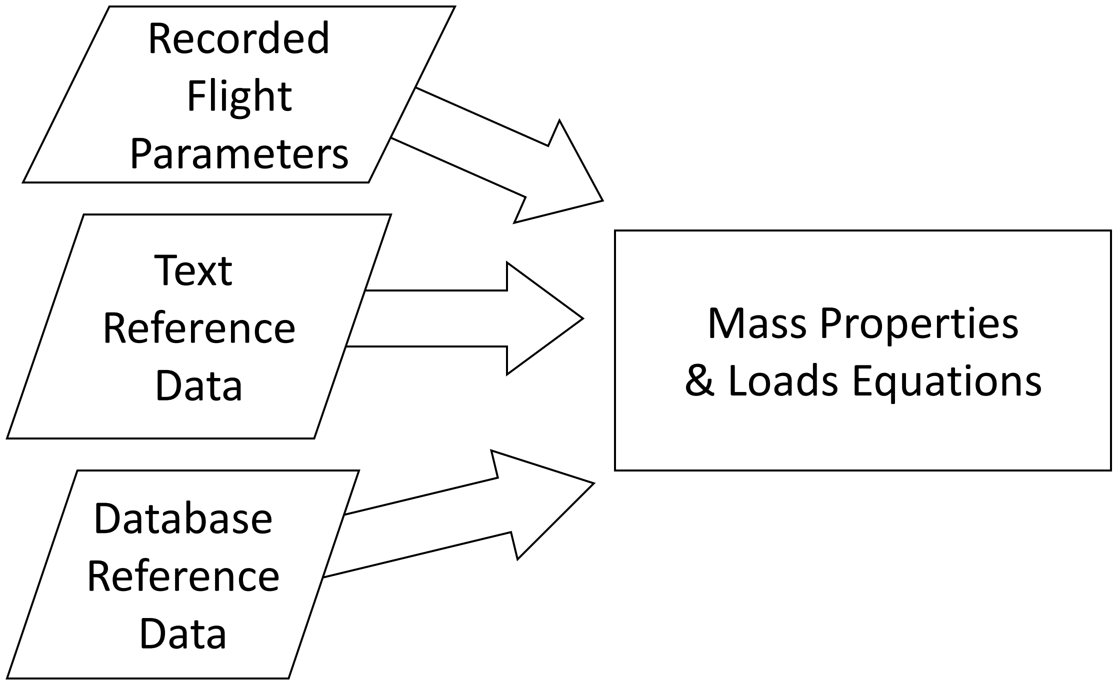
**Unsymmetrical Maneuvers**

Rolling Maneuvers

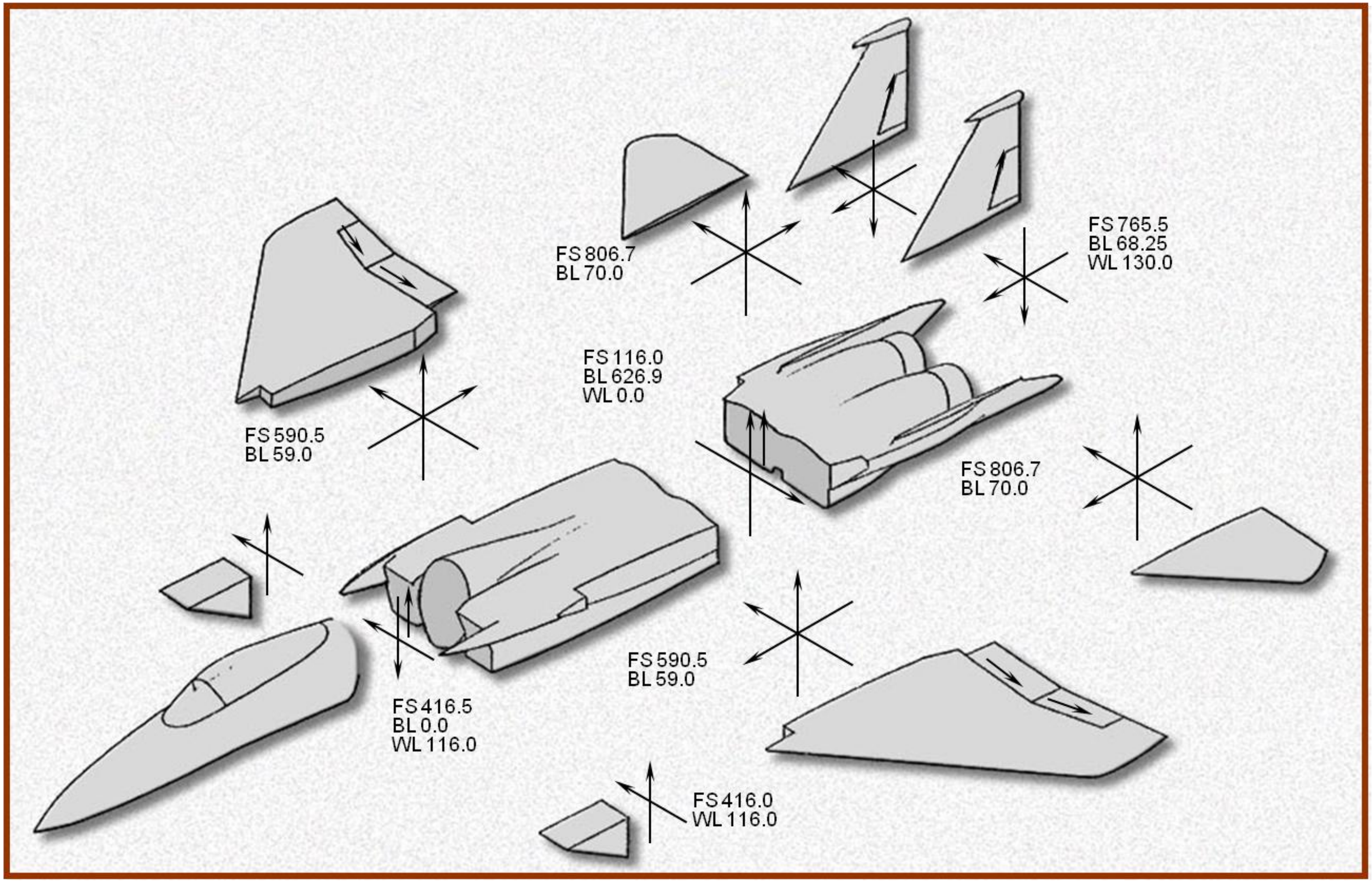


# Component Loads

- Loads are calculated using equations involving reference data and recorded flight parameters



# Component Loads



# Component Loads

- Component loads are load summations at ‘control’ points which are usually the manufacturing splice points.
- Component loads can more easily be analytically derived.
- Component loads can be directly measured in the wind tunnel and in flight test.

$$BENDING = \{C_{bending_{AoA}} + \frac{C_{bending}}{\delta_{Aileron}} \times \delta_{Aileron} \pm \frac{\frac{C_{bending}}{P} \times P_{(rad/sec)} \times b_{ref}}{2 \times VT_{(ft/sec)}}\} \times S_{ref} \times DP \times c_{ref}$$

Roll Rate

Aileron Deflection

True Airspeed

Dynamic Pressure

# Stress Transfer Functions

- Component Loads and Airframe States are used as "Curve Fitting" inputs for Stress Transfer Functions

$$\left(C_1 * L_1 + C_2 * L_2 + C_3\right) * C_4$$

$L_n$ are Loads (forces or moments)

$C_n$ are regression constants

- Example: MSLUGL – Left main spar lower lug

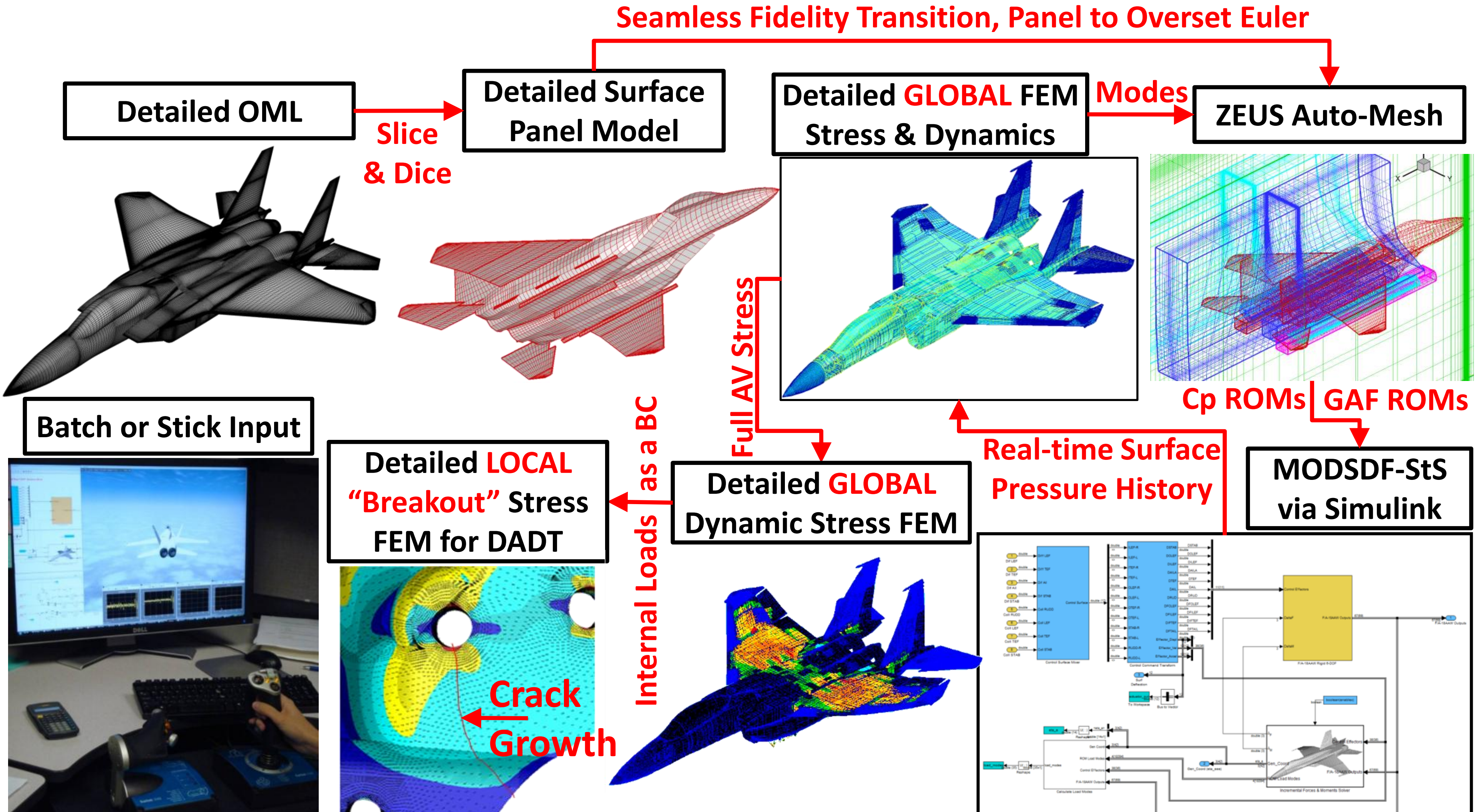
$$mslug = \left(2.9856E-7 * iwbml - 9.8864E-6 * iwsl - 1.9911E-5\right) * 16.7E3$$

Left inner wing bending moment

Left Inner wing shear

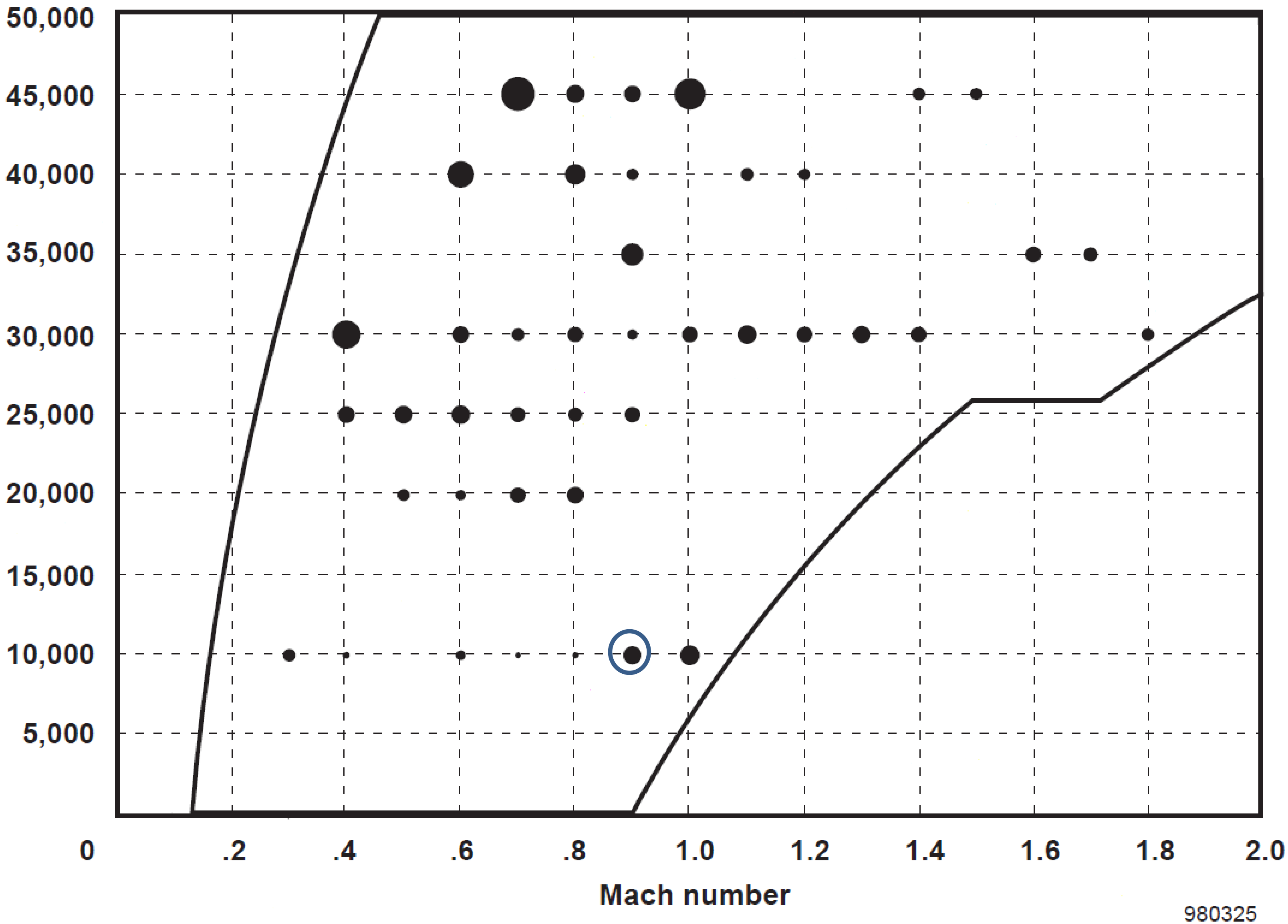
# Fatigue Life Testing

# StS-RtS Process Overview

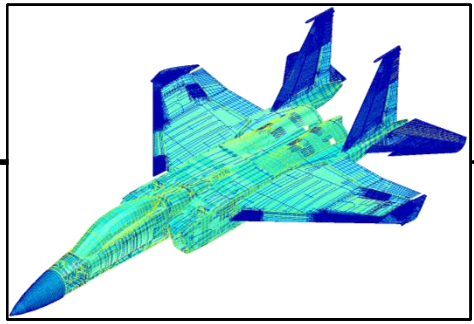


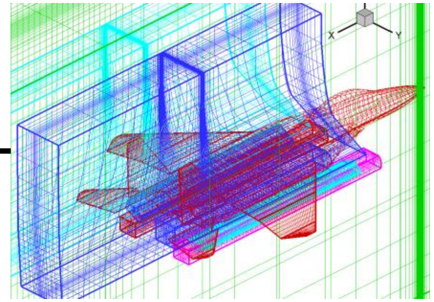

***Detailed Mission-Vehicle-Pilot-Specific Dynamic Stress Histories for Fatigue, DADT & Fleet Management Purposes, all via Real-time Euler-based Simulation***

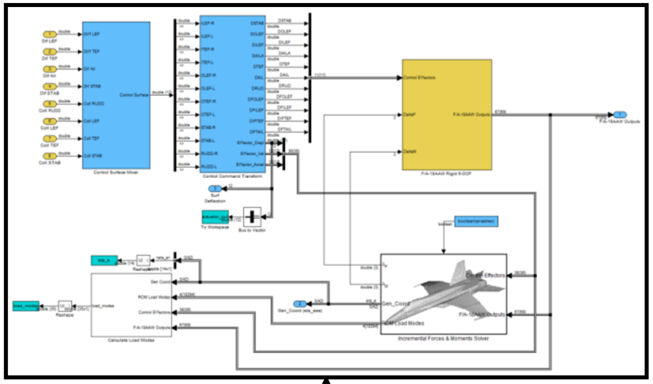
# For each Point in Flight Envelope …

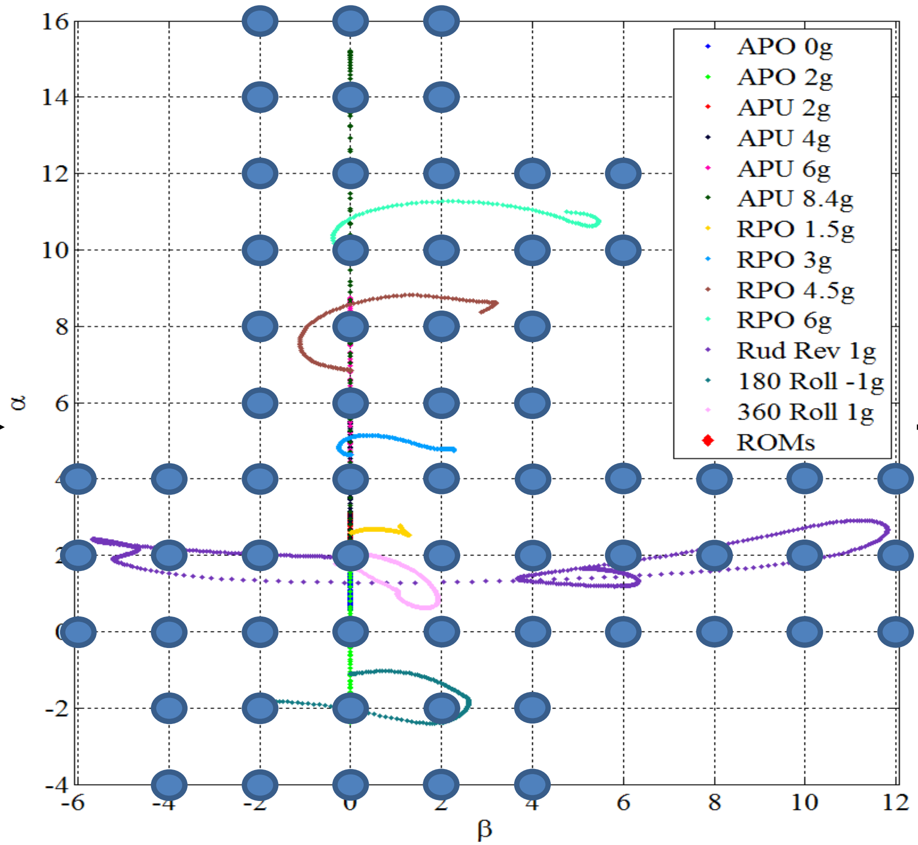


# … Build ROMs and put in Simulator










For each Mach-Altitude "point-in- the-sky", there is an alpha-beta ROM matrix

# Approach, 6-DOF Compatibility

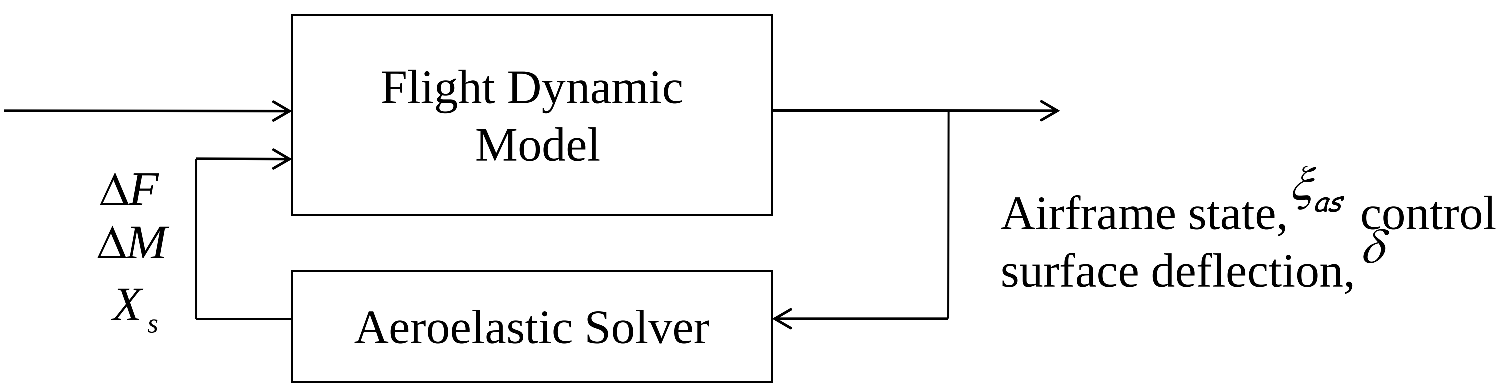
- Incorporates the add-on incremental forces and moments, $\Delta F$ and $\Delta M$, due to aeroelastic effects in the nonlinear flight simulation model.

$$m\left[\dot{V}_b + \Omega_b \times V_b - T_{be} g_e\right] = F_{ext} + \Delta F$$

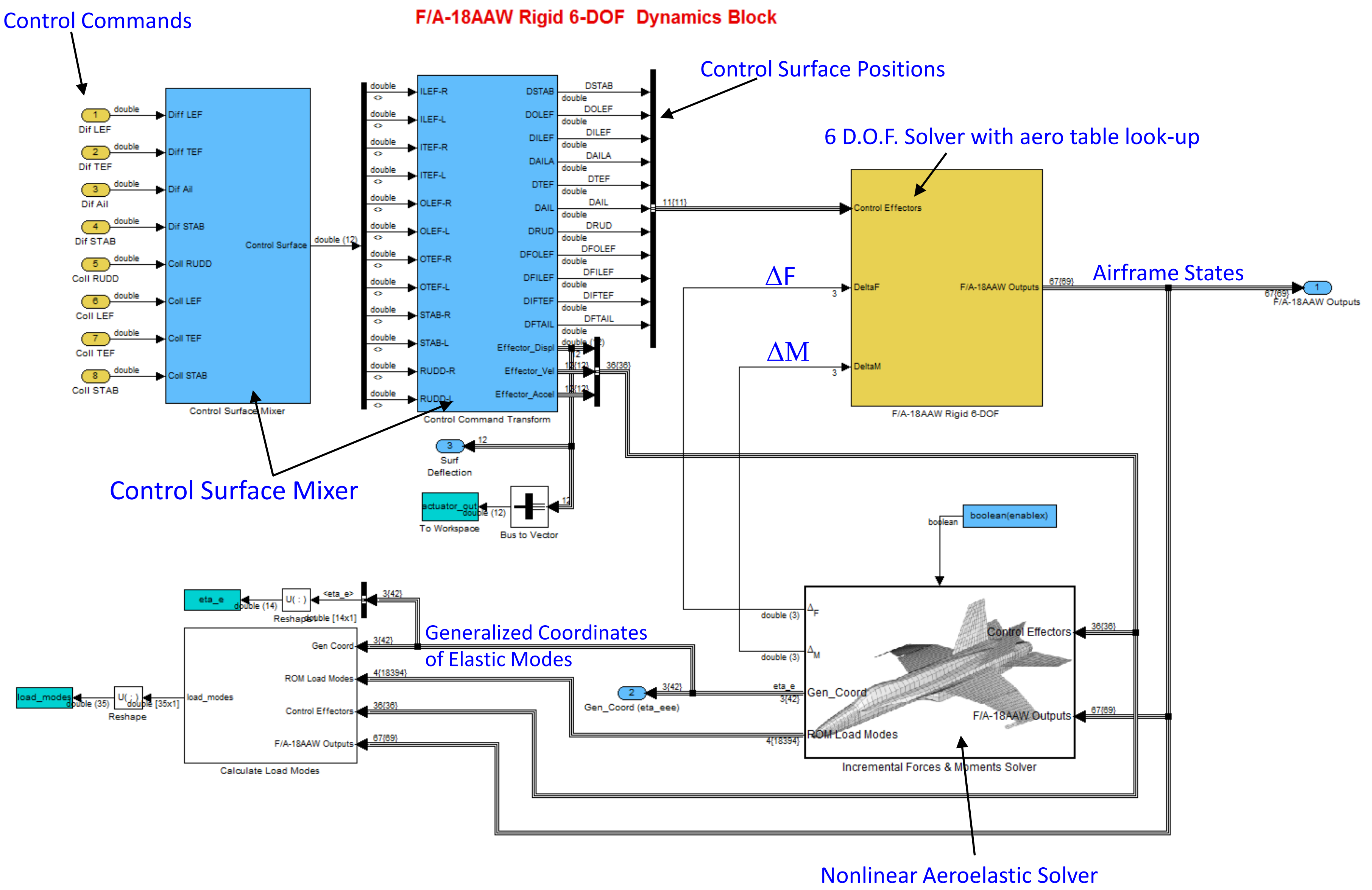
$$I_b \dot{\Omega}_b + \Omega_b \times I_b \Omega_b = M_{ext} + \Delta M$$

- Adds the structural oscillation, $X_s$, at the sensor locations to the sensor reading of rigid body motion.

- Modifies the linear aeroelastic equations of motion as an aeroelastic solver to provide $\Delta F$, $\Delta M$, and $X_s$ at each time step in the nonlinear flight simulation model.



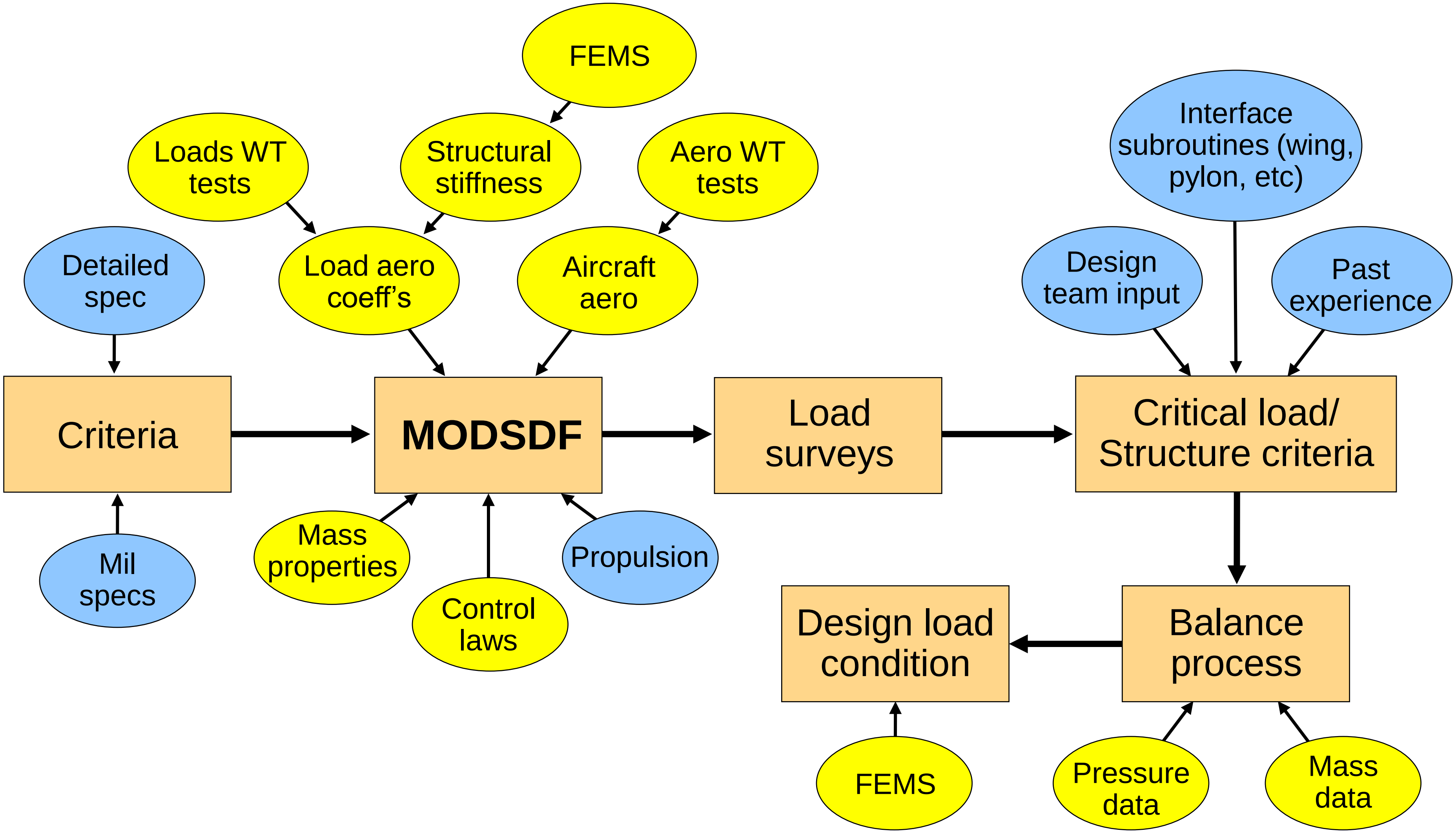
# Integration of Flight Dynamic Model and Nonlinear Aeroelastic Solver



# MODSDF (Modular Six Degree of Freedom) Overview

- **MODSDF predicts the trajectory and attitude of a vehicle in three dimensional space**
  - **A high fidelity, non-linear, stand-alone, simulation of vehicle motion that employs a fixed-step fourth-order Runge-Kutta integration scheme and six DOF algorithm**
  - **Structure allows project-specific analysis requirements to be incorporated while preserving the integrity and generic quality of its embedded methods**
    - » **For example: Named pipes**
- **Typical uses in St. Louis**
  - **Evaluations of Flight Control System Designs**
  - **Time-Dependent Flying Qualities and Performance Characteristics**
  - **Flight, Store, and Ground Loads**
  - **Weapons Separation Characteristics**
  - **Verification of Manned Simulator Models**
  - **Reproduction of Flight Anomalies for Incident/Accident Investigations**

# MODSDF-StS “Impacts”



# MODSDF Overview (StS)

Aircraft Aerodynamics Database

Aircraft Propulsion Database

A/C Component Aerodynamics & Mass Properties

Store Aerodynamics & Mass Properties

Structural Allowables at Manufacturing Splices and Store Interfaces

## MODSDF Software Library

Input Control Stick/Rudder Pedal Time History or Trajectory
*OR*
"Canned" Maneuvers For Loads Analysis - 6 DOF Eqns of Motion

- Steady or Abrupt Symmetric
- Rolling Pullouts
- +1g 360 Rolls
- -1g 180 Rolls
- Sideslips to Max β

F-15 A/B/C/D or E Flight Control Systems Modeled

- CAS On / Off

Menu Driven Configuration Buildup

OWS (Overload Warning System)

Structural Loads Equations

- Aircraft Components
- Store cog. Loads
- Aircraft / Store Interface
- % Design Limit Loads

**DYNAMIC Pressure on the Vehicle Surface (Cp)**

Aircraft Trajectory Time Histories

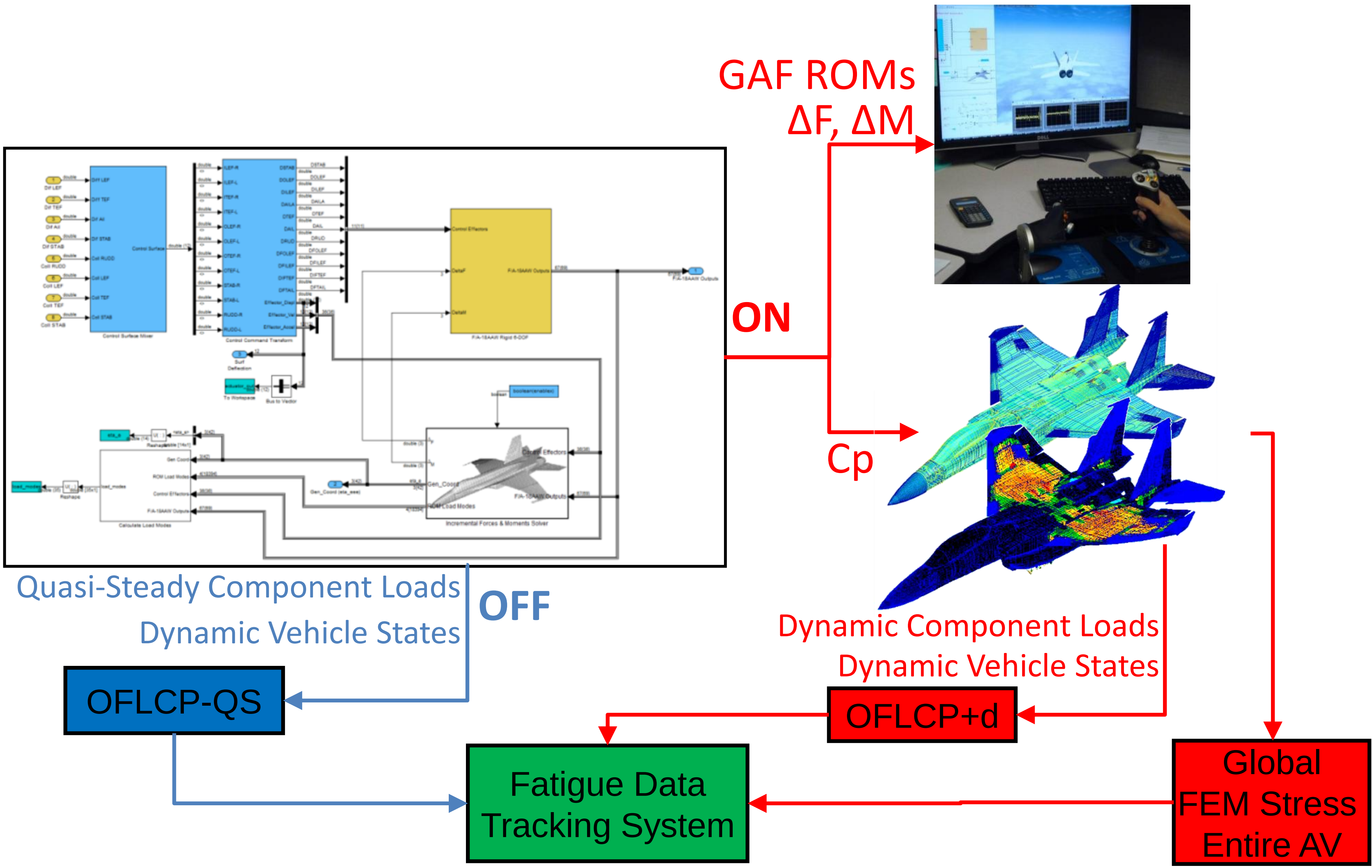
***** DYNAMIC *****

Loads Time Histories

- A/C Components
- Store CG
- Store Interface
- OWS Data
- %DLL Data

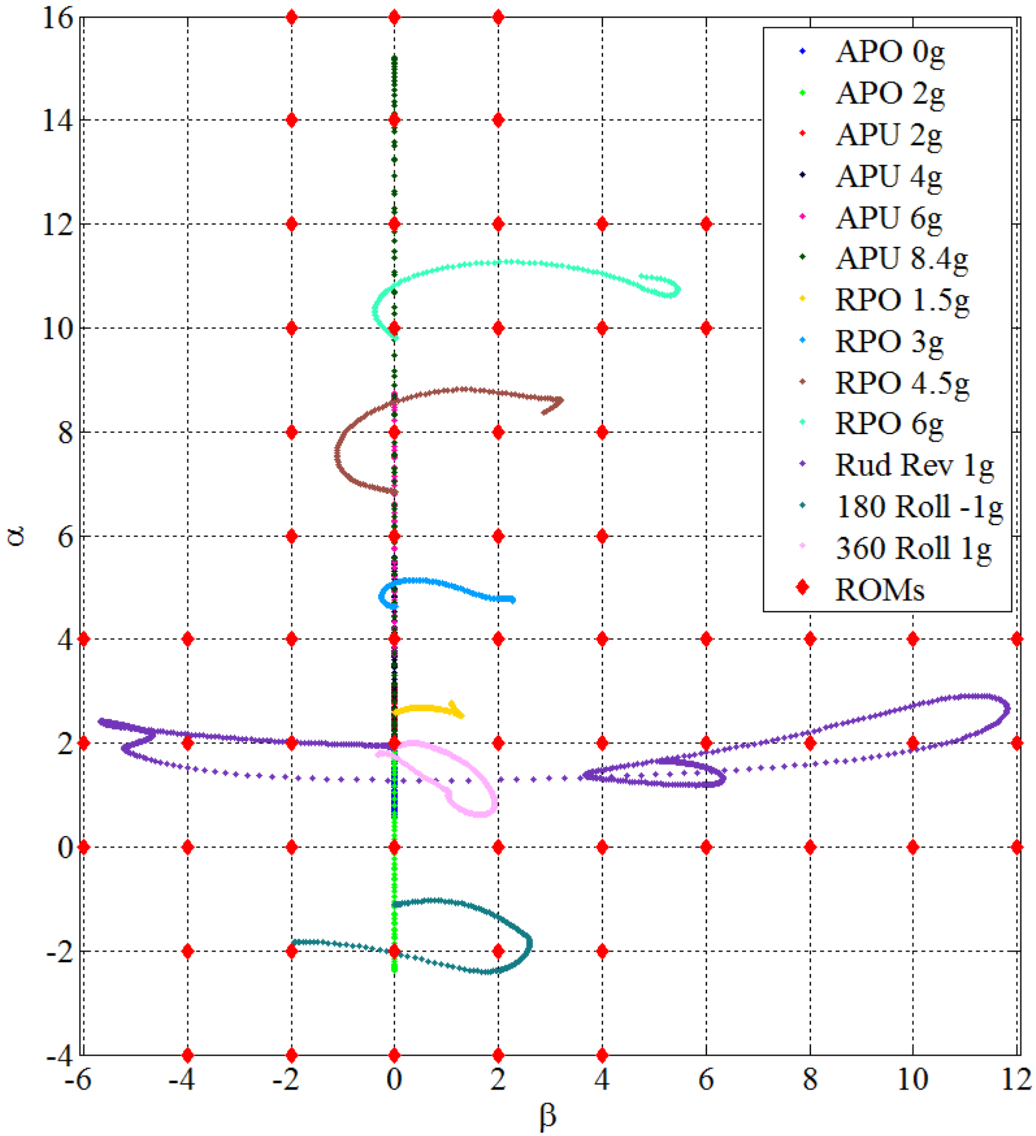
MAX / MIN Search Data For All Loads Along Trajectory

# MODSDF-StS to OFLCP & FDTS



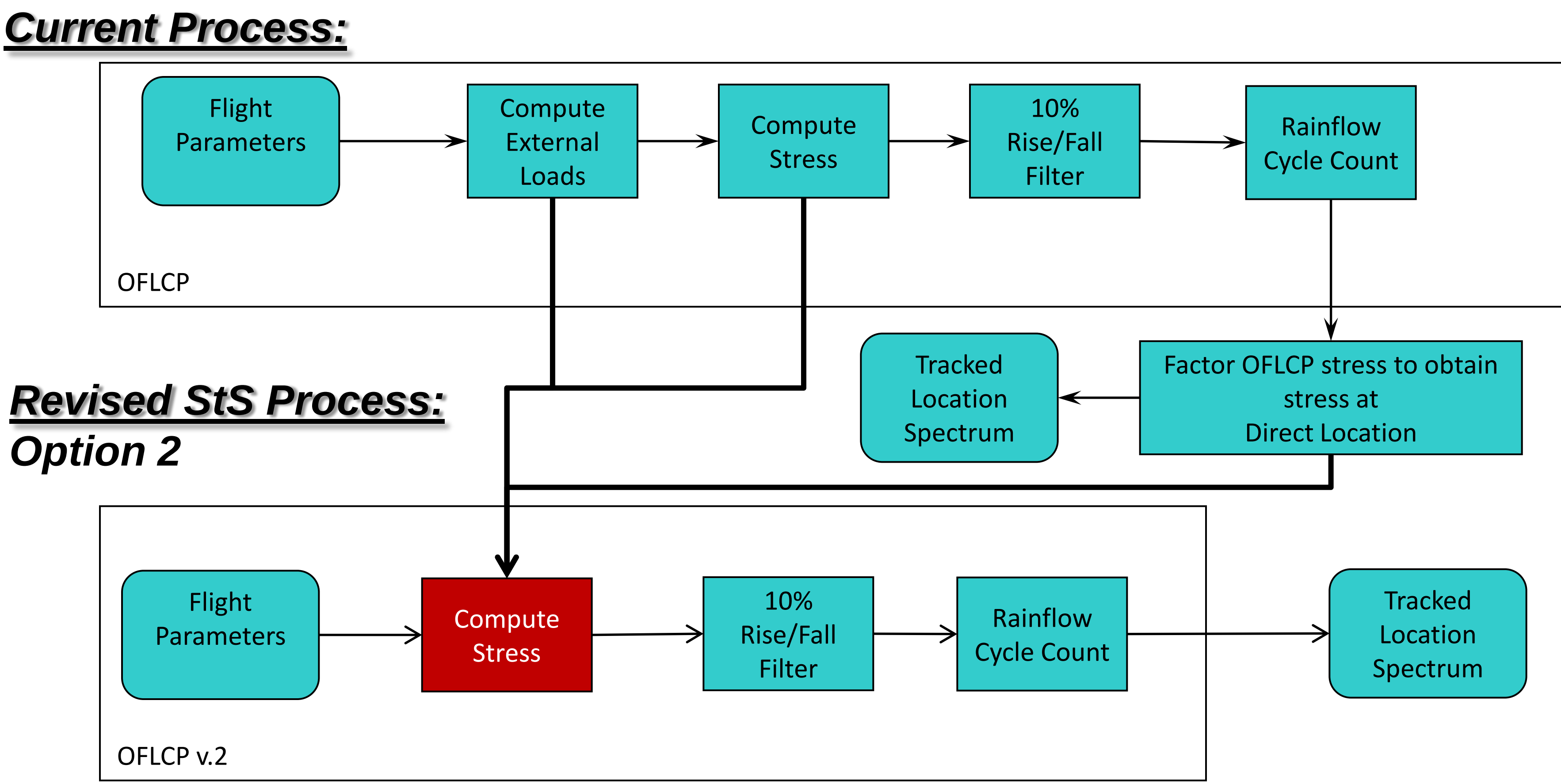
# ROM Flight Conditions

- α/β traces for maneuvers performed in MODSDF at Mach 0.95, 15kft
- Need an aeroelastic ROM at each α/β pair marked by a red diamond
- For APO/APU maneuvers only β=0 ROMs required
- APU 4g maneuver requires α=0, 2, 4, 6 ROMs, for example



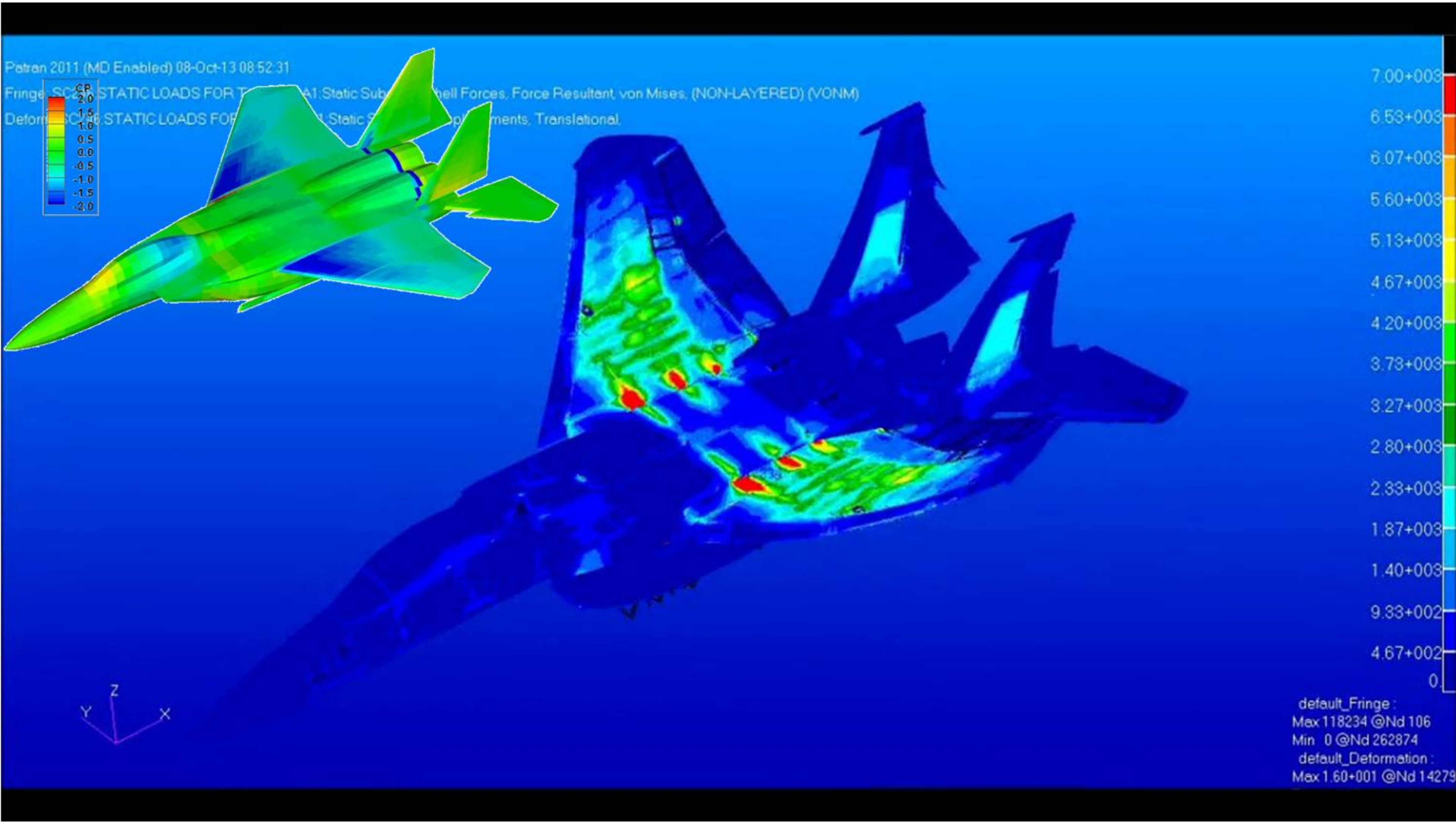
# Spectrum Development:

## *Option 2 – Revise the Process*

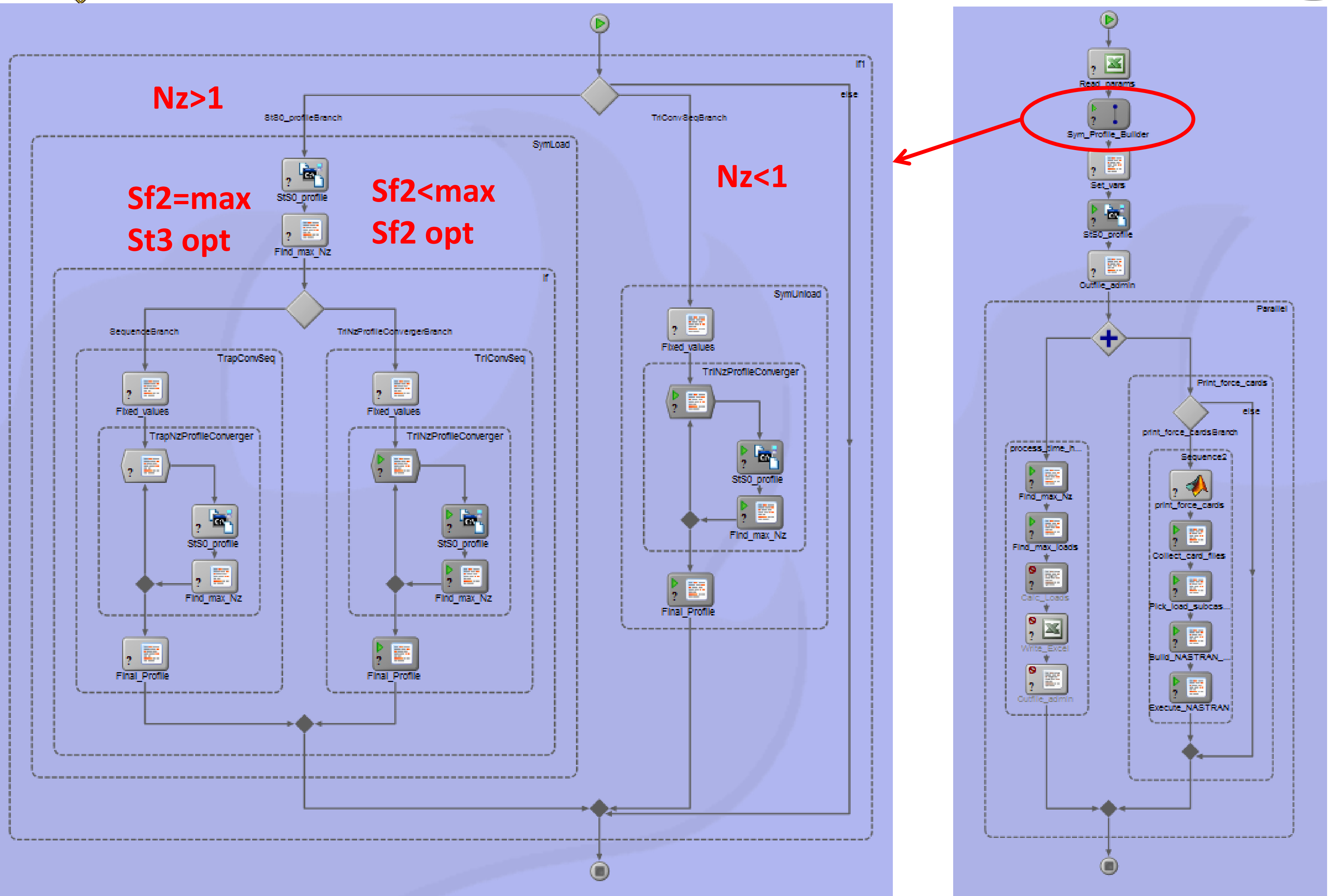



**Direct calculation of stress spectrum for any fatigue critical location**

# Beyond Component Loads



# The Process in Model Center



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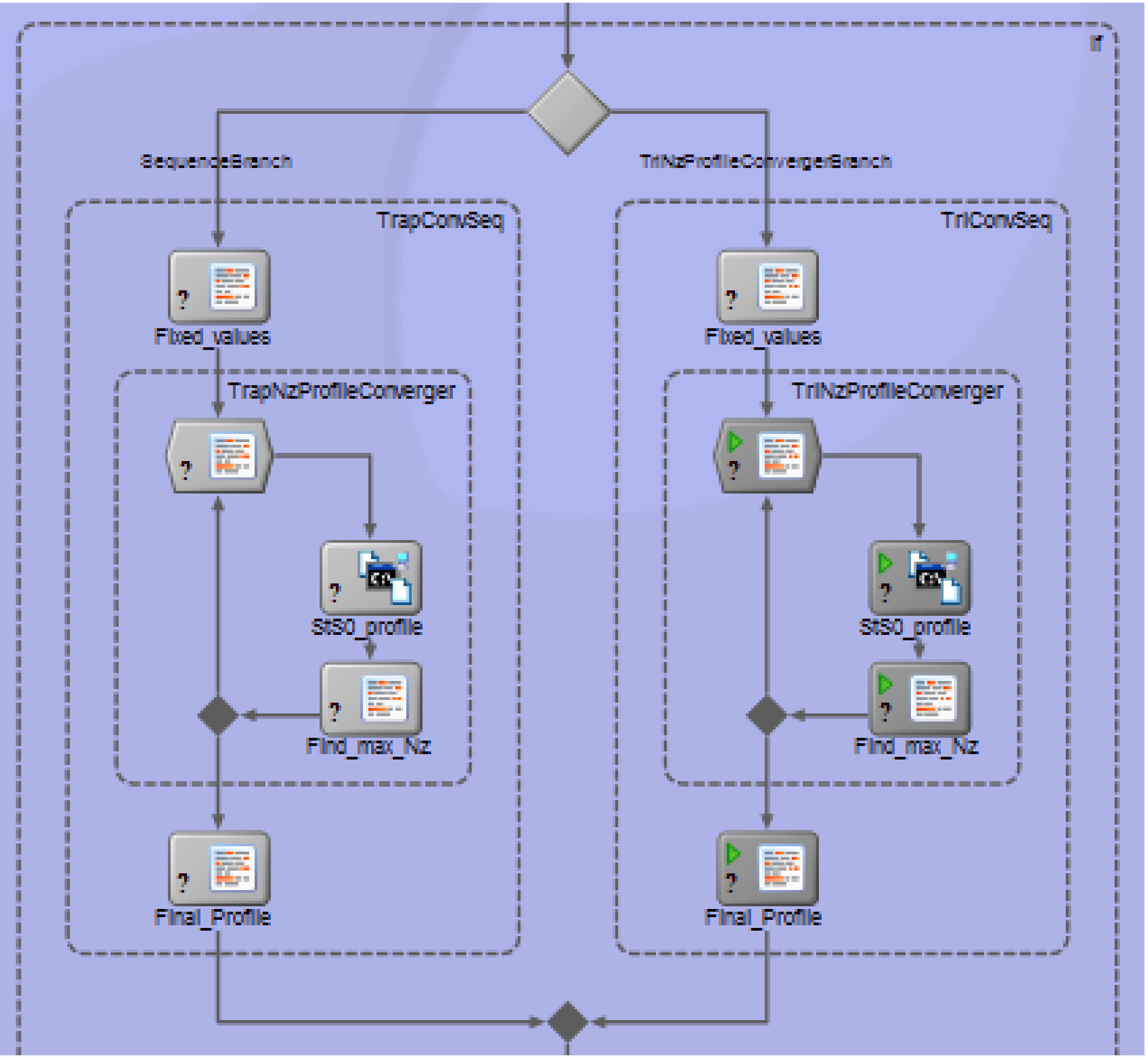


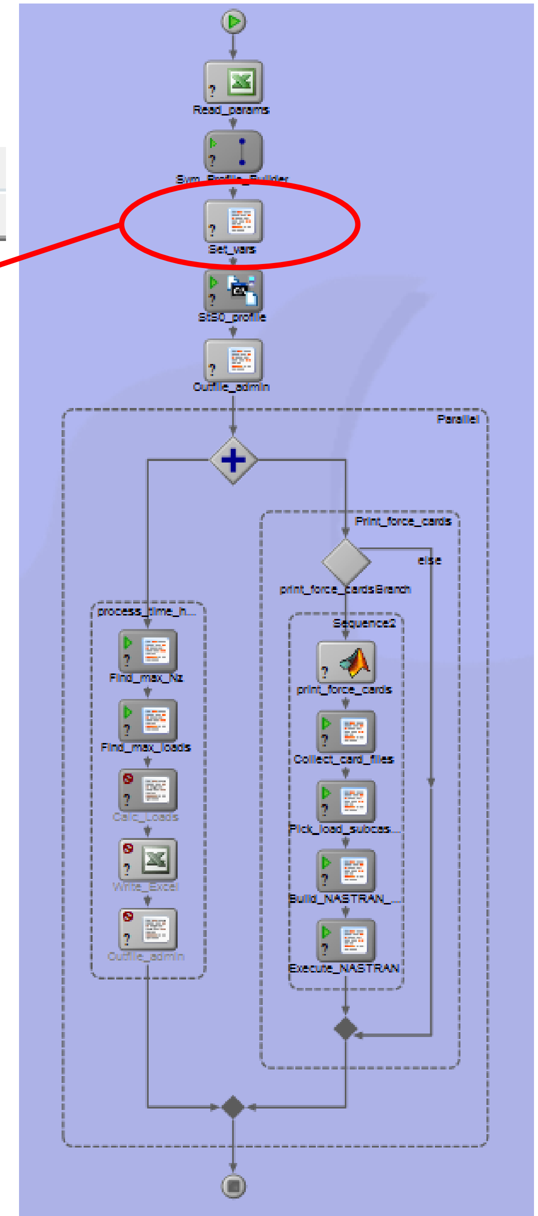
# The Process in Model Center

ModelCenter Variables

- Set_vars
  - st3list[]
  - sf2list[]
  - sf3list[]
  - ICFLAG
  - TgtNzlist[]
  - TgtNz
  - st3
  - st4
  - sf2
  - sf3
  - <click to add variable...>

Script

```
sub run
st3 = st3list(ICFLAG-1)
st4 = st3+0.2
sf2 = sf2list(ICFLAG-1)
sf3 = sf3list(ICFLAG-1)
TgtNz = TgtNzlist(ICFLAG-1)
end sub
```



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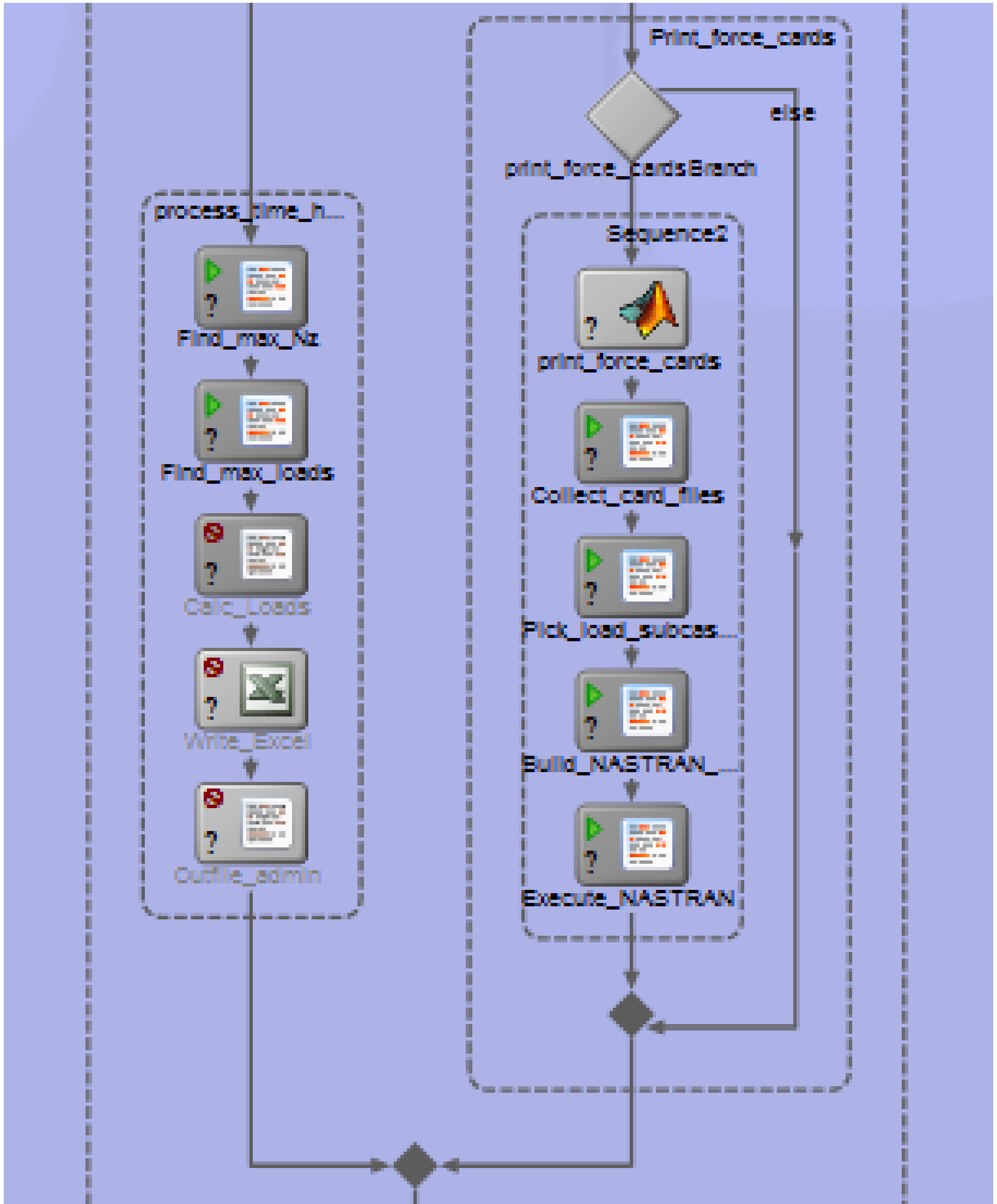

# Conclusions

- StS DFS essentially adds the incremental dynamic aeroelastic loads to the wind tunnel measured loads with or without static aeroelastic correction.
- StS DFS can be modified to import the flight recorded aircraft states for generating loads spectrums of individual fleet members.
- StS DFS can identify previously undefined high stress monitoring areas (hot spots).
- The loads spectrum generated by StS DFS can be used to perform ground fatigue tests or fatigue analysis to identify the residual fatigue life of aircrafts.

# Demo