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

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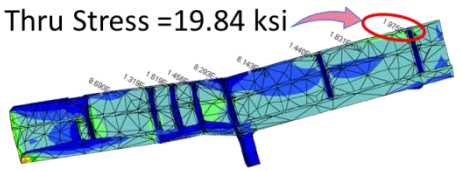
Transition Success Story:

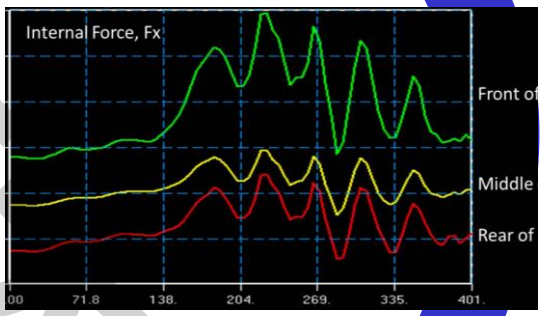
Stick-to-Stress Real-time Simulator (StS-RtS) Applied to F-15C/D

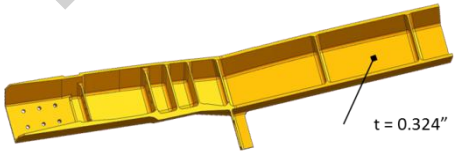
U.S. AIR FORCE

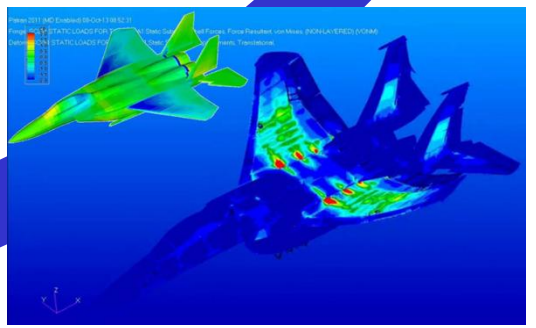
- **Background**
  - Clearly established need for more accurate & rapid analysis tools to manage cracking in legacy aircraft
  - Using aircraft past their design service life leads to:
    - Unexpected new cracking locations
    - Requirement for extensive re-analysis
    - More frequent inspections; 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

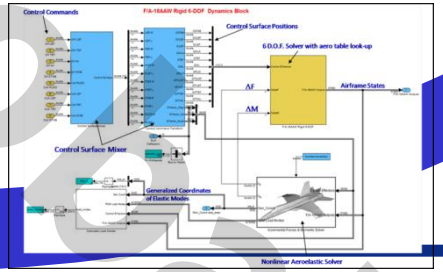
Remaining Useful Life via Dynamic Internal Loads On Critical Components











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

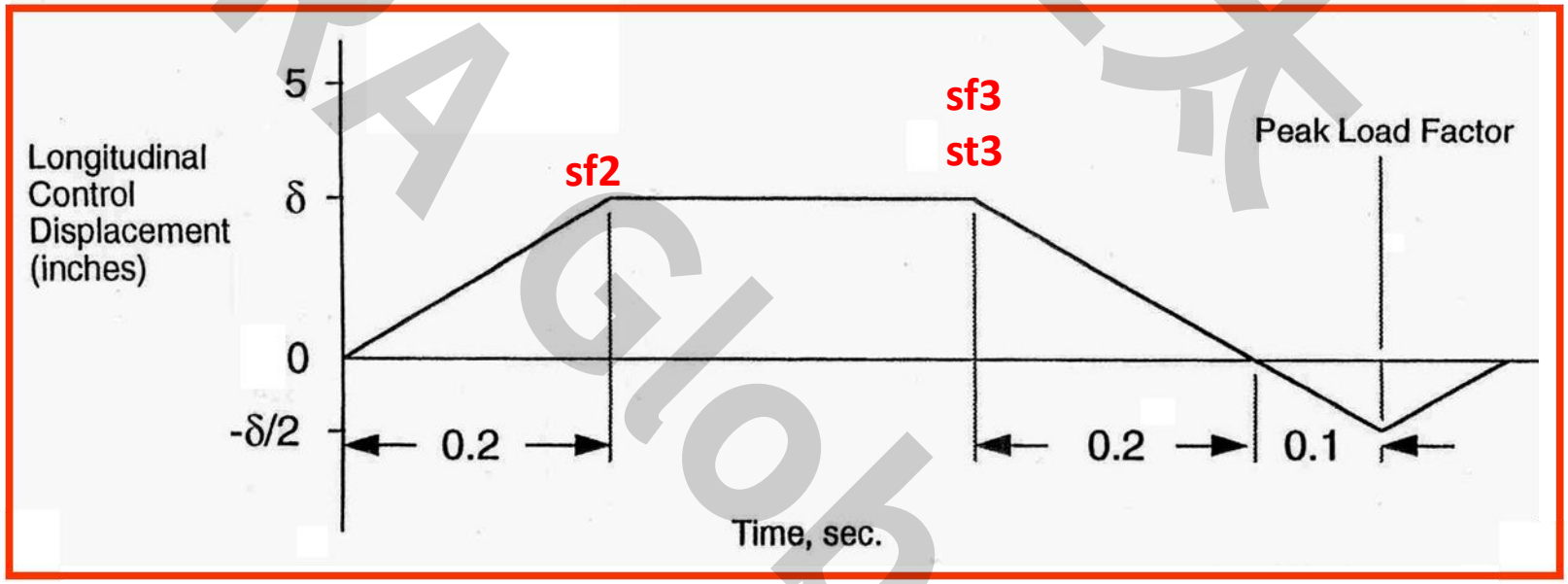
- SOA:
  - Quasi-steady, empirical, stress-transfer functions (STF)
  - Expensive to create, utilize and modify
  - New “hot spots” only from field
    - Curve-fit the curve-fit, usage severity amplification factors
- MODSDF-StS:
  - Dynamic, physics-based global stresses
  - Component Load comparison (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

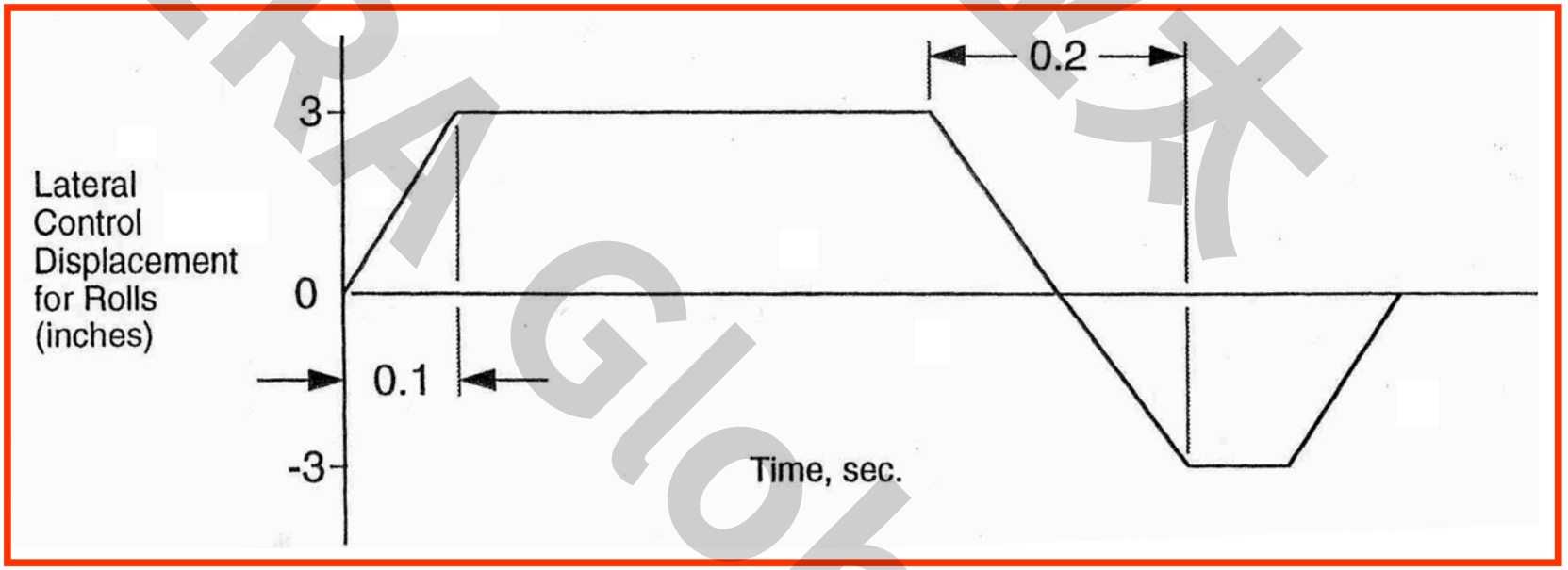
Abrupt Maneuvers (continued):

(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 .



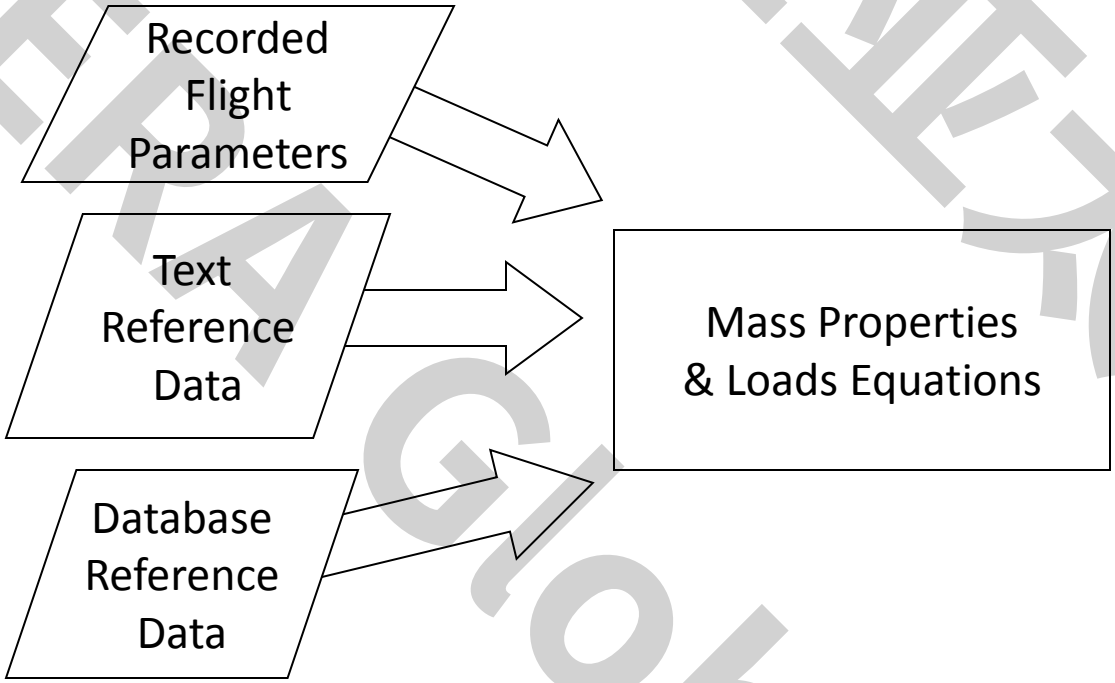
Mil-Spec Maneuvers

Unsymmetrical Maneuvers

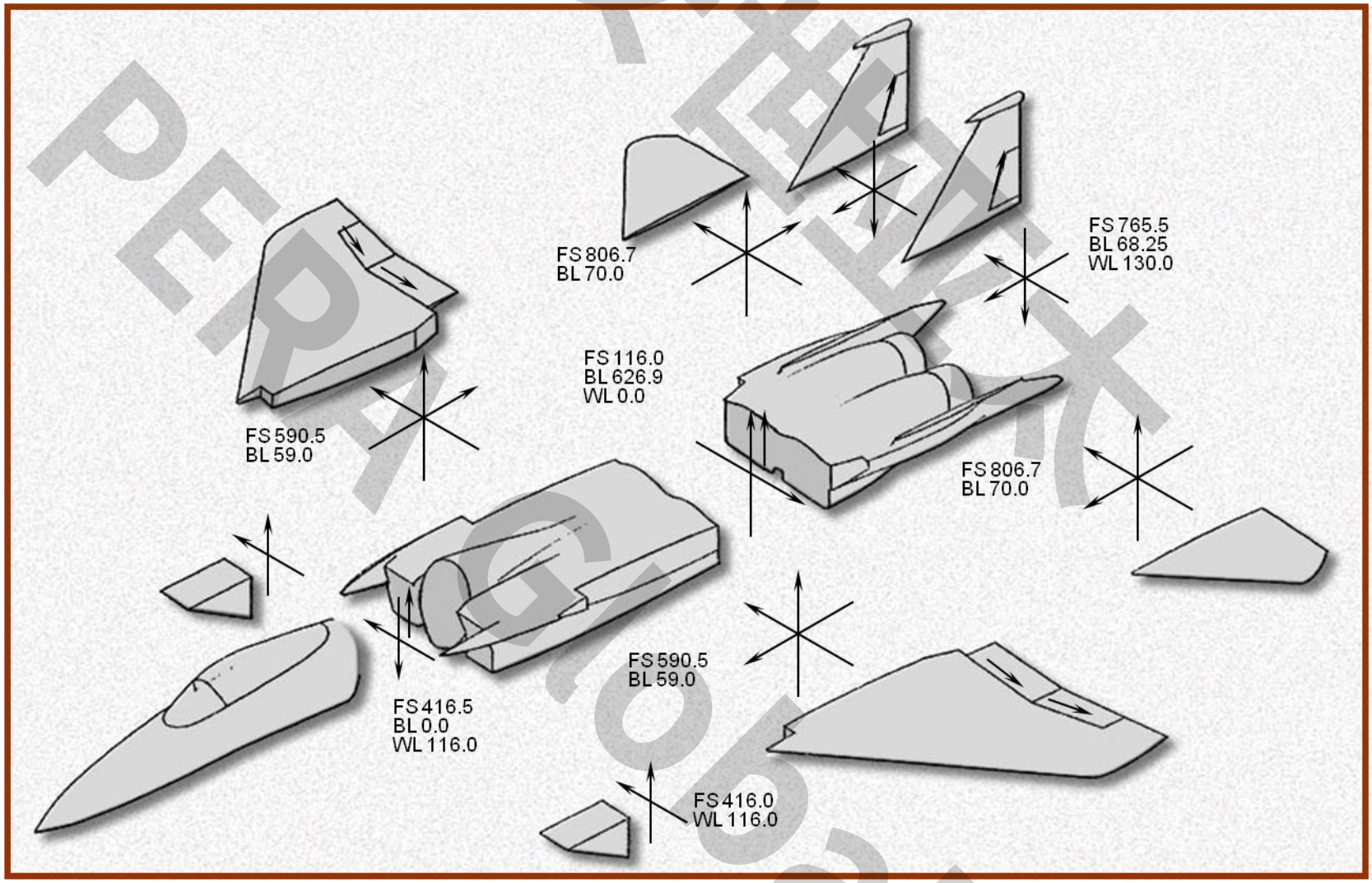


Component Loads

- 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.

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

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

$$(C_1 * L_1 + C_2 * L_2 + C_3) * C_4$$

L_n are Loads (forces or moments)

C_n are regression constants

- Example: MSLUGL – Left main spar lower lug

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

Left inner wing bending moment

Left Inner wing shear

Fatigue Life Testing

StS-RtS Process Overview

Seamless Fidelity Transition, Panel to Overset Euler

Detailed OML

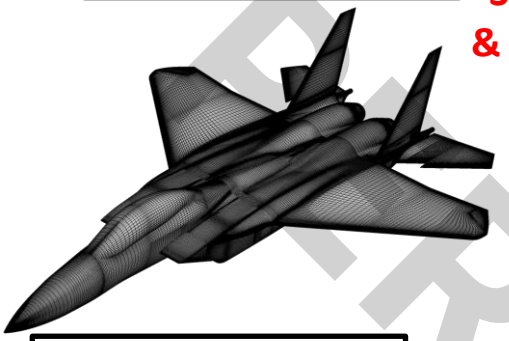
Slice & Dice

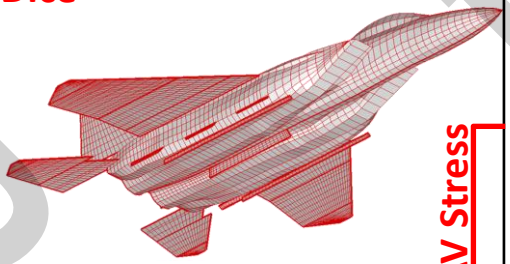
Detailed Surface Panel Model

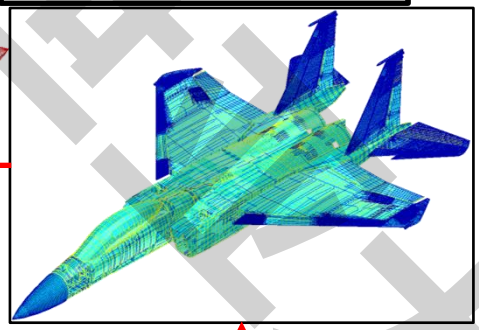
Detailed GLOBAL FEM Stress & Dynamics

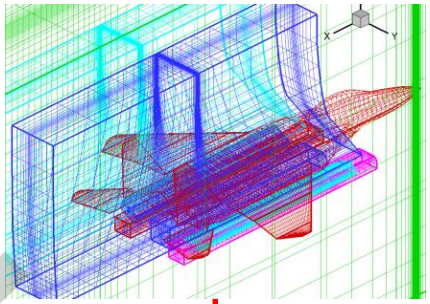
Modes

ZEUS Auto-Mesh









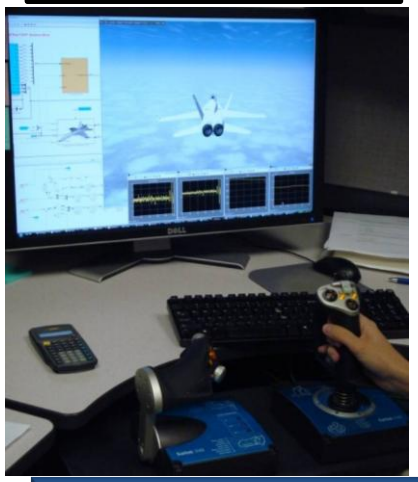
Full AV Stress

Real-time Surface Pressure History

Cp ROMs

GAF ROMs

Batch or Stick Input

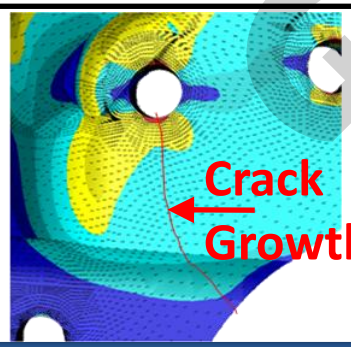


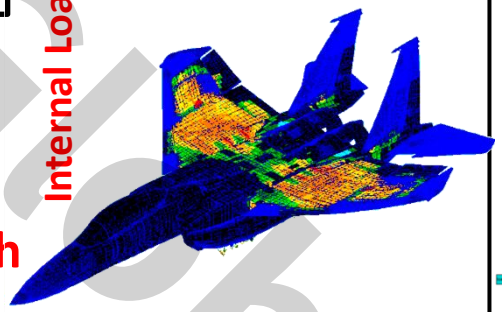
Detailed LOCAL "Breakout" Stress FEM for DADT

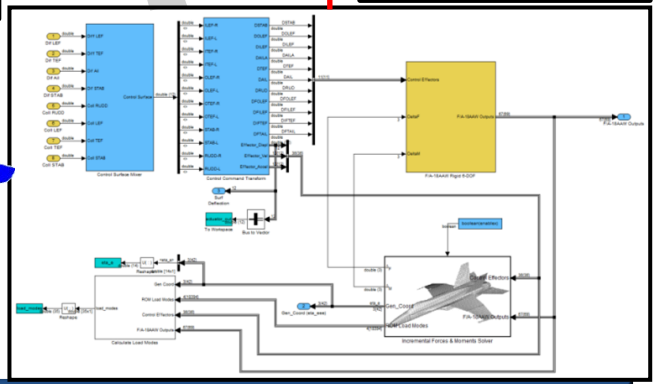
Internal Loads as a BC

Detailed GLOBAL Dynamic Stress FEM

MODSDF-StS via Simulink

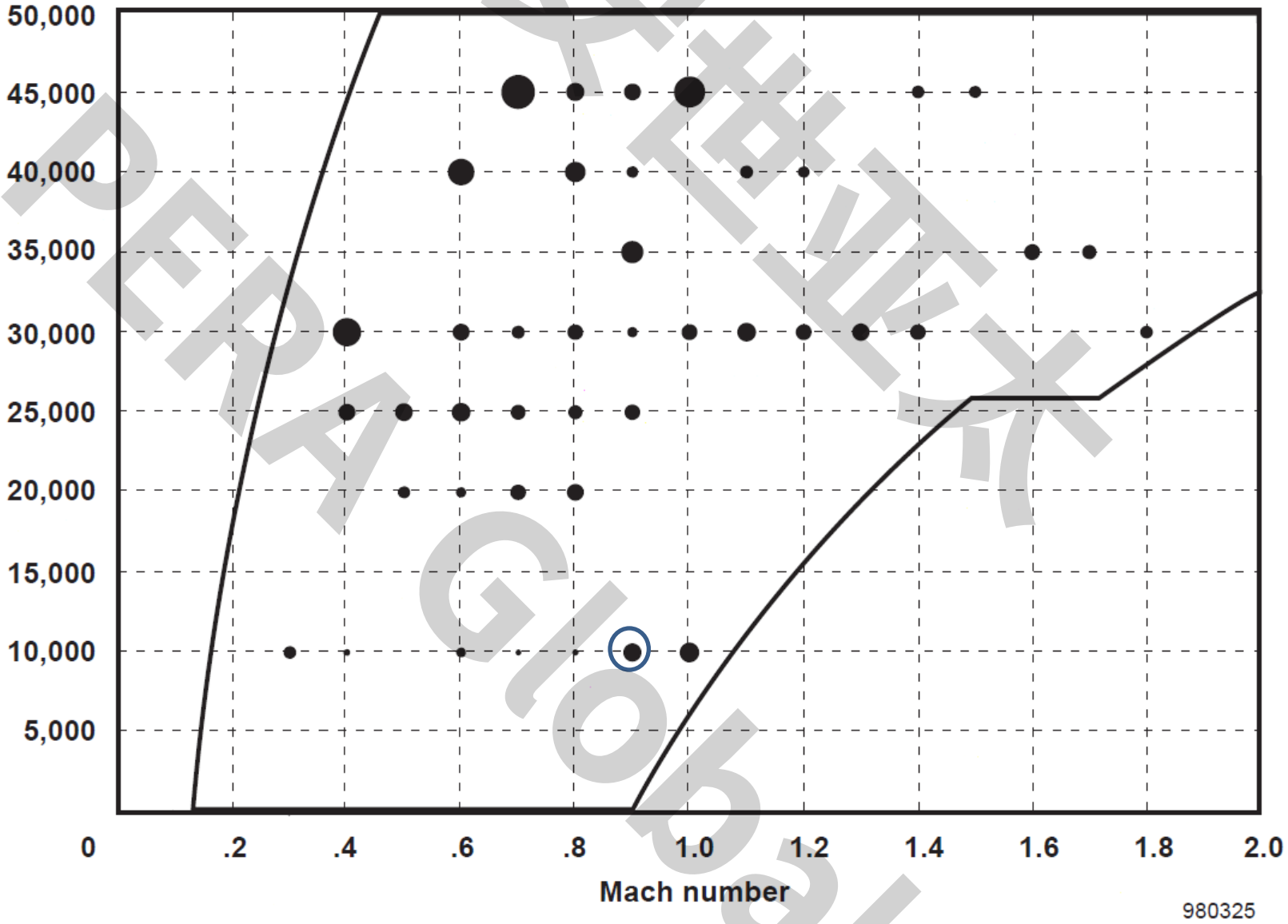




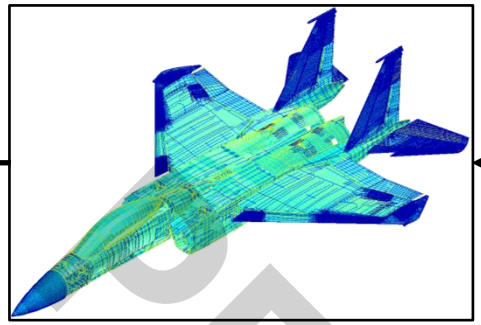


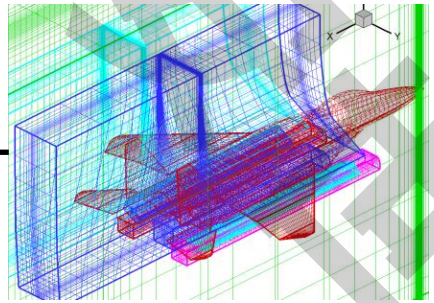
Detailed Mission-Vehicle-Pilot-Specific Dynamic Stress Histories for Fatigue, DADT & Fleet Management Purposes, all via Real-time Euler-based Simulation

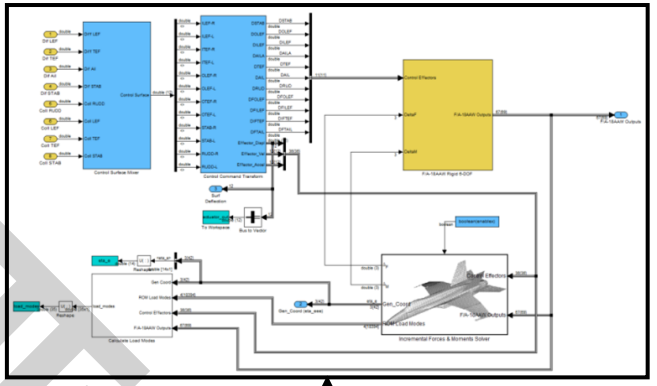
For each Point in Flight Envelope …

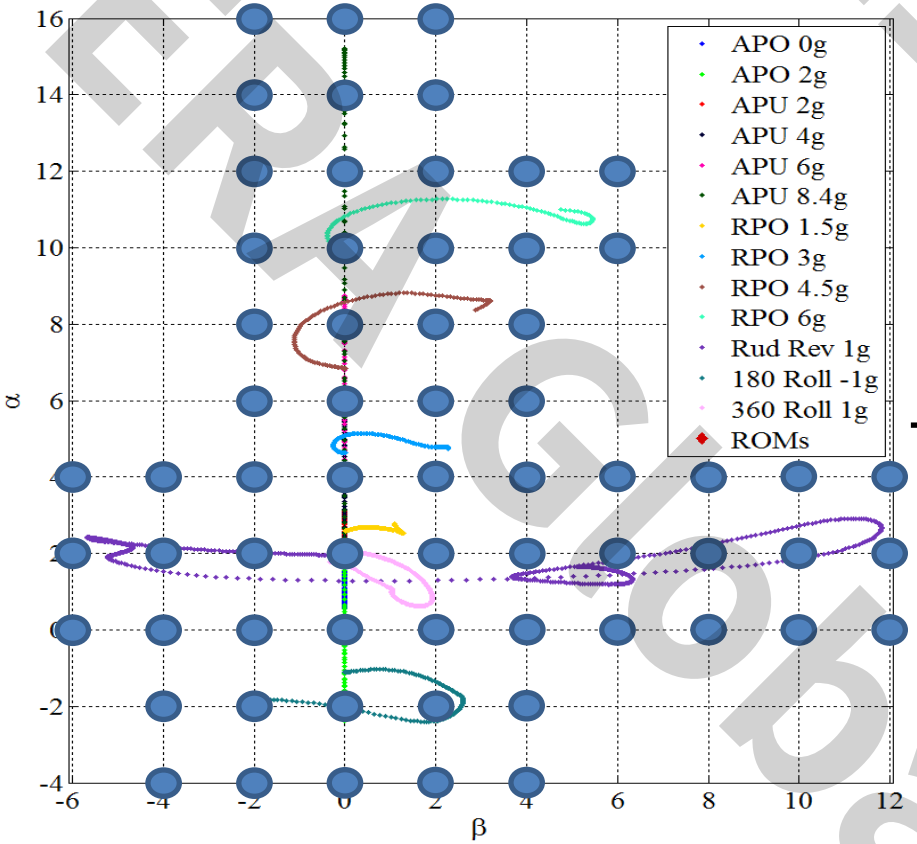


… Build ROMs and put in Simulator









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

Approach, 6-DOF Compatibility

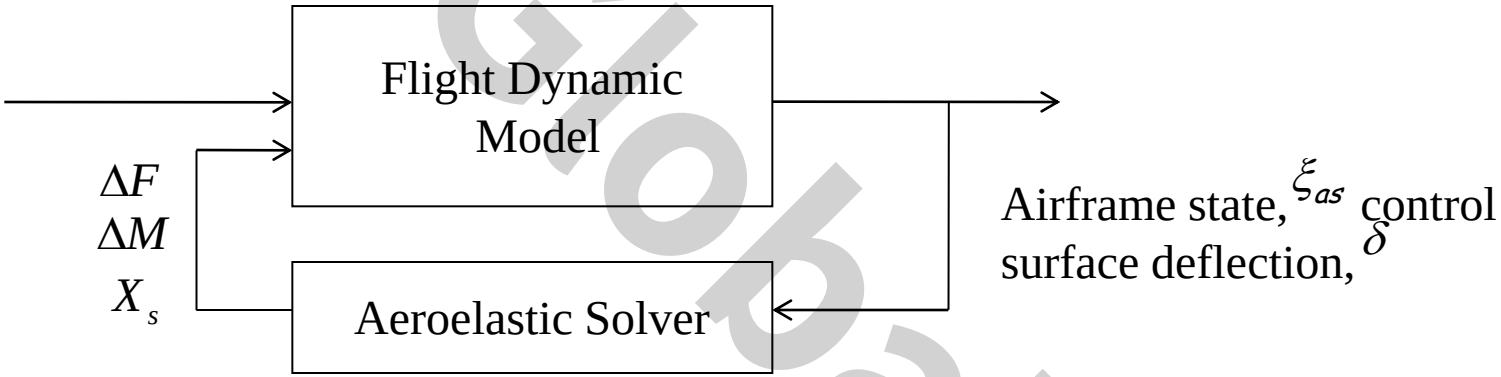
- Incorporates the add-on incremental forces and moments, ΔF and ΔM, due to aeroelastic effects in the nonlinear flight simulation model.

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

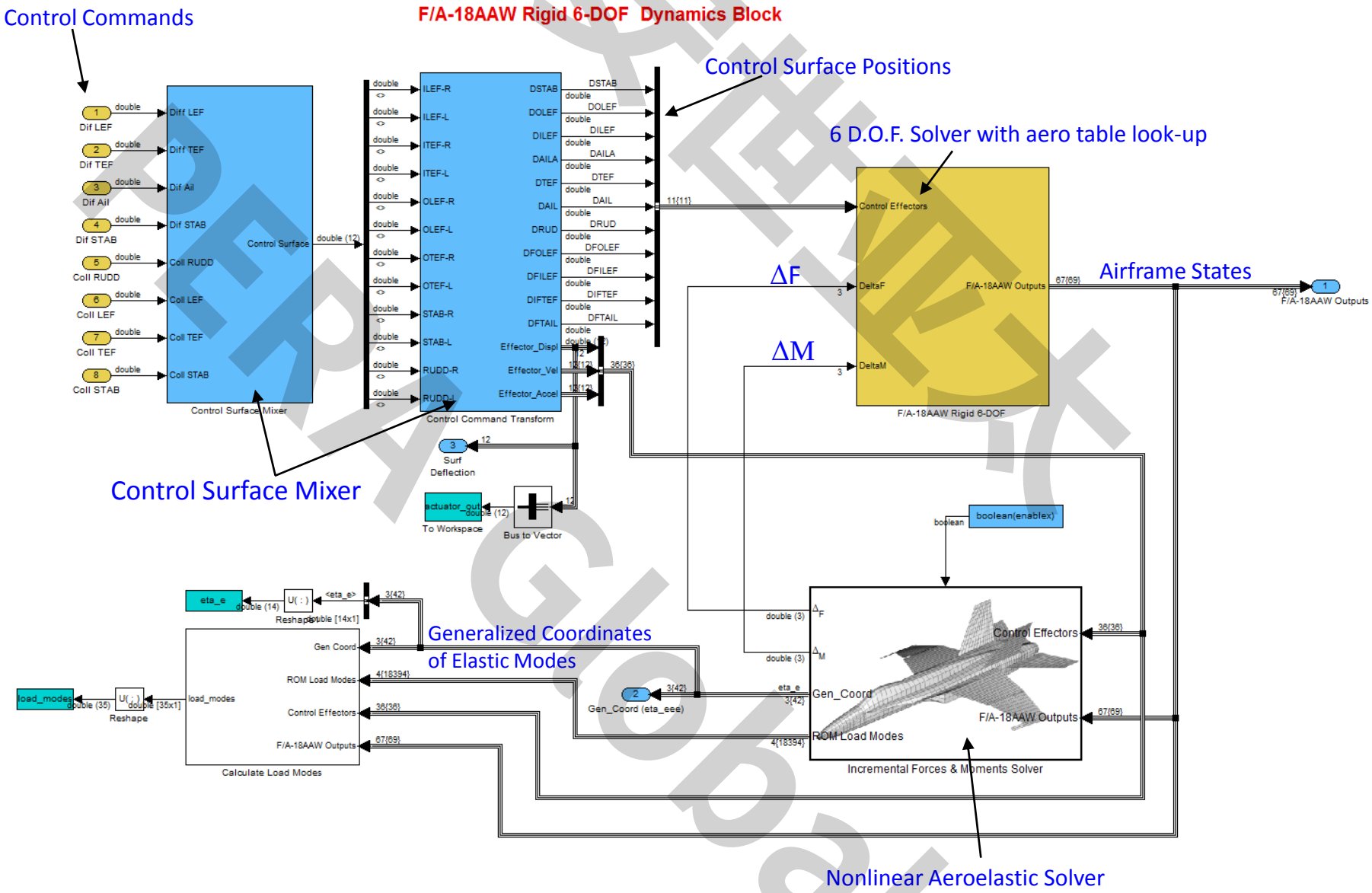
$$I_b \dot{\Omega}_b + \Omega_b \times I_b \Omega_b = M_{ext} + \Delta M$$

- 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 ΔF, ΔM, and X_s at each time step in the nonlinear flight simulation model.



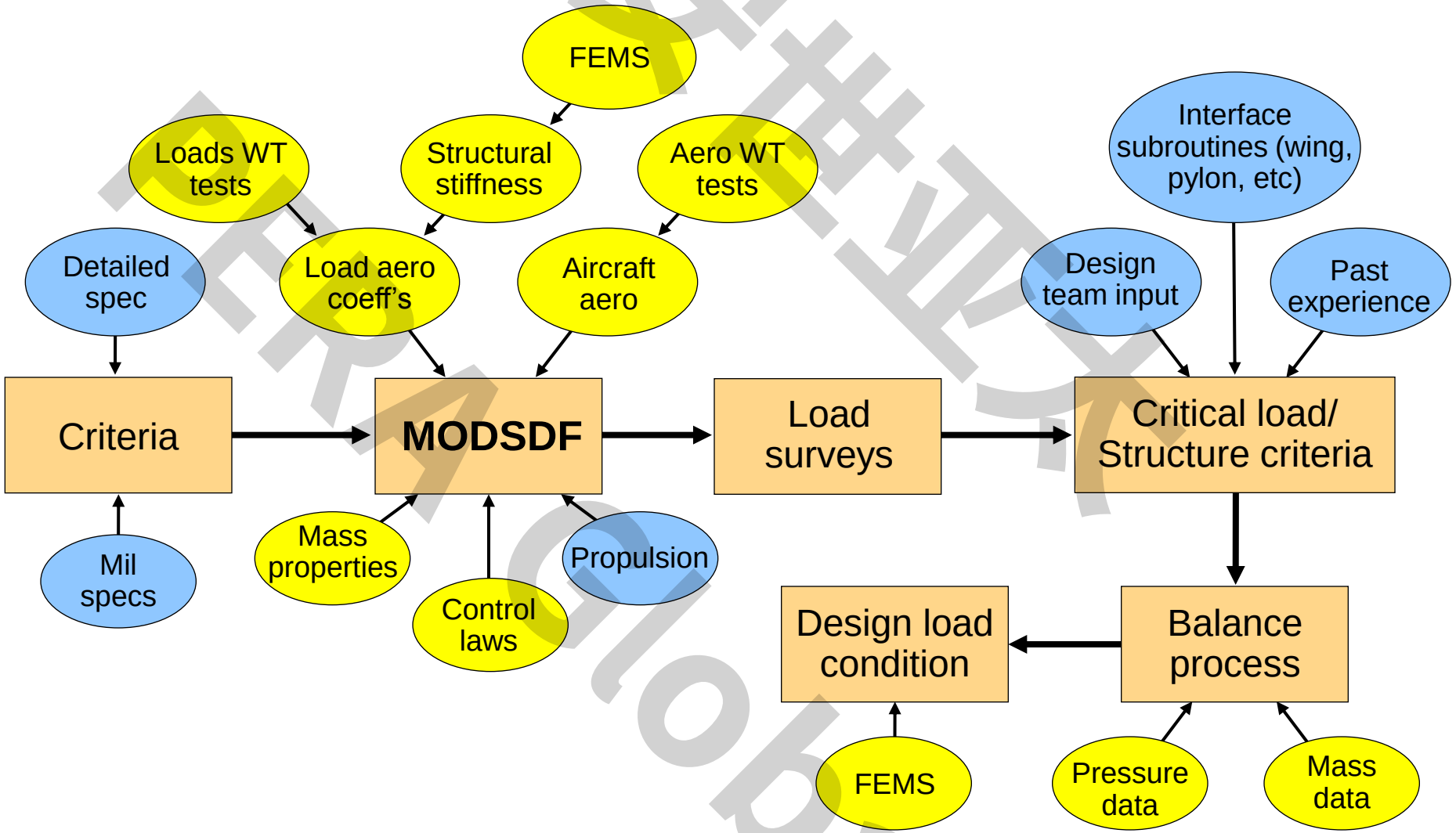
Integration of Flight Dynamic Model and Nonlinear Aeroelastic Solver



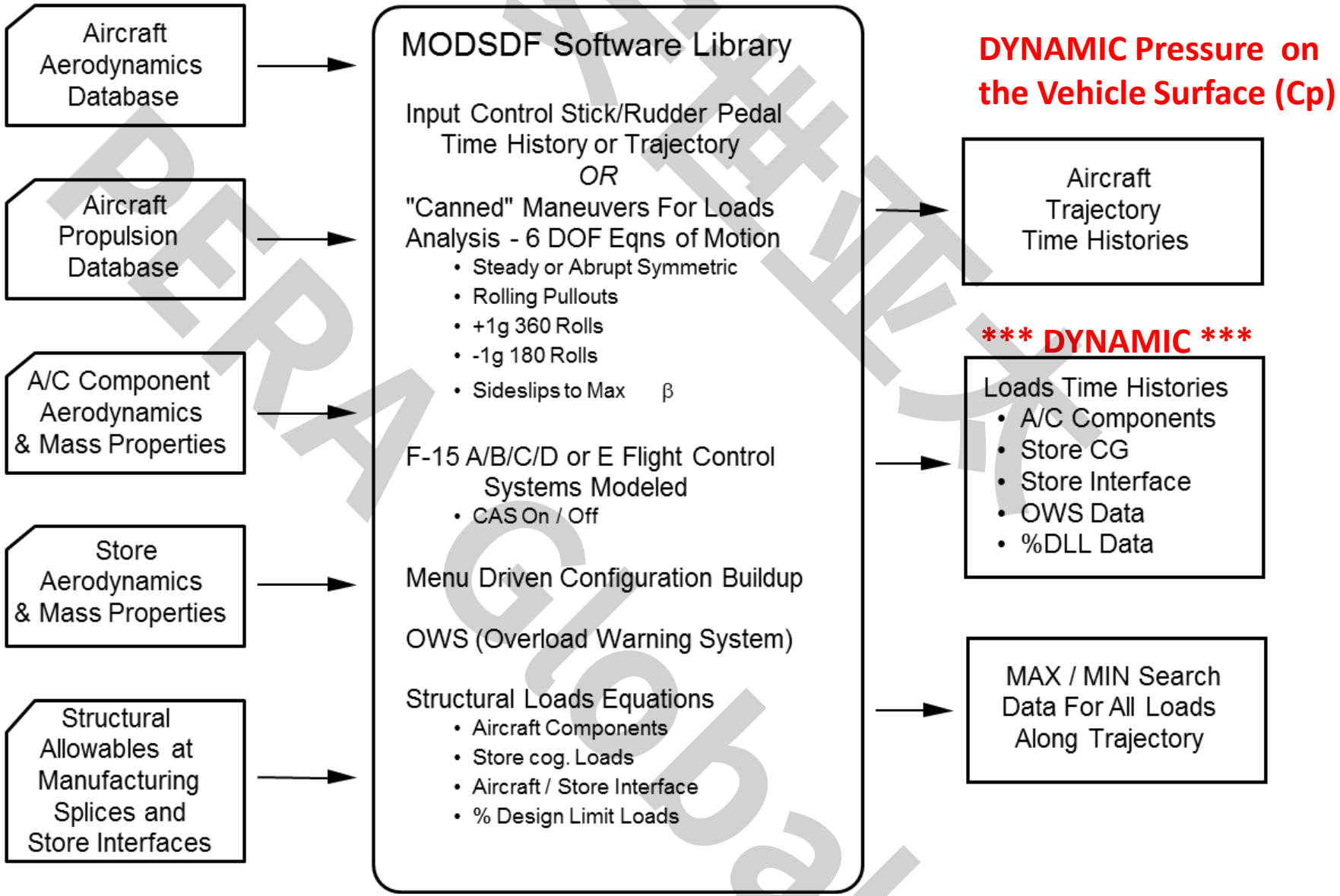
MODSDF (Modular Six Degree of Freedom) Overview

- **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**

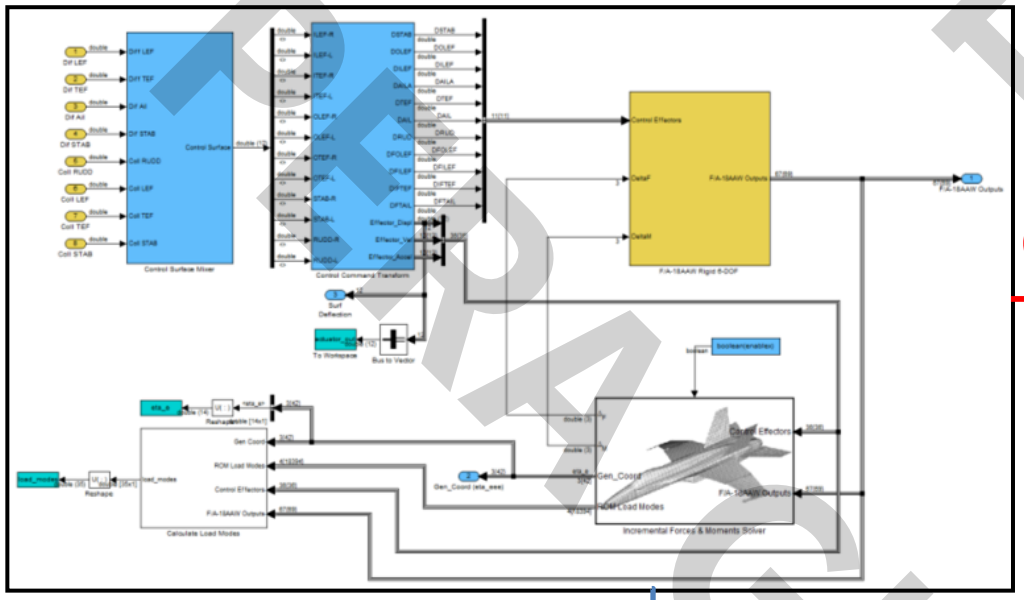
MODSDF-StS “Impacts”



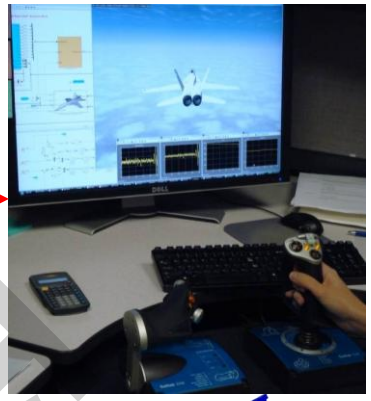
MODSDF Overview (StS)



MODSDF-StS to OFLCP & FDTS

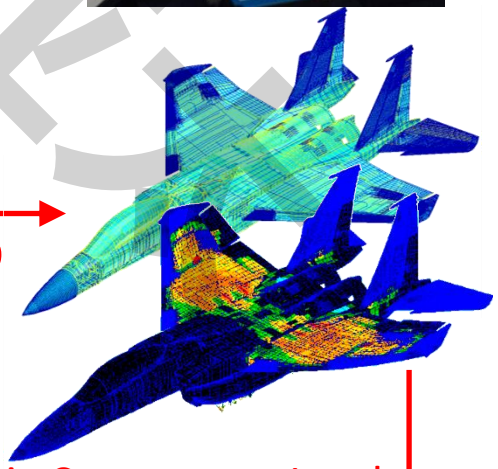


GAF ROMs
ΔF, ΔM



ON

Cp



Quasi-Steady Component Loads
Dynamic Vehicle States

OFF

Dynamic Component Loads
Dynamic Vehicle States

OFLCP-QS

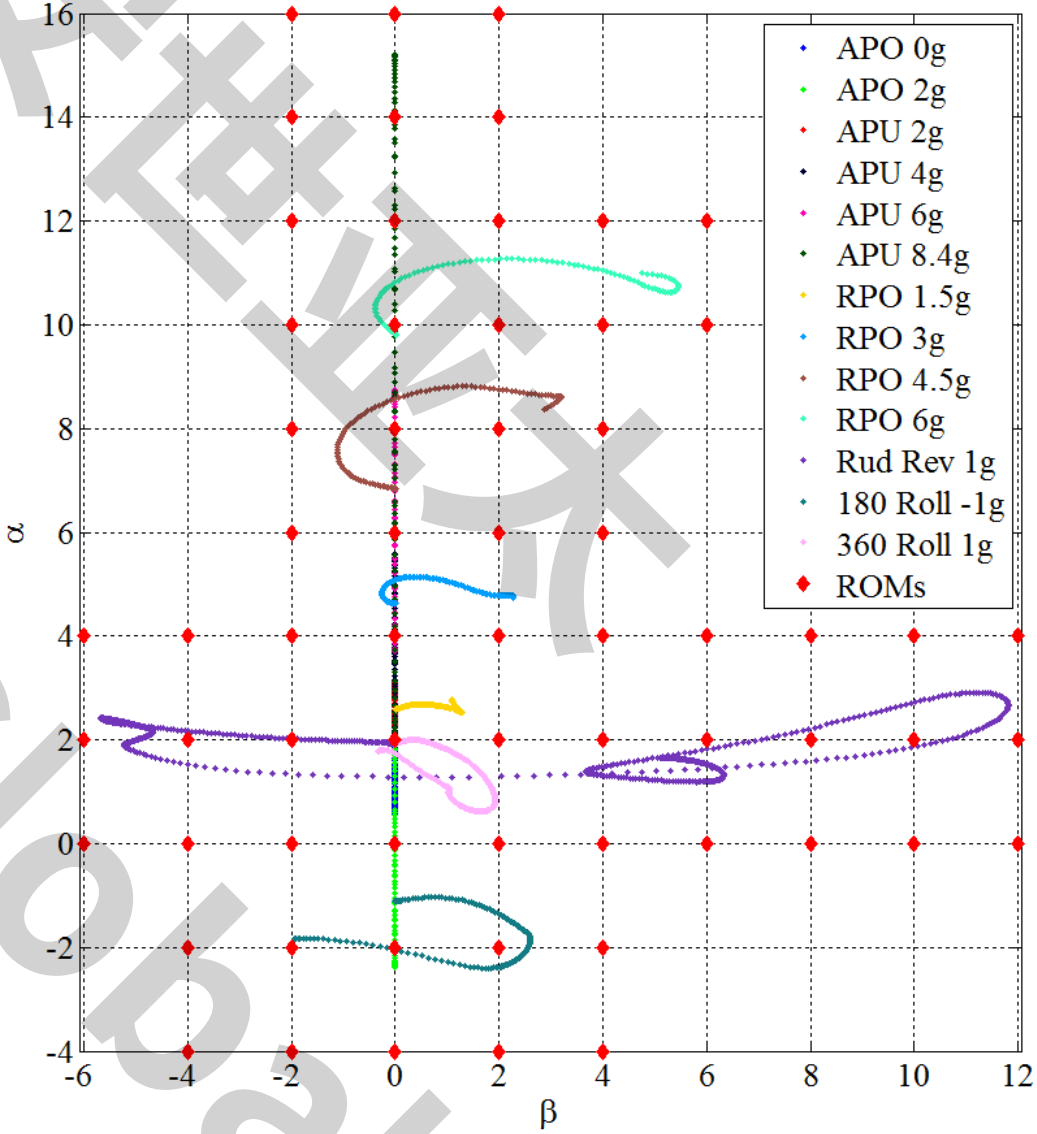
OFLCP+d

Fatigue Data Tracking System

Global FEM Stress Entire AV

ROM Flight Conditions

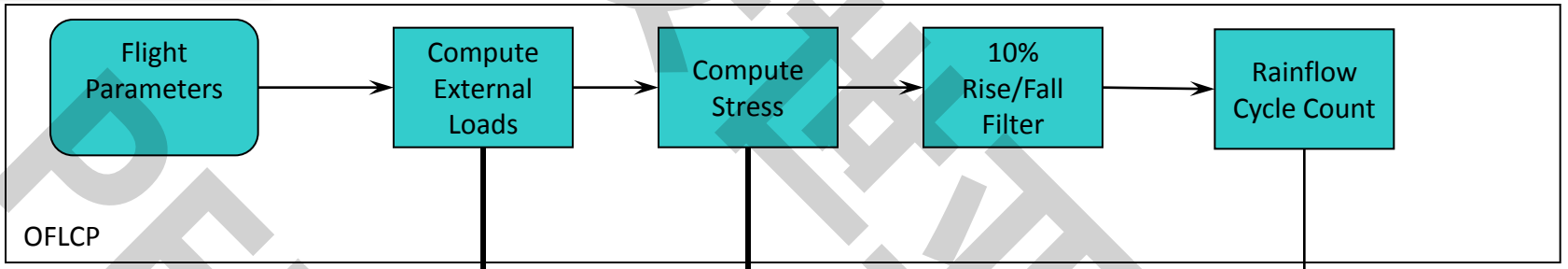
- α/β traces for maneuvers performed in MODSDF at Mach 0.95, 15kft
- Need an aeroelastic ROM at each α/β pair marked by a red diamond
- For APO/APU maneuvers only β=0 ROMs required
- APU 4g maneuver requires α=0, 2, 4, 6 ROMs, for example



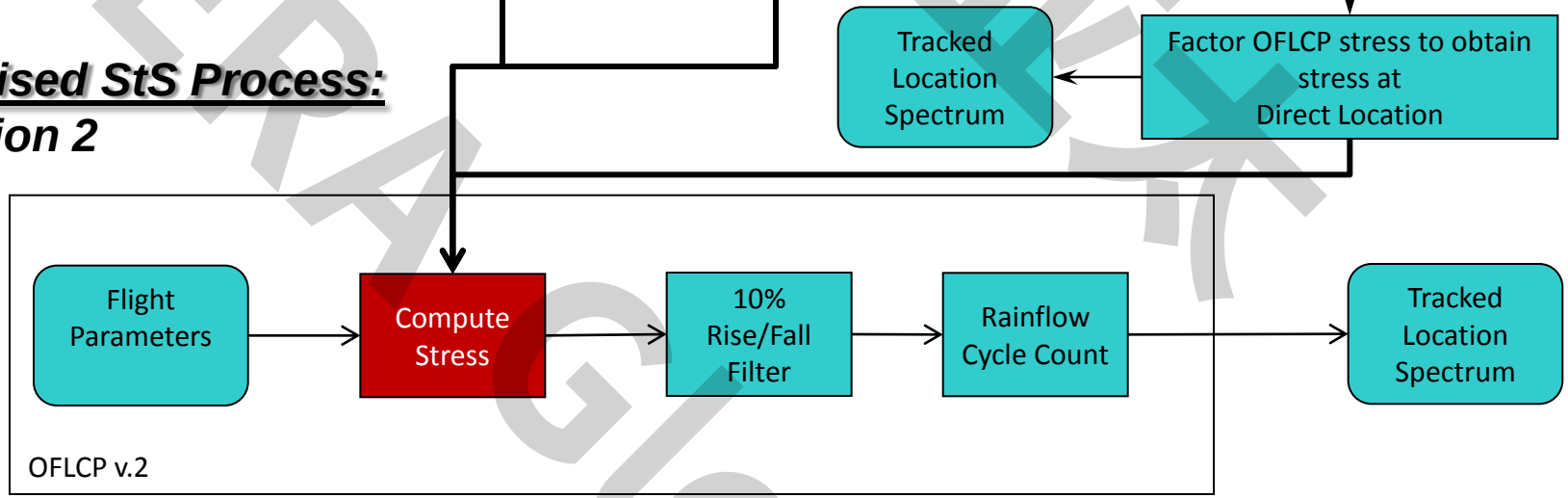
Spectrum Development:

Option 2 – Revise the Process

Current Process:

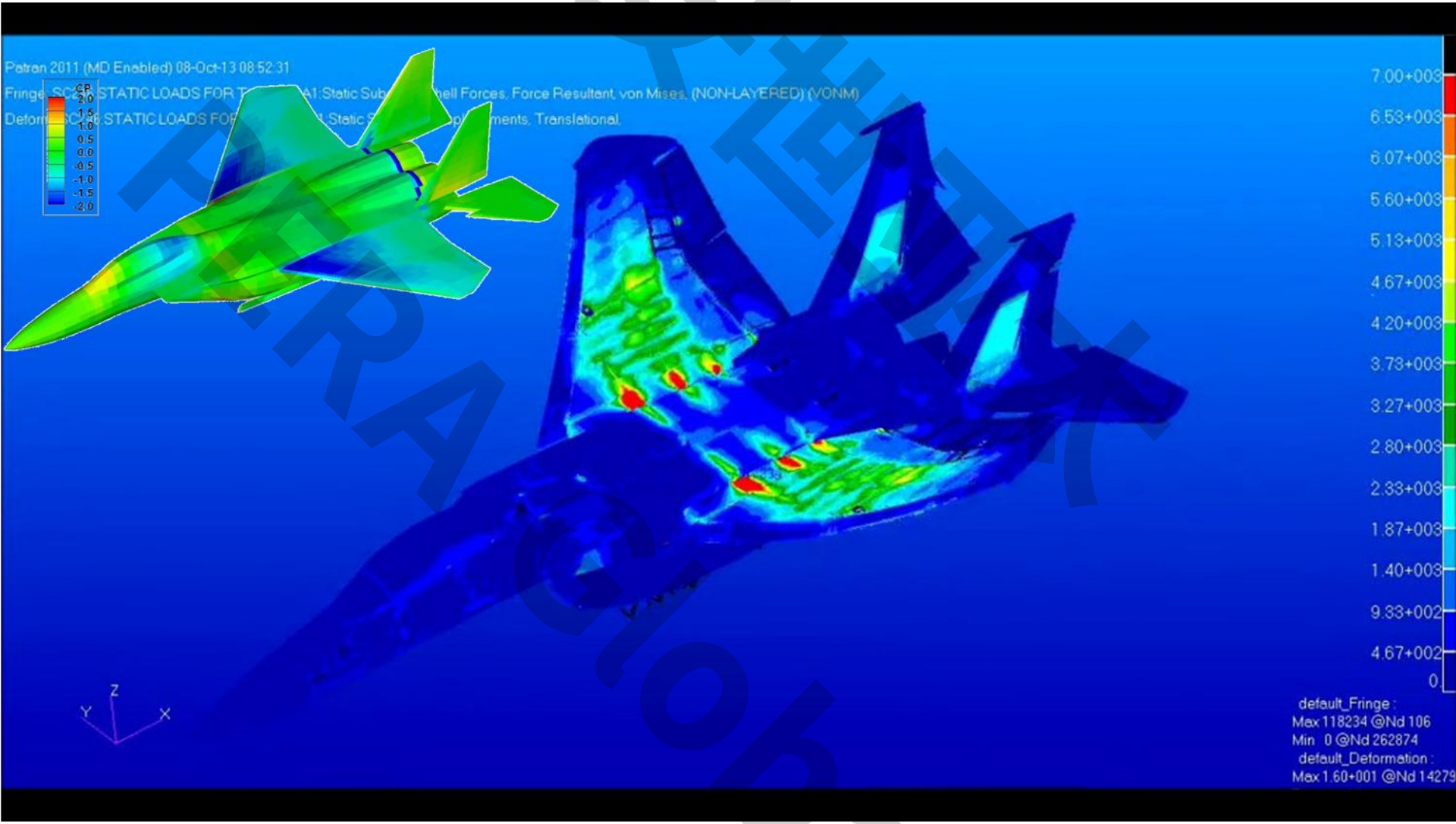


Revised StS Process:
Option 2

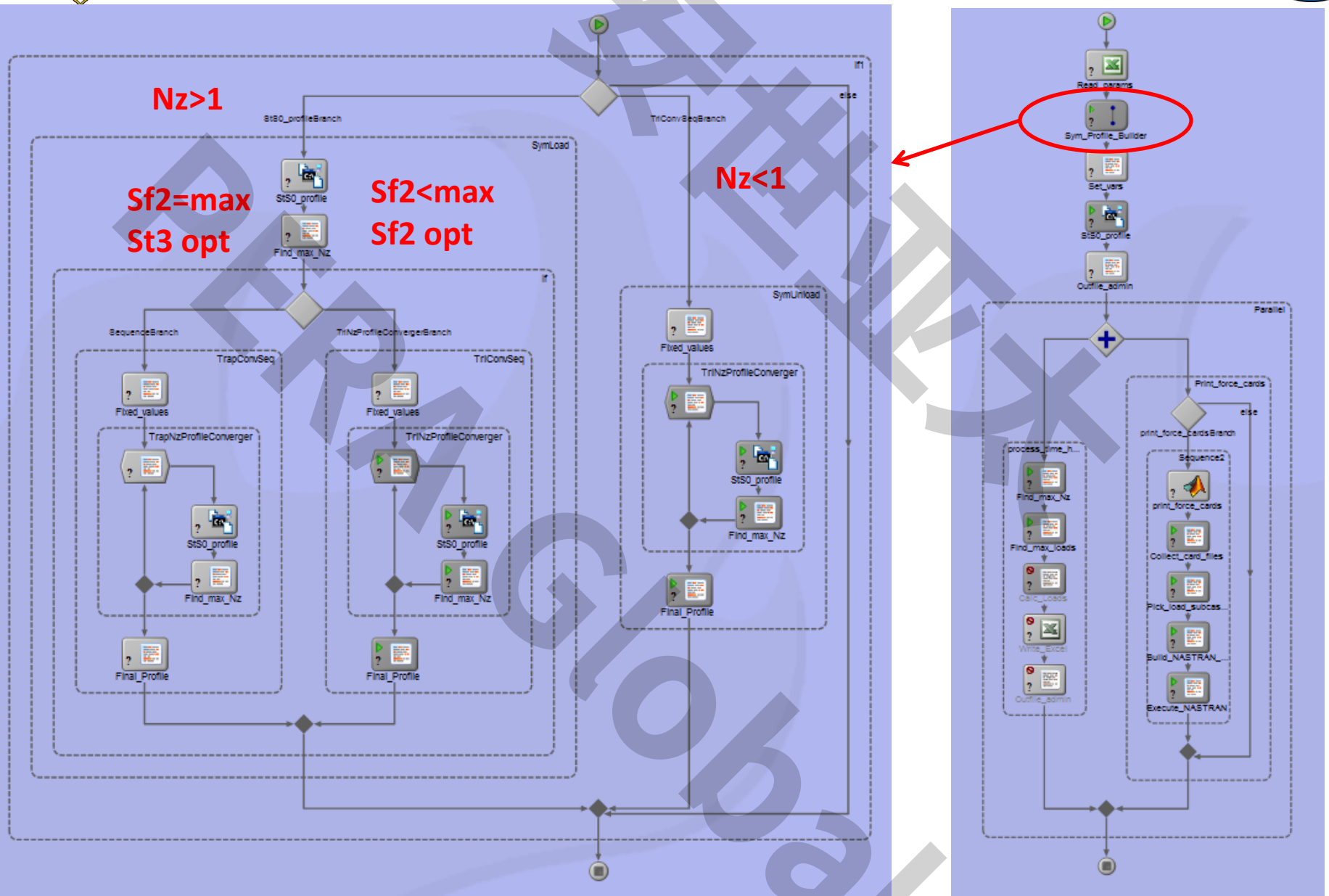


Direct calculation of stress spectrum for any fatigue critical location

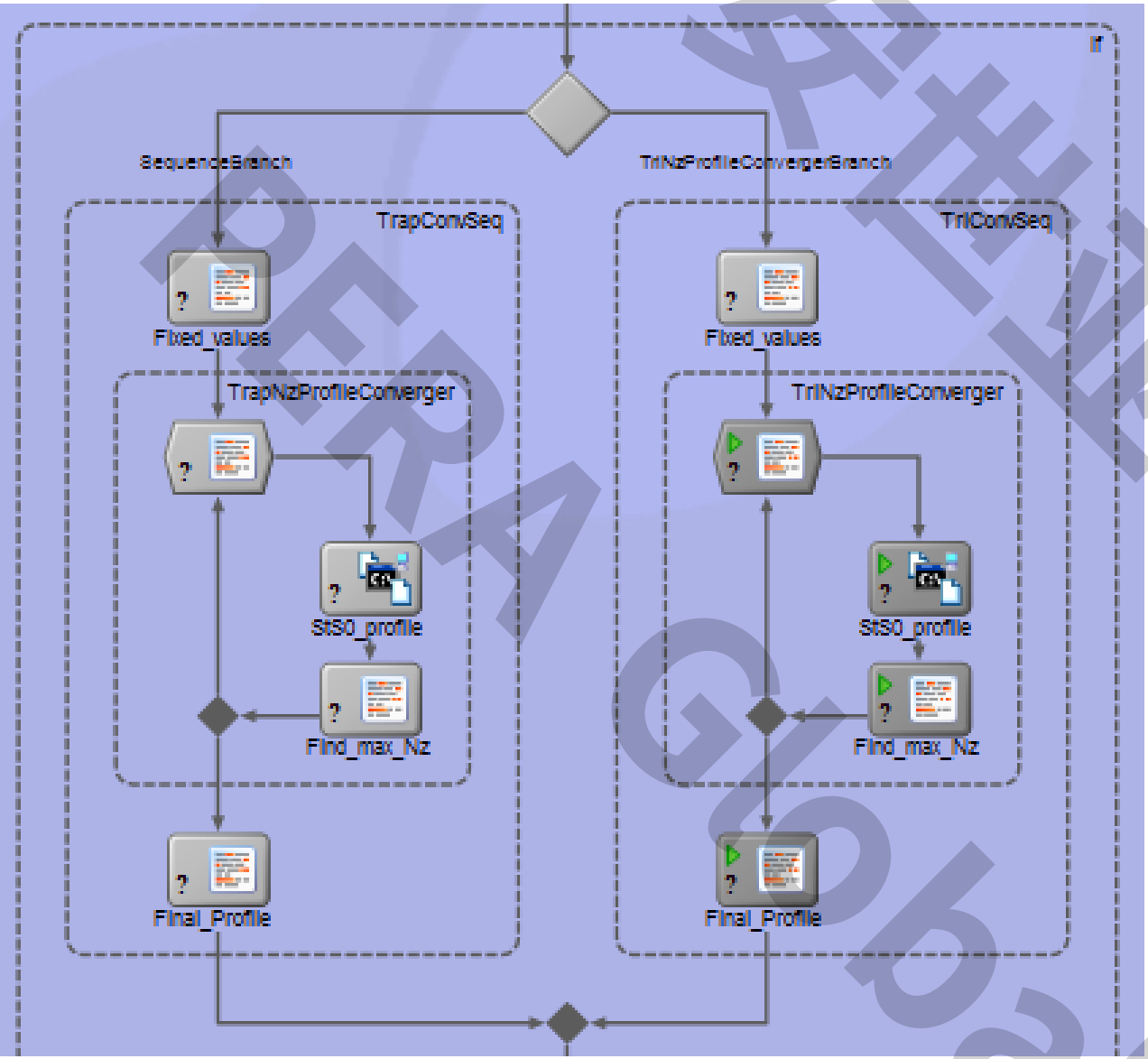
Beyond Component Loads



The Process in Model Center



The Process in Model Center



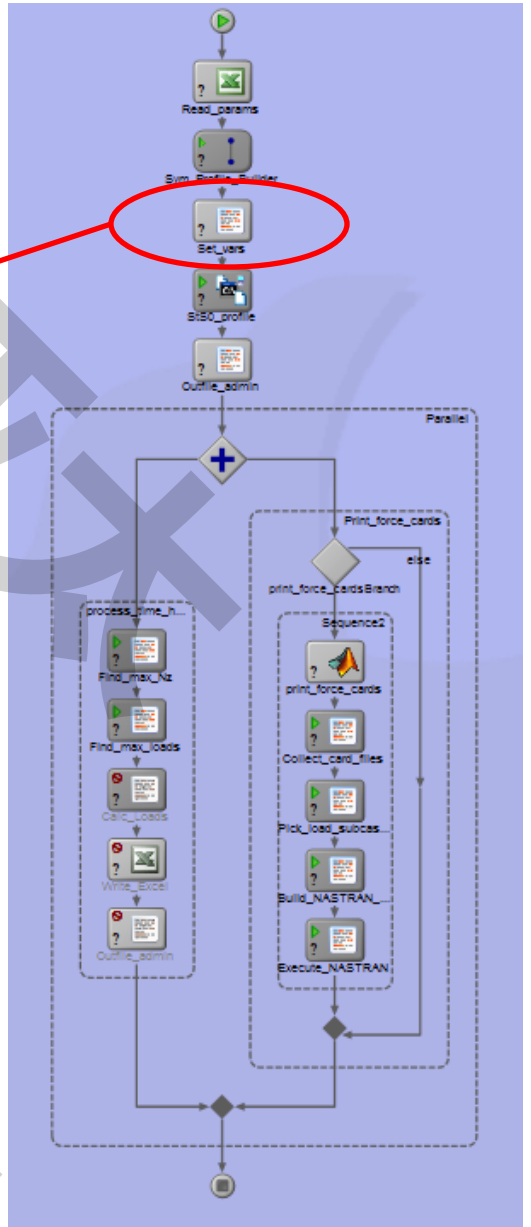
The Process in Model Center

ModelCenter Variables

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

Script

```
1  sub run
2   st3 = st3list(ICFLAG-1)
3   st4 = st3+0.2
4   sf2 = sf2list(ICFLAG-1)
5   sf3 = sf3list(ICFLAG-1)
6   TgtNz = TgtNzlist(ICFLAG-1)
7  end sub
8
```



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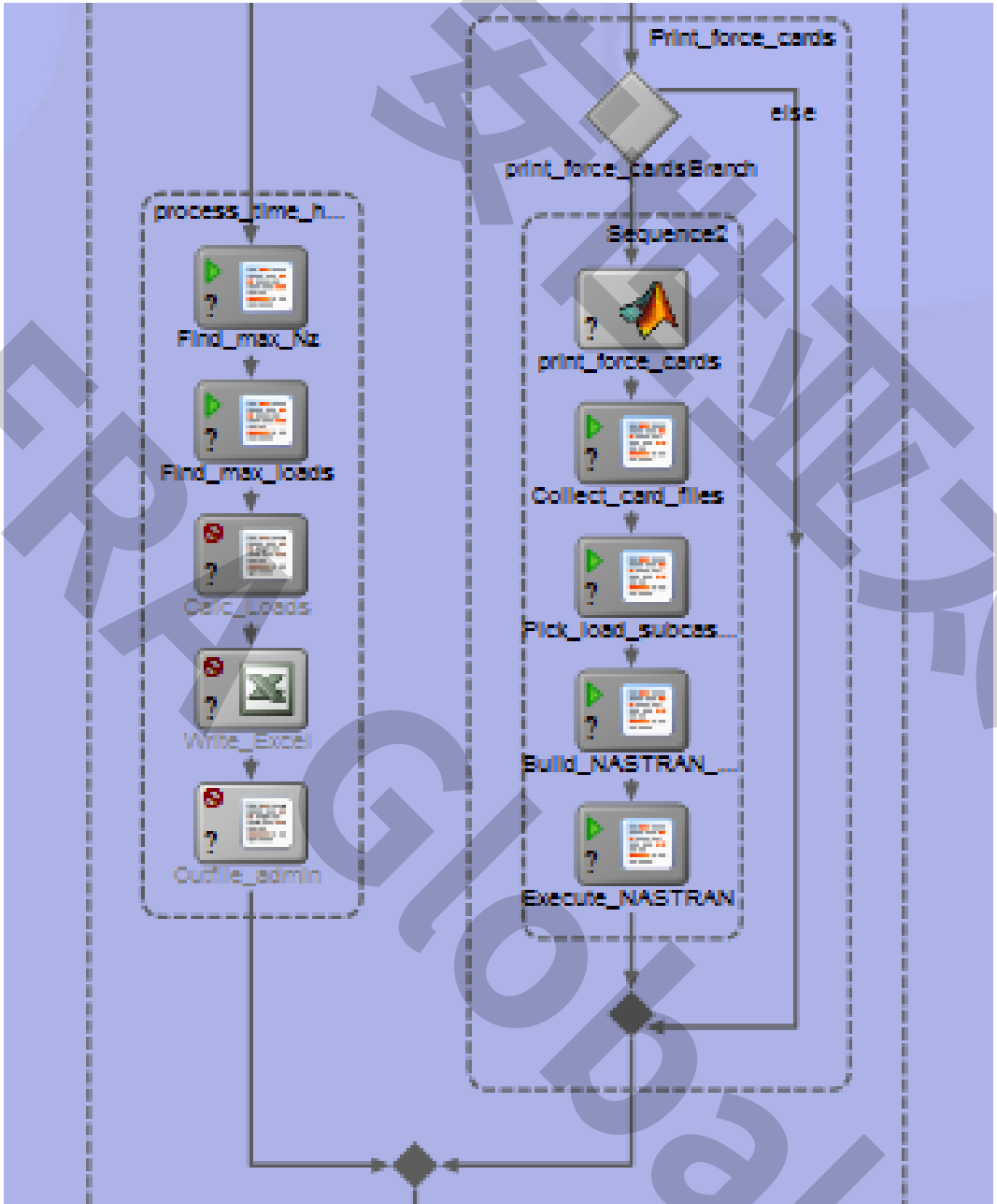

Conclusions

- 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