Internal Loads

Class Objectives

- Identify Internal Loads group functions
- Understand total airplane FEM process
- Apply basic modeling concepts

Internal Loads Group Has a Crucial Role in Airplane Design

Develops integrated Finite Element Model (FEM)

Coordinates between stress group and external loads group

Internal loads data is critical to airplane schedule

Supports Stress group with modeling expertise

Documents internal load results (needed for life of airplane)

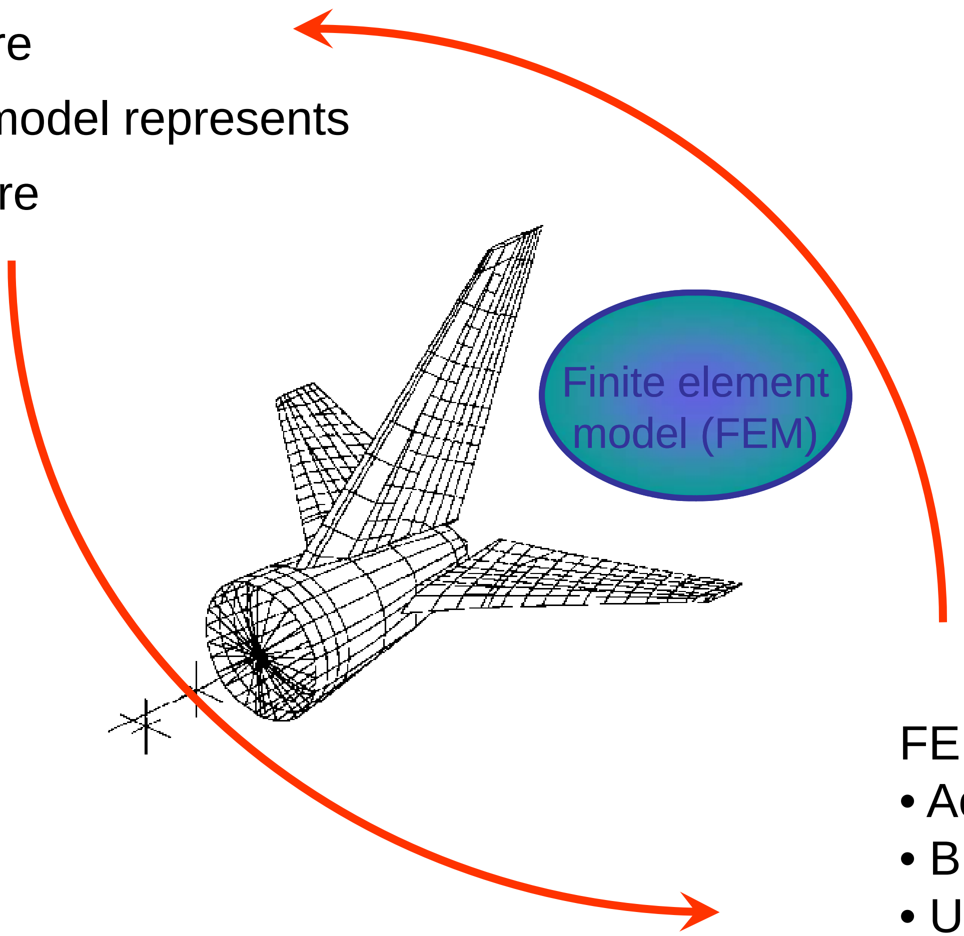
The Internal Loads Group Brings the External Loads Inside

- **Produces internal loads for various stress groups**
- **Generates stiffness data for external loads group**
- **Develops and maintains major finite element models used for internal loads analysis in support of an airplane certification process**
- **Coordinates between external loads and stress groups**

Internal Loads

Structural analyst engineer

- Sizes structure
- Verifies that model represents actual structure



FEM engineer

- Acts as a go-between
- Builds models
- Understands models
- Understands theory

Agenda

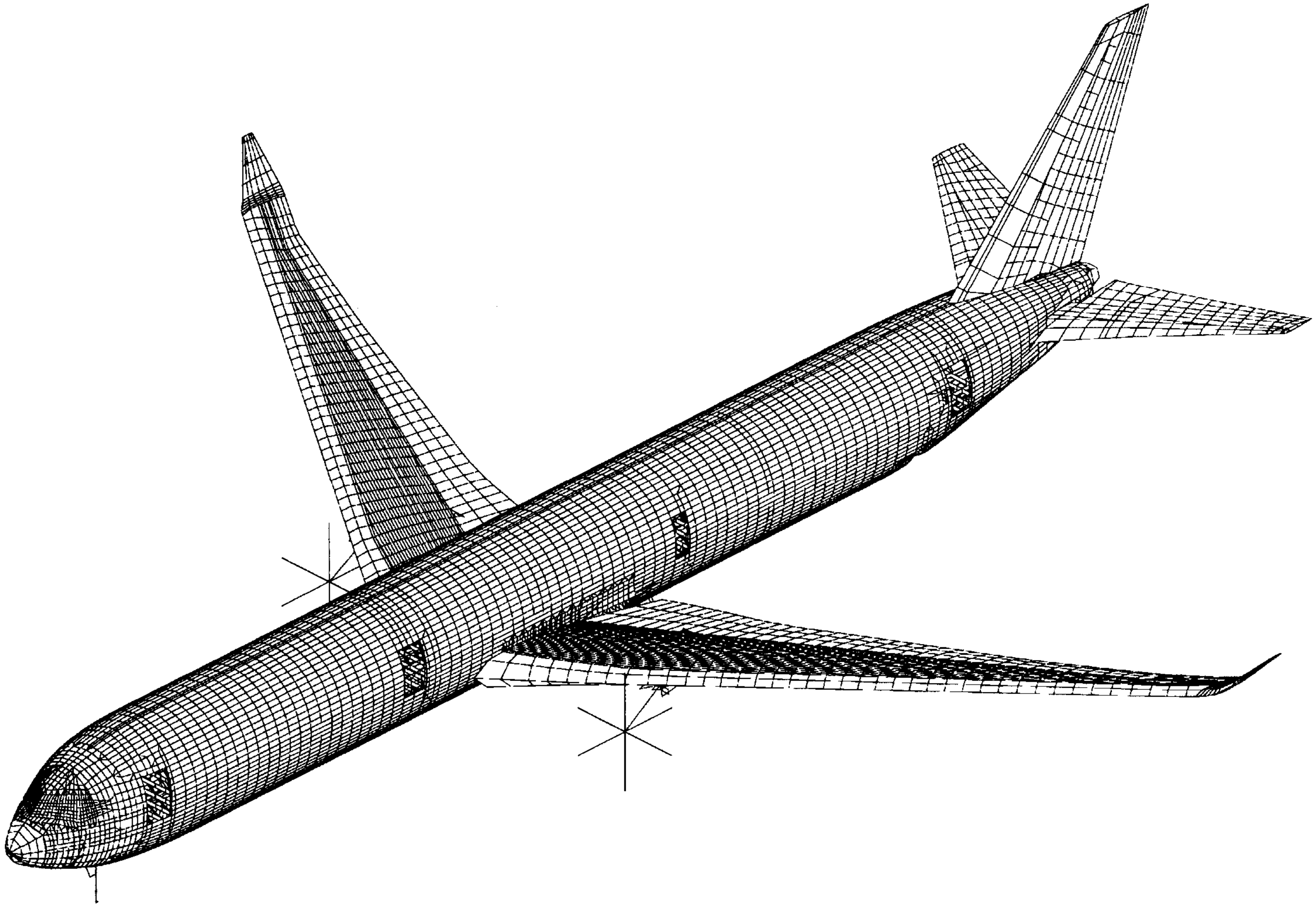
Integrated FEM

Support

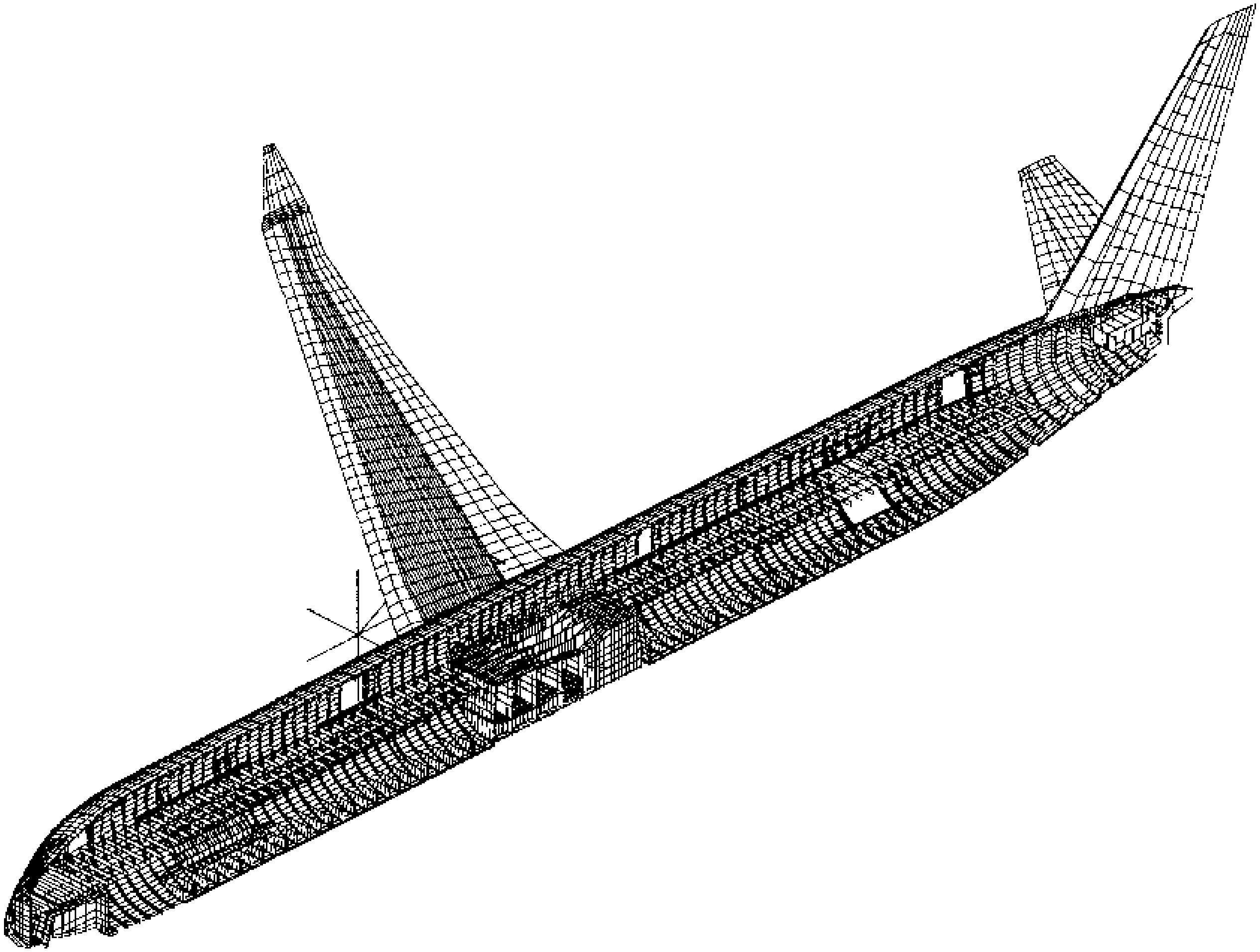
Technical Background

Validation

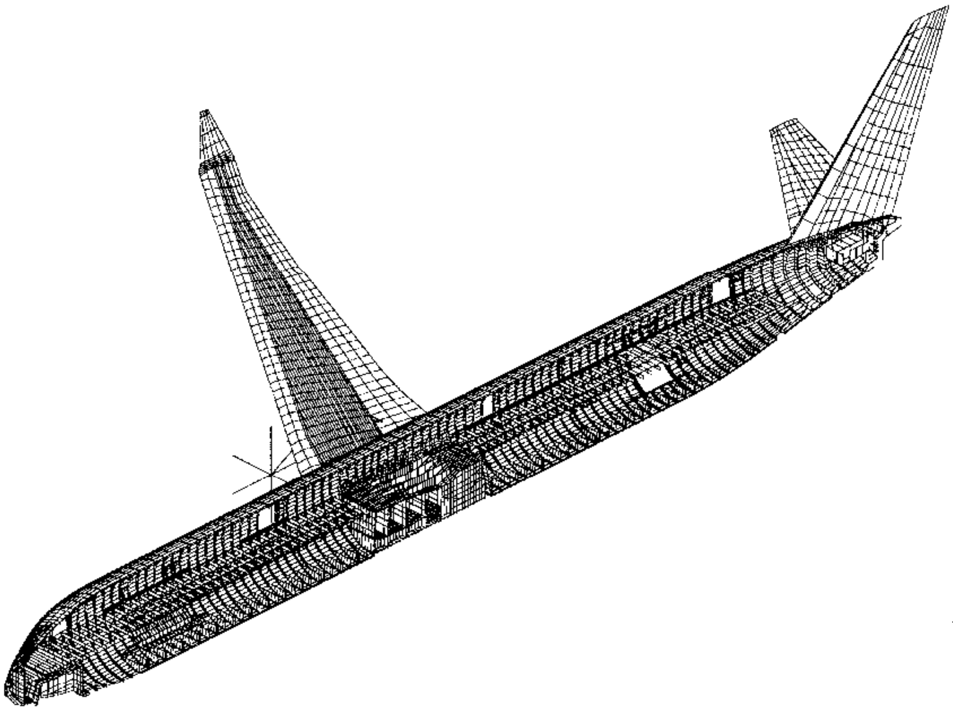
Complete Integrated Finite Element Model (FEM)



Integrated FEM Contains Enough Detail to Accurately Describe the Structural Behavior



Integrated FEM Includes the Major Structural Elements



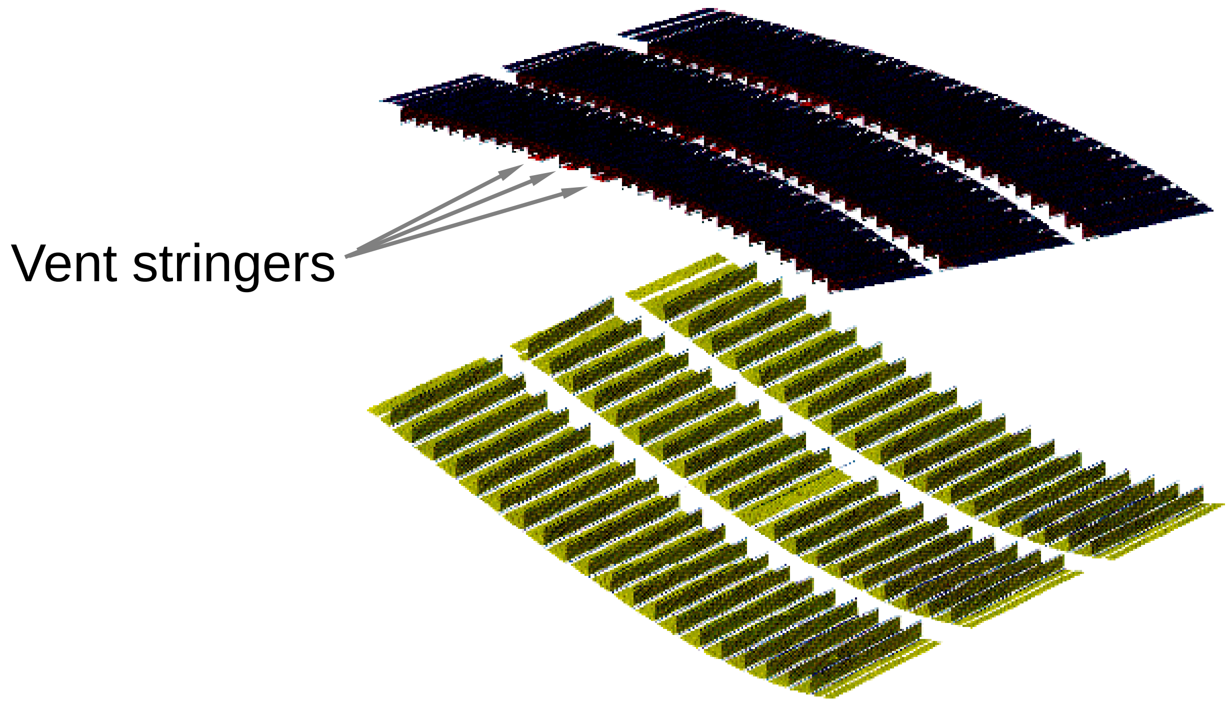
Skins
Stringers
Frames
Ribs
Floor beams
Load-carrying doors
Sills
Bulkheads
Pressure deck
Keel beam
Pickle forks
Wheel wells
Longerons
Window belt
Door cutouts
Seat tracks
***Landing gear**
***Nacelles/struts**

*Not used for stress analysis.

The Integrated FEM Does Not Use Detailed Models For Components

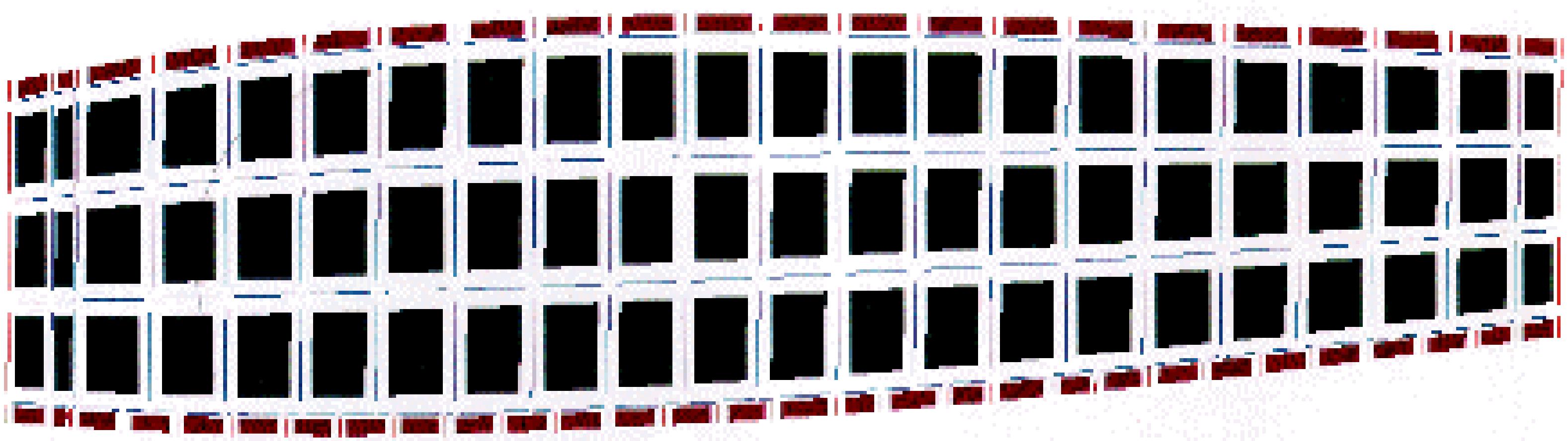
- **Leading and trailing edges of both wing and empennage**
- **Control Surfaces**
- **Plug-type doors**
- **Fairings**

Wing Models Use Simple Concepts

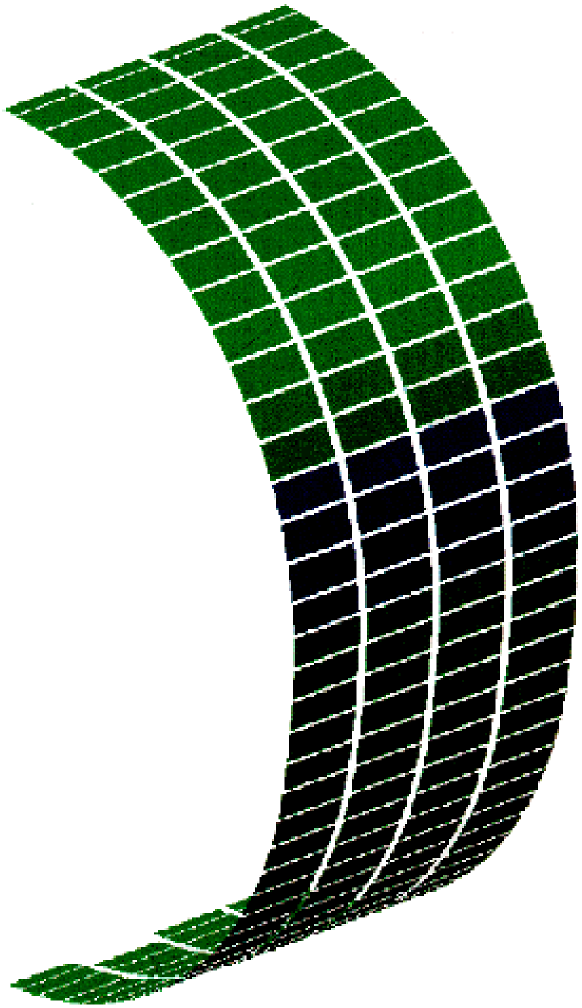


- Skins: modeled with membranes
- Stringers: modeled with bars and shears to create fixed and free flanges

Ribs Are Modeled With Bars and Shears

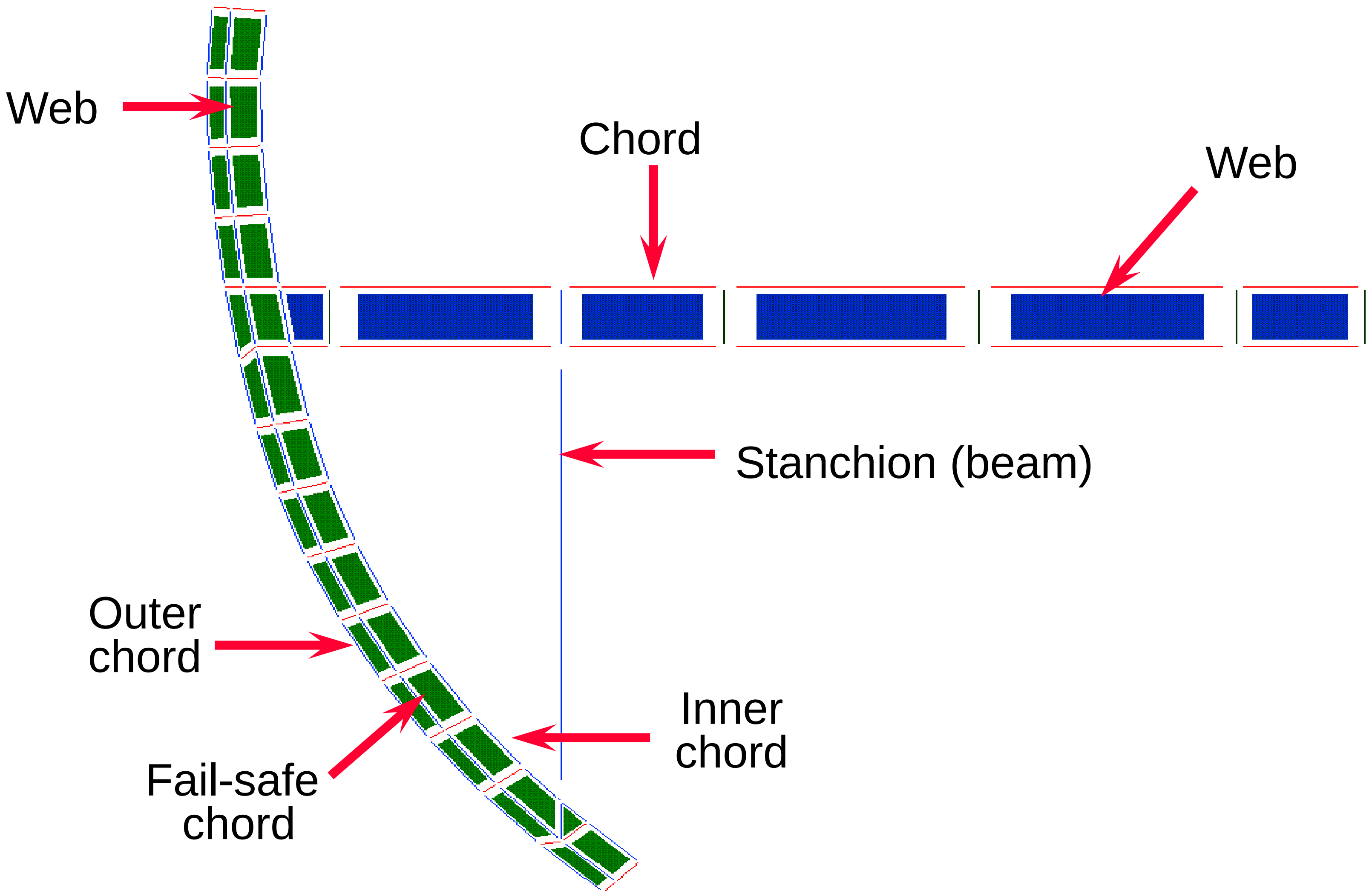


Body Models Have More Variety

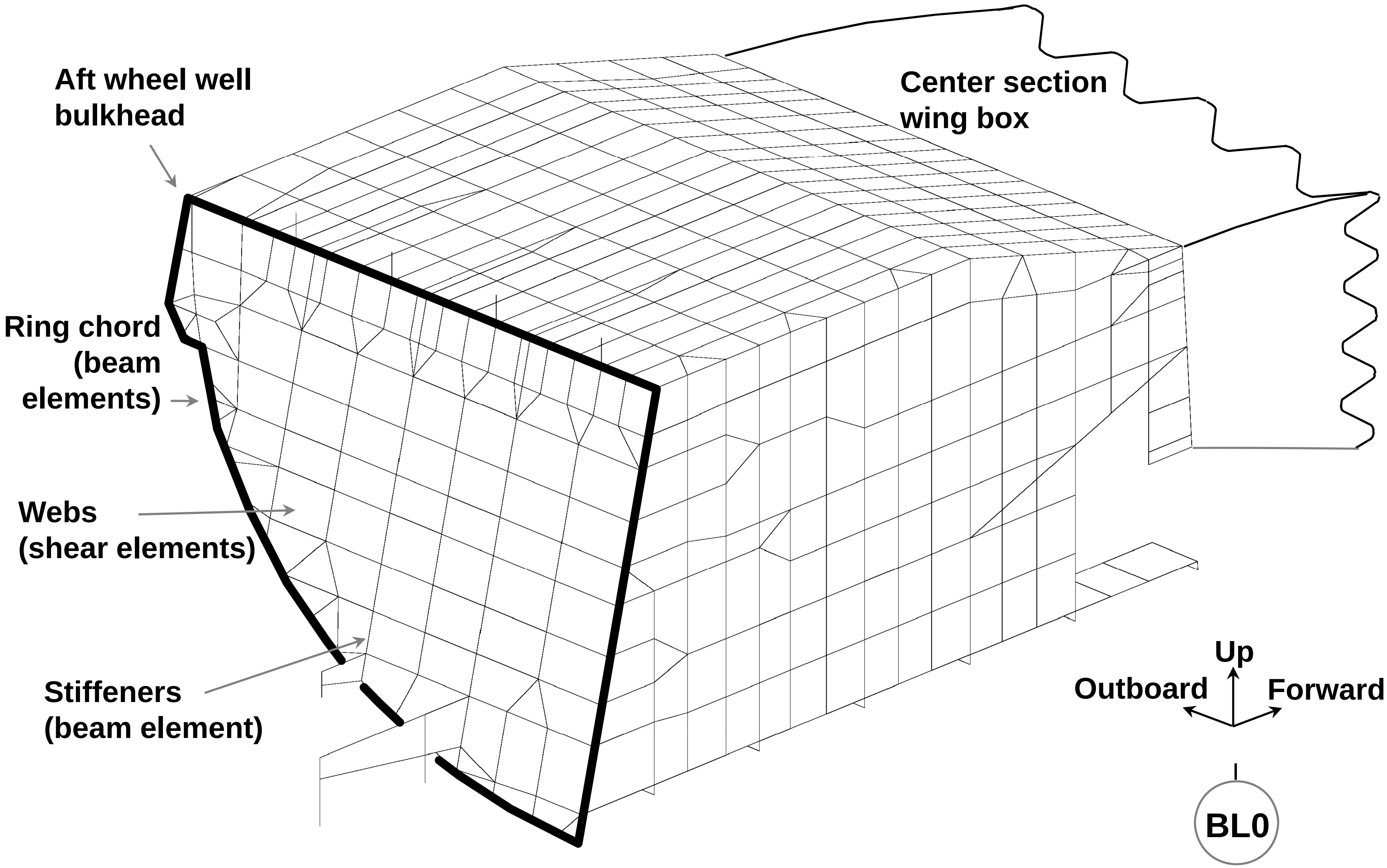


- Skins: modeled with membranes
- Stringers: have bending inertia (beams)
- Window belt is included (anisotropic properties)

Frames and Floor Beams Use Bars and Shears



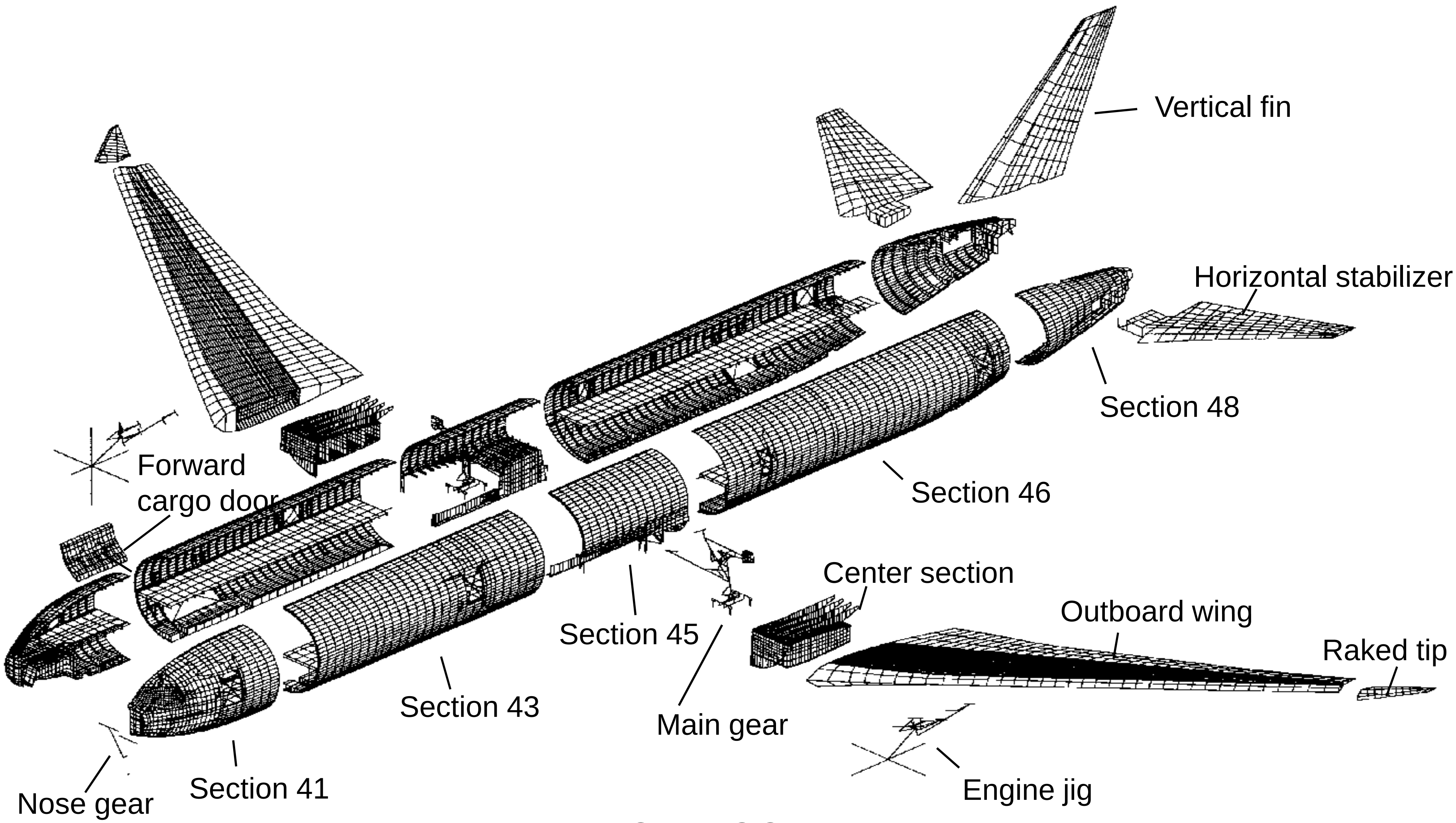
Bulkheads Use Beams and Shears



FEM Sizing Comes From a Variety of Sources

- **Wing and section 41 groups provide complete sized models.**
- **Some models are converted from other codes (e.g., landing gear: ATLAS)**
- **Most body sizing comes from stress group's Oracle database "APARD" (Analysis PARameter Database).**
- **Other body sizing comes on paper or in Excel (e.g., floor beams, keel beam, door sills).**

The Integrated FEM IS a Collection of Several Individual Models



767-400ER

The Model Is Subject to Many Types of Load Conditions

Ultimate and fatigue: Loads due to flight maneuver, gusts, ground maneuver, and landing

Floor/frame: loads due to such items as seats, lavs, galleys, and cargo.

Pressure: loads due to cabin pressure and sudden decompression (13.65 psi internal cabin pressure is added to all flight cases).

Miscellaneous: loads due to such conditions as tire burst or center section fuel slosh.

Each FEM Scenario Causes the Engineer's Workload to Multiply

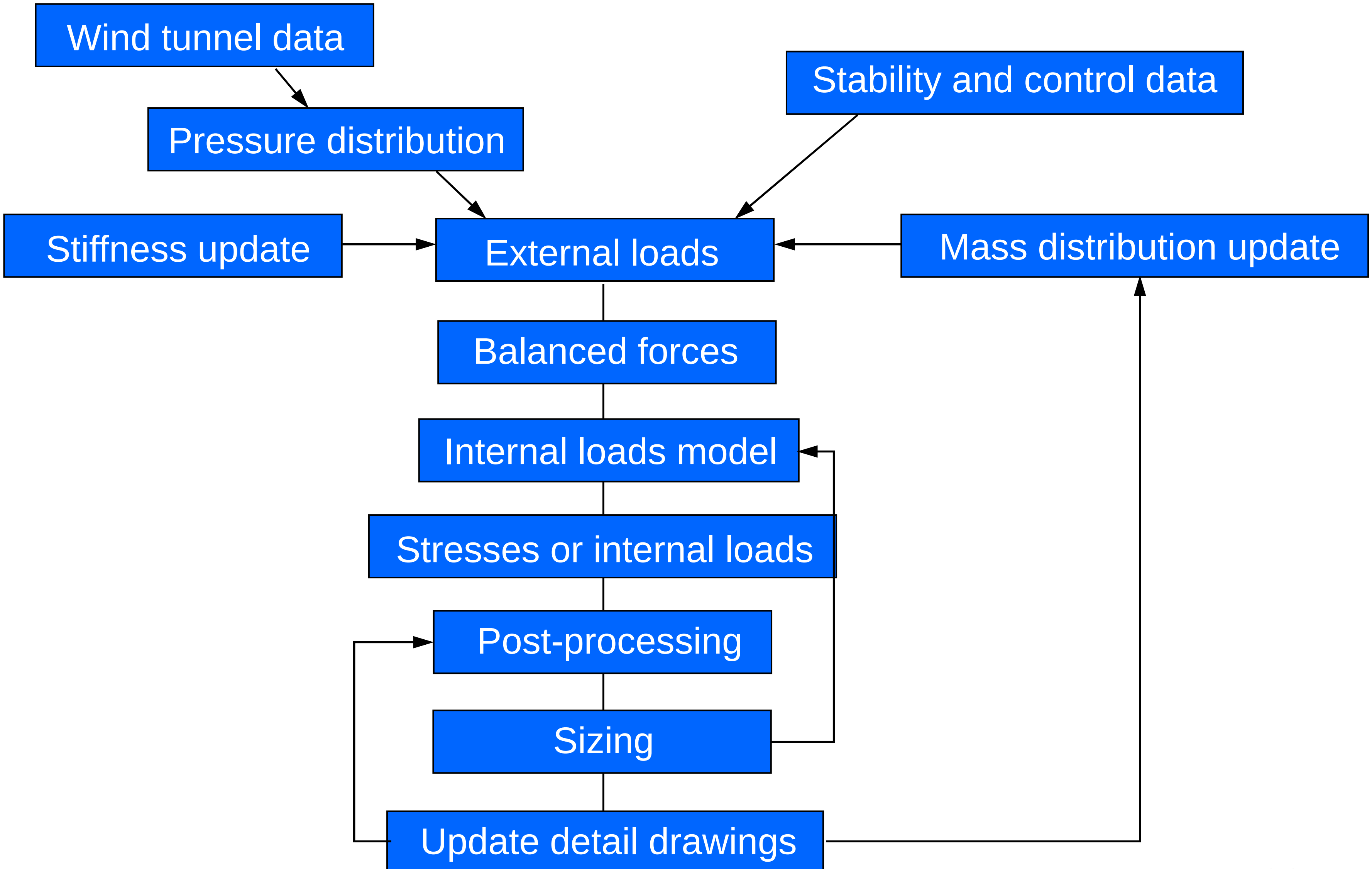
- **Load-carrying doors (door-in and door-out)**
- **Main landing gear (up and down)**
- **Fail-safe conditions (limit load)**
- **Discrete-source damage conditions (70% of limit load)**

Results From the Model Are Used in Several Ways

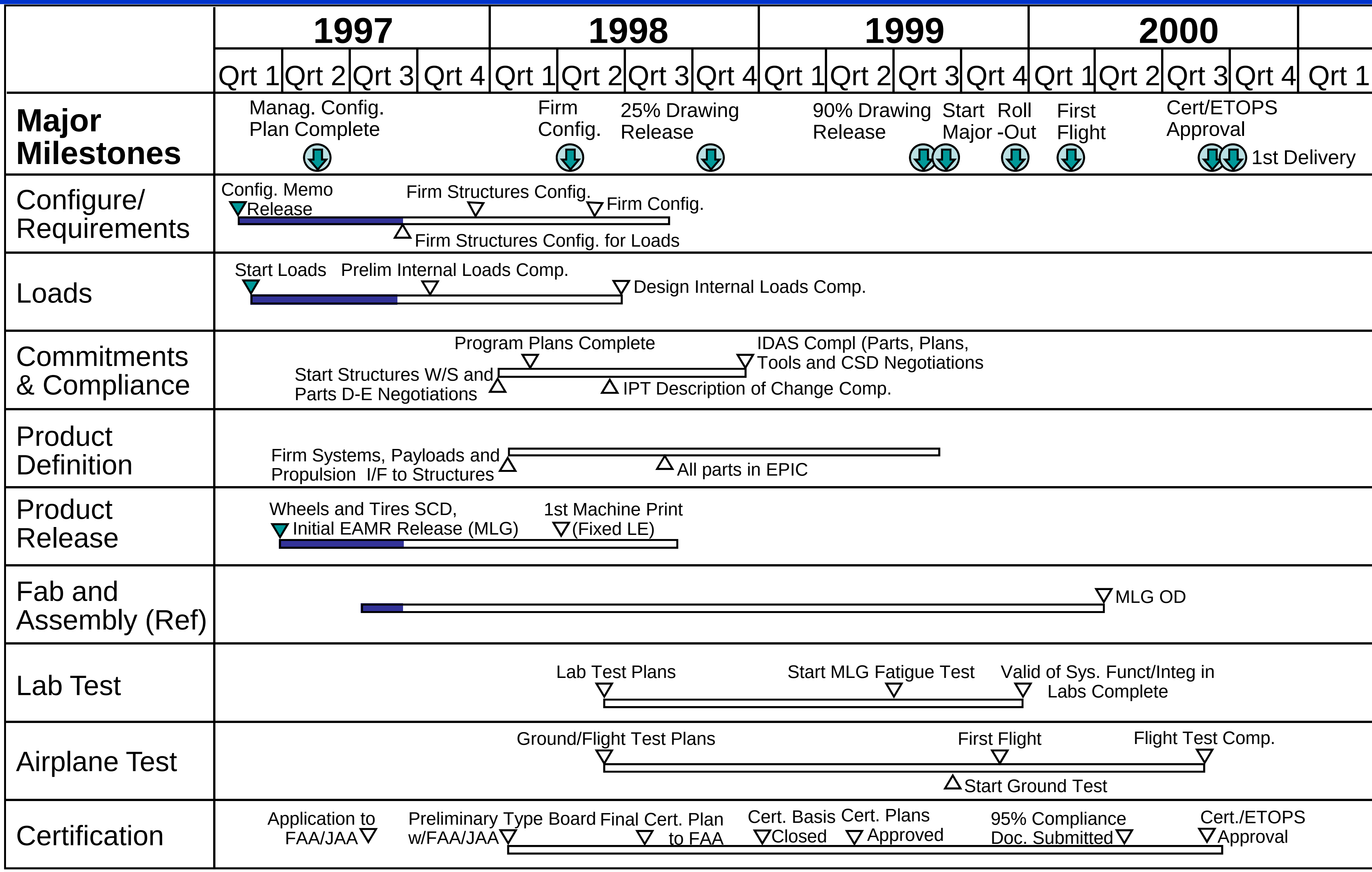
Structures workstation

- **Stresses and internal loads are post-processed to calculate margins of safety**
- **Deflections are provided to the control surface groups (e.g., flaps) and systems groups**
- **Stiffnesses (EI/GJ) provided to loads and flutter groups**
- **Super-elements (reduced stiffness and loads) given to stress groups to iterate the component FEM's**
- **Deflections are sometimes provided to solve manufacturing problems**

The Integrated FEM Plays a Key Role in the Overall Design Process



Internal Load Schedule is Critical and Highly Visible



Why Use the Integrated FEM?

Pros

- **Serves as a means of uniting disparate groups**
- **Consistency of idealization and analysis**
- **Preserves lessons learned from previous programs**
- **Easier to find errors (debug)**
- **Better interface loads**

Cons

- **Stress group is somewhat dependent on FEM results**
- **Requires coordination**
- **Idealization disagreements**
- **Culture clashes**
  - 767 versus 777
  - SAMECS versus ELFINI

Use of the Finite Element Method Is Diverse

- **Typical applications**
- **Structural modeling (static, dynamic, and weight analysis)**
- **Preliminary-design airframe stress**
- **Airplane wing/body junction**
- **Detailed internal loads**
- **Crack growth and residual strength**
- **Nonlinear geometry**
- **Propulsion/structures integration**
- **Structure/acoustic interaction**
- **Bird/blade impact**
- **Controlled airplane crash**

Guidelines for Modeling

- **Use simple elements.**
- **Use simple modeling concepts.**
- **Keep the model size small.**
- **Spend time to verify/validate/check out the model.**

Integrated FEM Summary

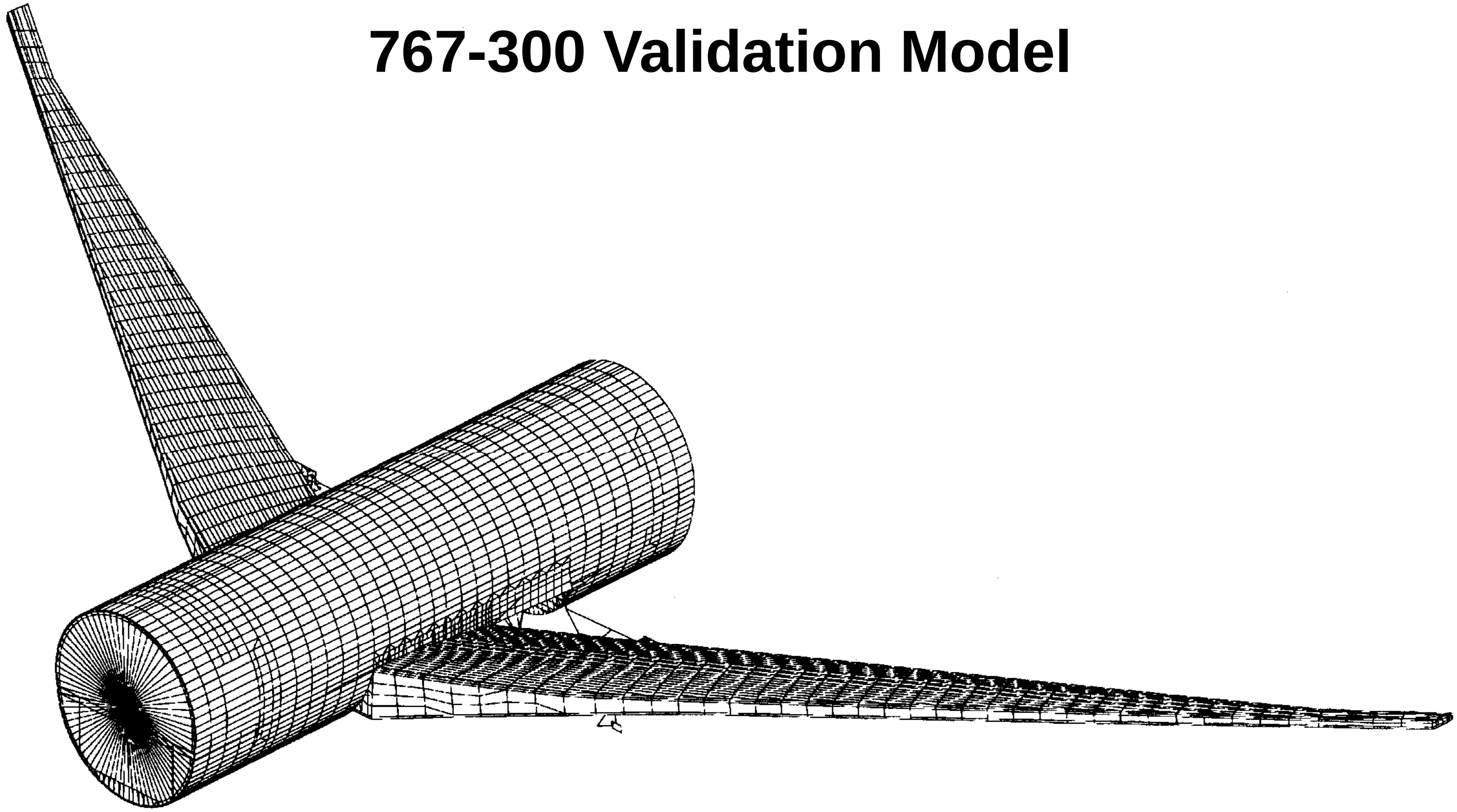
- **A collection of separate models (similar in detail and idealization)**
- **Contains the major structural details**
- **A cooperative effort (internal loads, external loads, and stress groups)**
- **Subject to many demands**
  - Many load cases
  - Many scenarios
  - Many groups use the results
- **Critical item in the program schedule**

Agenda

- Integrated FEM
  - **Support**
    - Technical Background
      - Validation

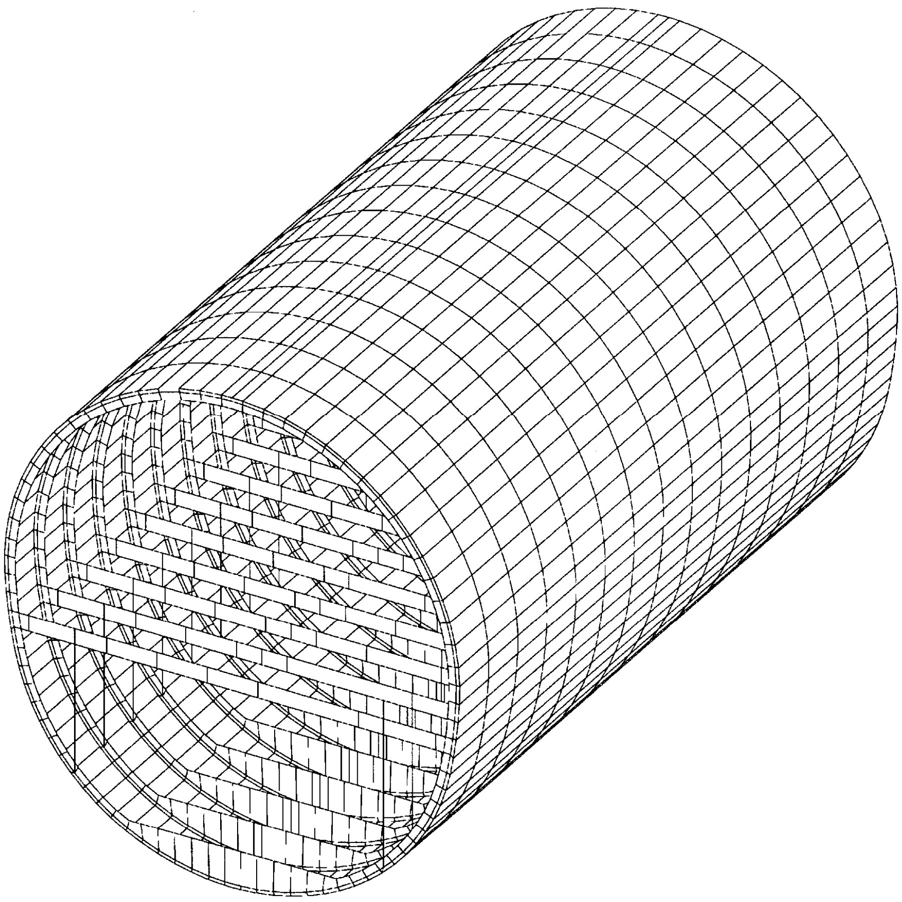
Study Models are Built to Support Stress Groups

767-300 Validation Model

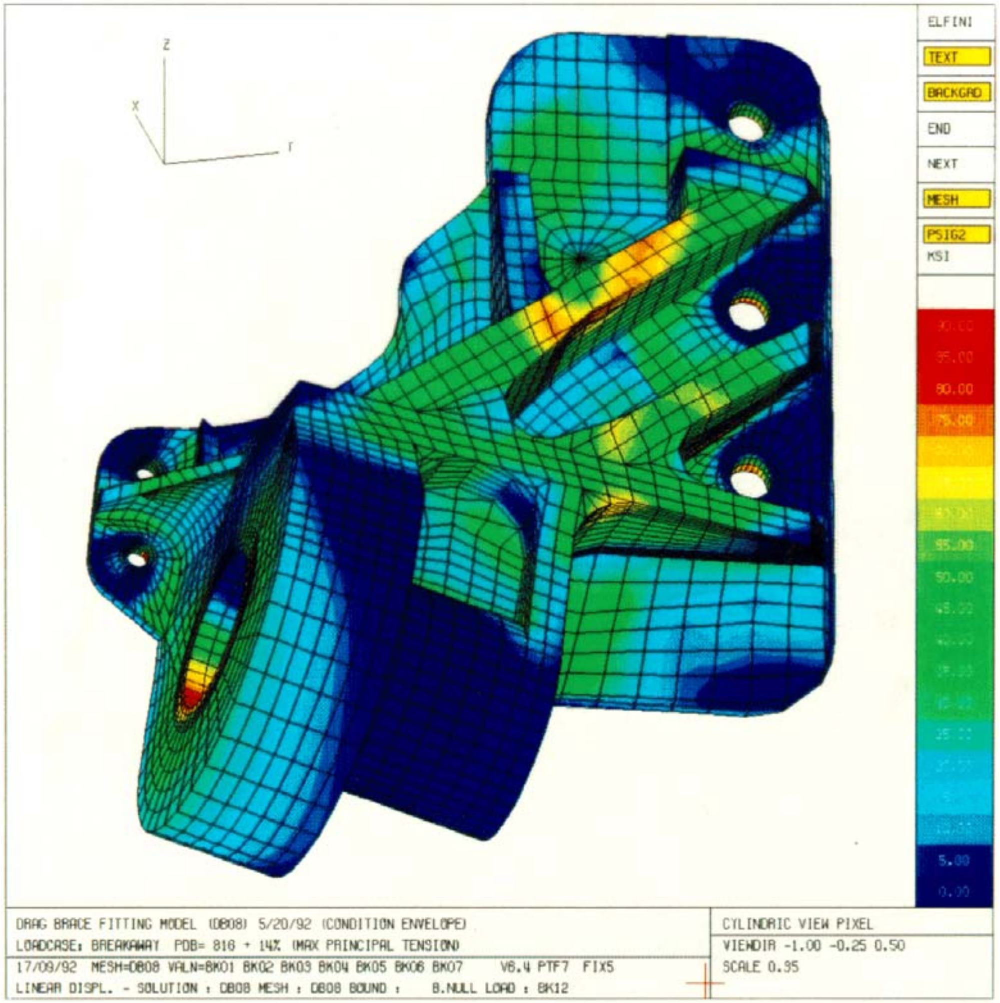


Study Models Are Built to Support Stress Groups

767-400ER Frame Idealization Study Model

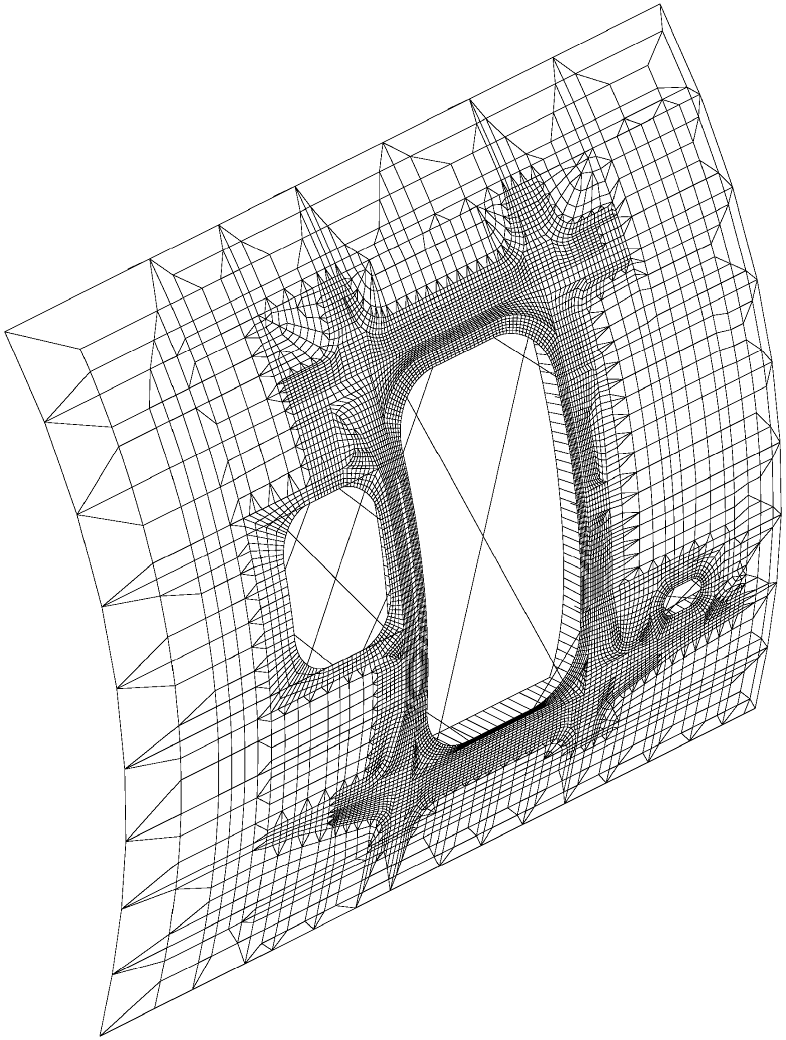


Internal Loads Group Builds Detailed Stress Models for Analysis and Verification



777 Drag Brace Fitting

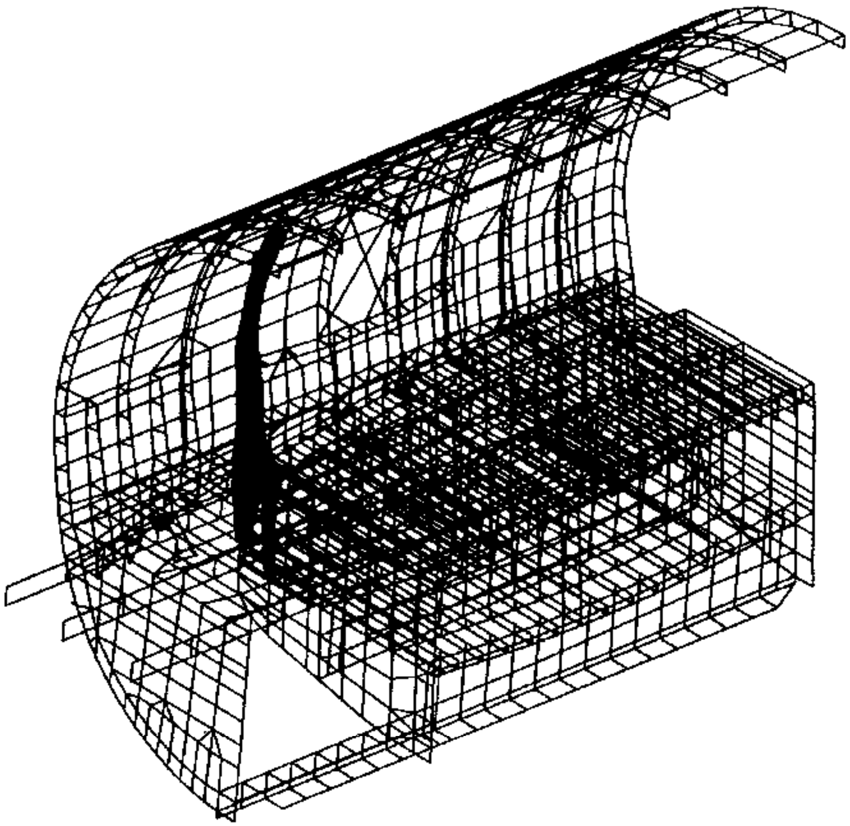
737-X Overwing Escape Hatch Cutout



Stress group worried about fatigue interactions between corners of the three cutouts

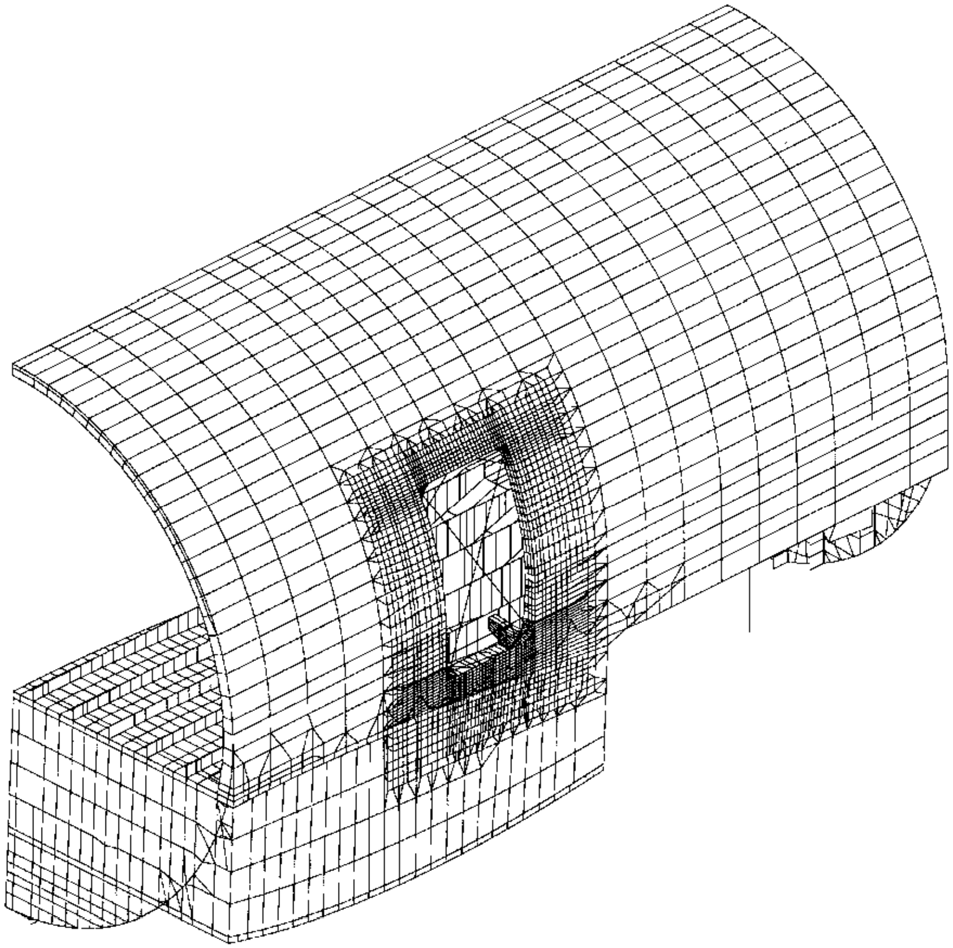
Total weight savings of 10 lb
per airplane

737NG Rear Spar Pickle Fork



Model used to analyze bolt loads

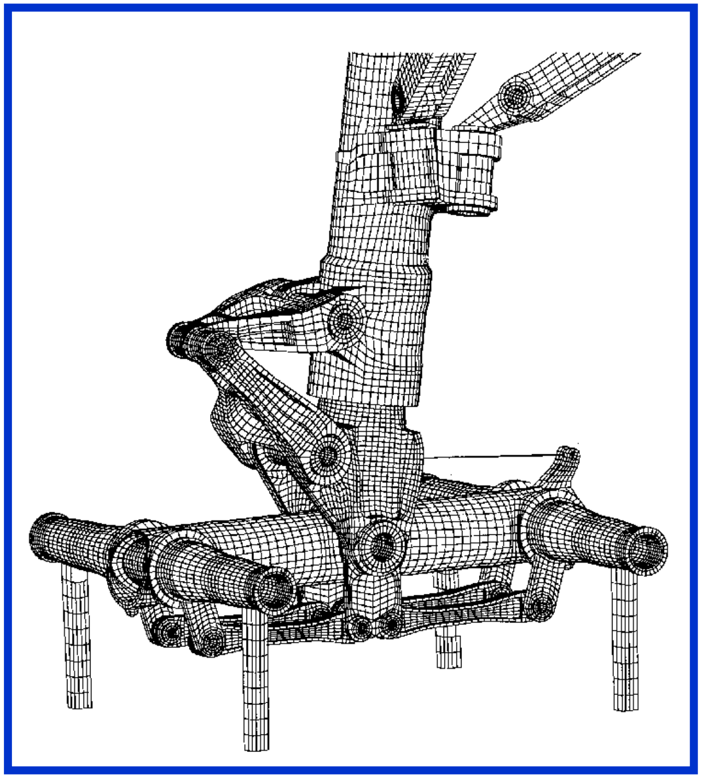
Internal Loads Group Builds "Hybrid" Models



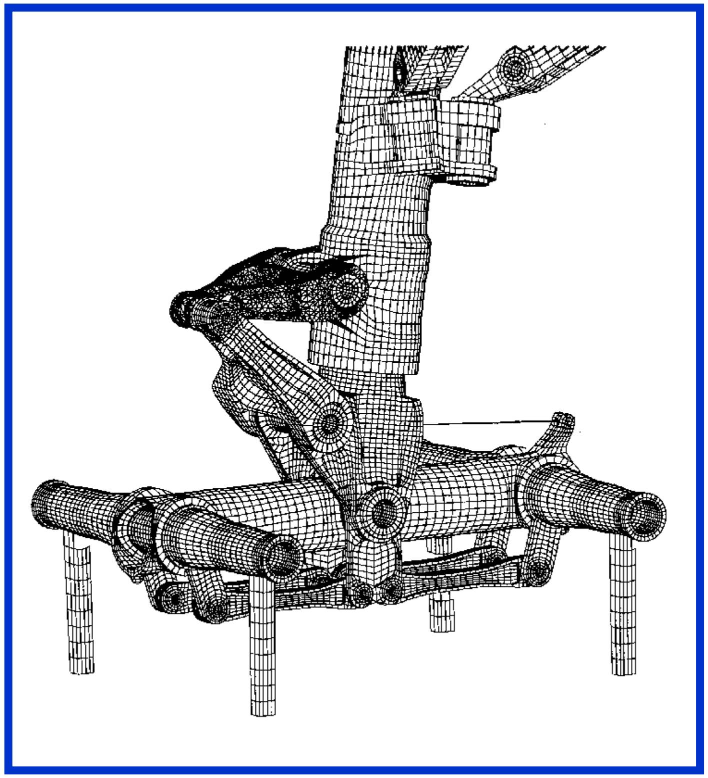
777-300 Overwing Door

- **Goal was to find optimum contour for corners of door cutout**
- **Optimizer was used to minimize weight**
- **Skins are 1-inch thick in this area**

Internal Loads Group Loaned Engineers to Stress Group for 767-400ER Main Landing Gear Analysis



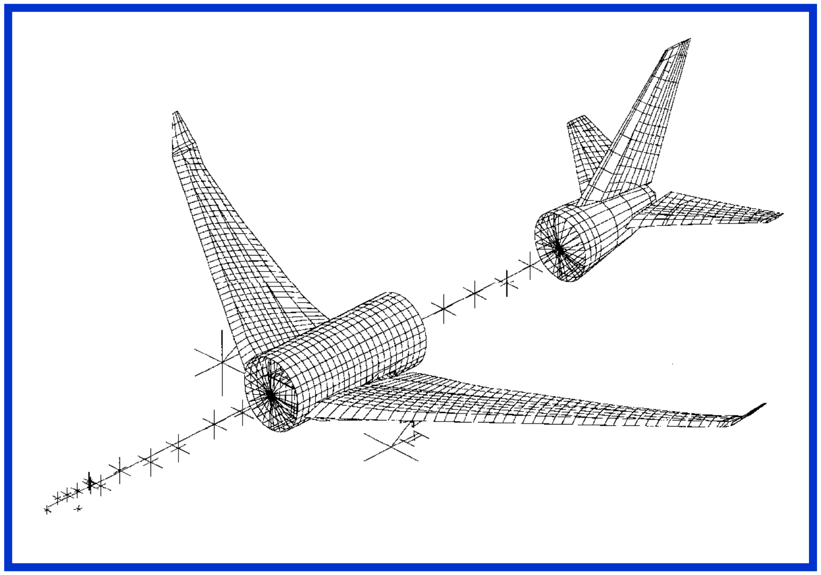
Coarse model



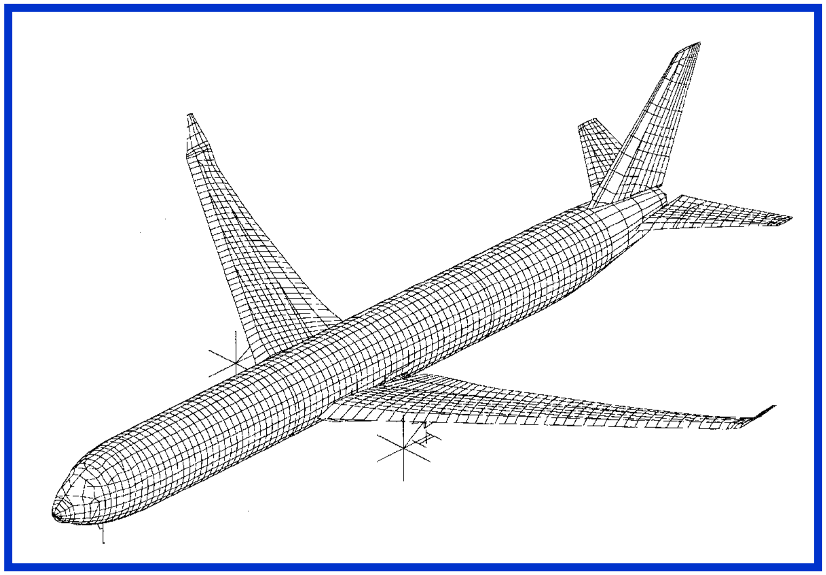
Coarse model with fine-meshed upper torque link

Internal Loads Group Supports External Loads and Flutter Groups

- **Creates finite element models**
- **Provides stiffness data**



767-400ER flutter FEM



767-400ER external loads FEM

Support Summary

- Internal loads builds detailed stress models for analysis and verification.
- Hybrid models are built to be more detailed than the regular internal loads model.
- Study models investigate software or idealization changes.
- Internal loads engineers are sometimes loaned to other groups to assist with modeling efforts.
- Internal loads group supports flutter and external loads with FEM data.

Agenda

- Integrated FEM
- Support
- **Technical Background**
- Validation

Textbook Definition: What Are Internal Loads?

Forces and Moments Carried by the Structure of the Aircraft

Examples

- **Axial force in a fuselage stringer**
- **Shear flow in a bulkhead**
- **Hoop load in a fuselage skin panel**
- **Segment load (skin plus stringer) in a wing**

Simple, Easily Understandable Elements, and Properties Are Used

Internal Loads Model	Solid Models
• Spring • Bar • Beam • Shear* • Membrane* • Bending Plate*	• 10-noded tetrahedron • 8-noded brick • 20-noded brick

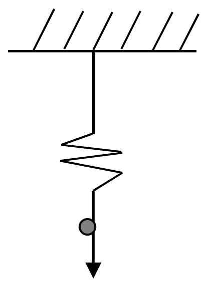
* Properties for shear/membrane/bending elements

Isotropic	Composite	Honeycomb	Sandwich

More common ⟷ Less Common

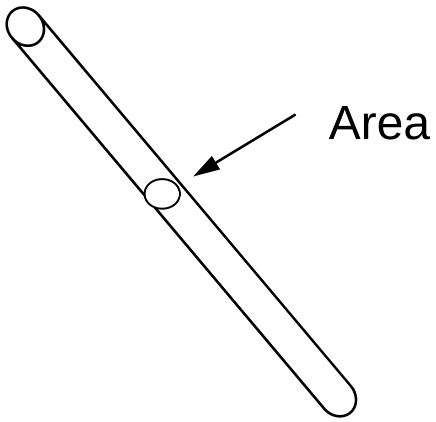
Springs

$F = K\,x$



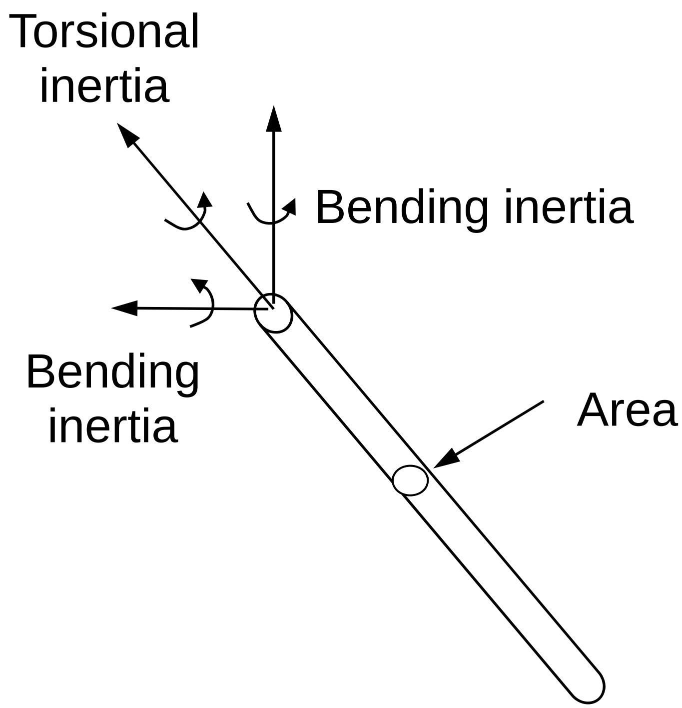
- **Easy to understand**
- **Control direction of load**
- **Allow for easy, quick check of load path**
- **Used to attach pieces of major structure in the FEM**
- **For very stiff elements set K= ∞**
- **Use 3 translational and 3 rotational stiffnesses at each node**

Bars



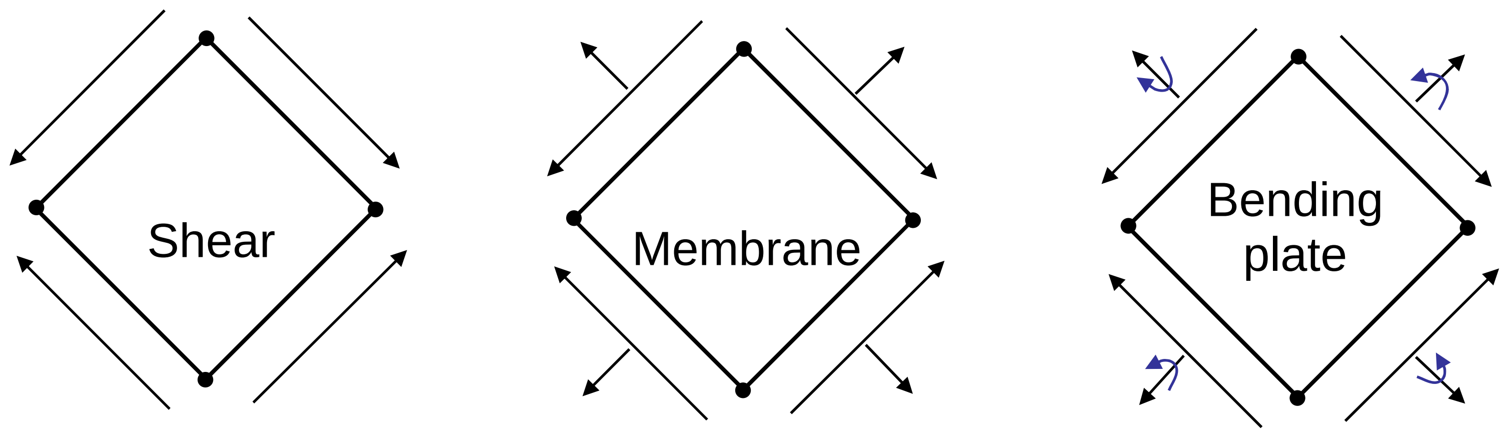
- **Easy to understand**
- **Allow for quick check of load path**
- **Used for modeling of**
  - Fuselage stringers
  - Built-up structure ("chord-web-chord")
- **The only variable is the area**

Beam



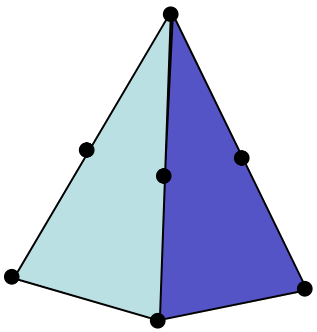
- **Advanced features:**
  - Hinges (releases) at each end
  - Variable area
  - Variable inertia (3 per beam)
  - Variable shear area

Shear, Membrane and Bending Plate

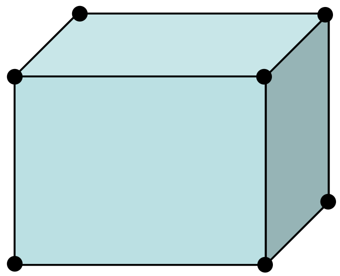


- Carries shear force only
- Adds axial capability
- Adds bending capability

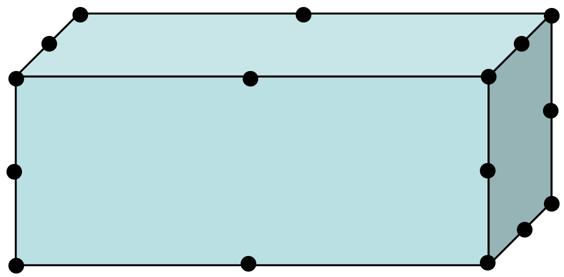
Solid Elements



10-noded tetrahedron



8-noded brick



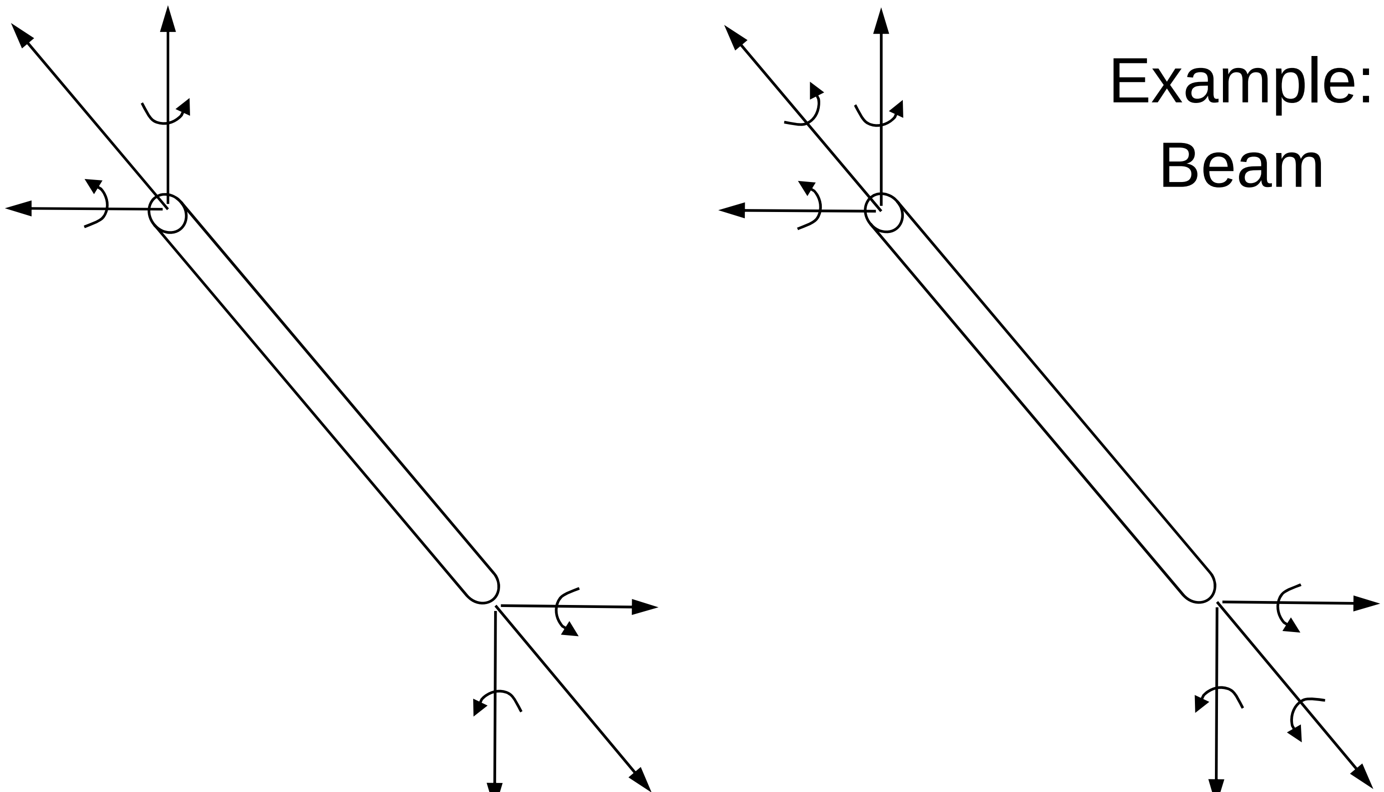
20-noded brick

What Is a Degree of Freedom (DOF)?

- **A node can have 6 structural degrees of freedom**
  - 3 translations relative to an axis system
  - 3 rotations about an axis system

Degrees of Freedom are Determined by Element Properties

Example:
Beam



Without torsional inertia

10 DOF

With torsional inertia

12 DOF

All elements attached to a given node can potentially affect the degrees of freedom at that node

Finite Element Method

Each element contributes to the overall stiffness of the model

Stress/ strain relationship (spring f = Kx)

↓

Write stiffness matrix for each element

↓

Assemble global stiffness matrix

↓

Invert global stiffness matrix

↓

Back-substitute to obtain displacements

What Software Tools Do Internal Loads Use to Create an Integrated FEM?

Preprocessor: **CATIA**

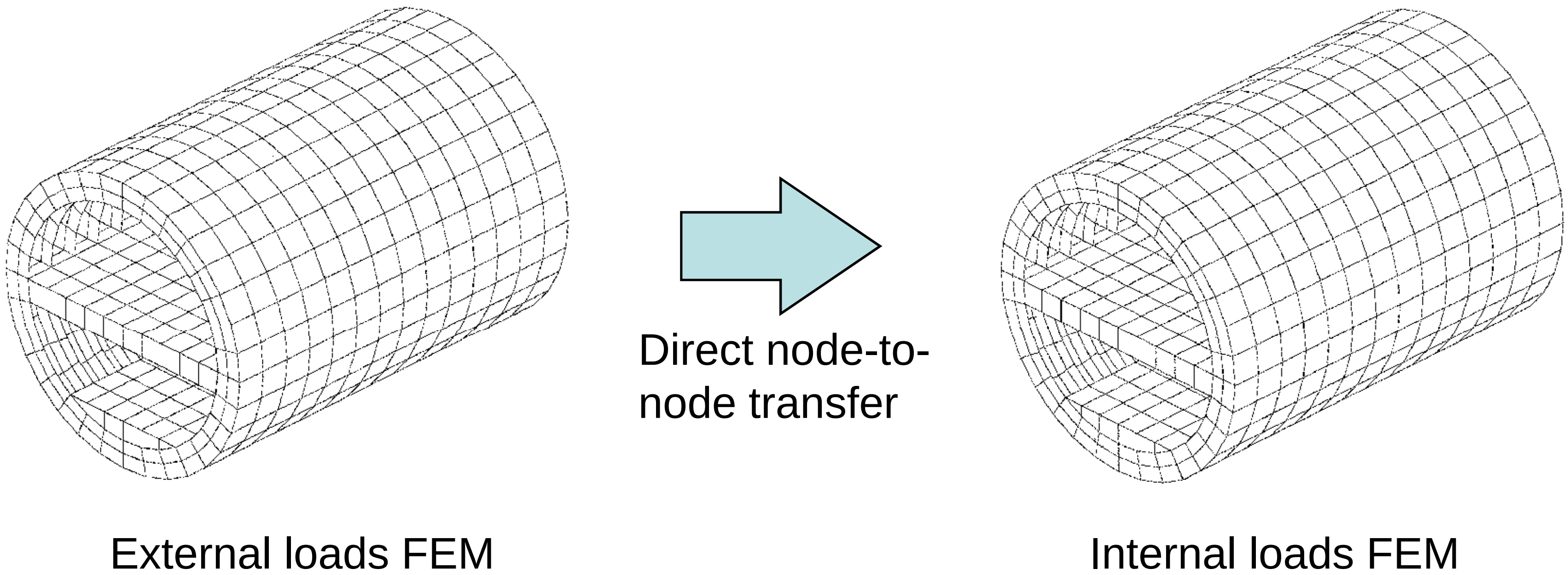
Solver: **CATIA-ELFINI** (batch, *not* interactive)

Post-processor: **CATIA-ELFINI** (interactive)
<or>
Create a large ASCII text file to transfer to other codes

How Are Loads Applied to the Integrated FEM?

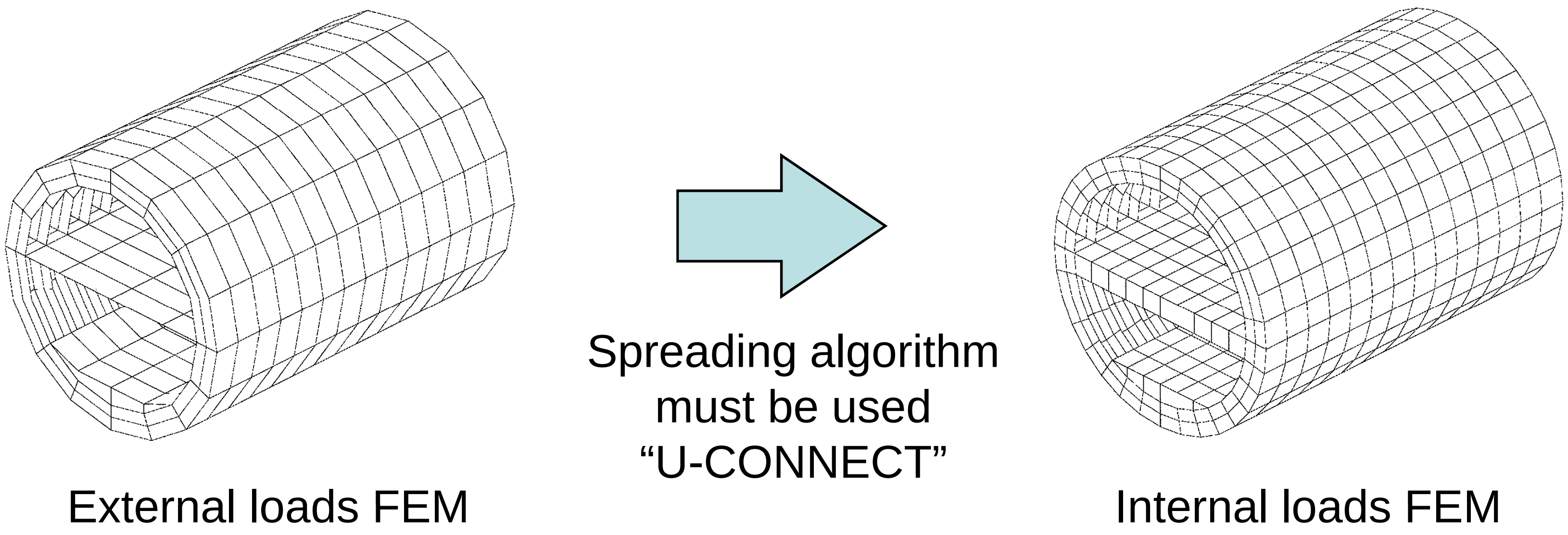
- **ELFINI** aeroelastic using detailed model (“TRLOAD”)
- **ELFINI** aeroelastic using coarse model (“U-CONNECT”)
- Using “point loads” (Unit loads and factors)

"ELFINI Aeroelastic" Using Detailed Model



- External loads calculated using a model that is 95% common with the internal loads model
- CATIA-ELFINI "TRLOAD" function used to transfer node loads
- Used on 737NG

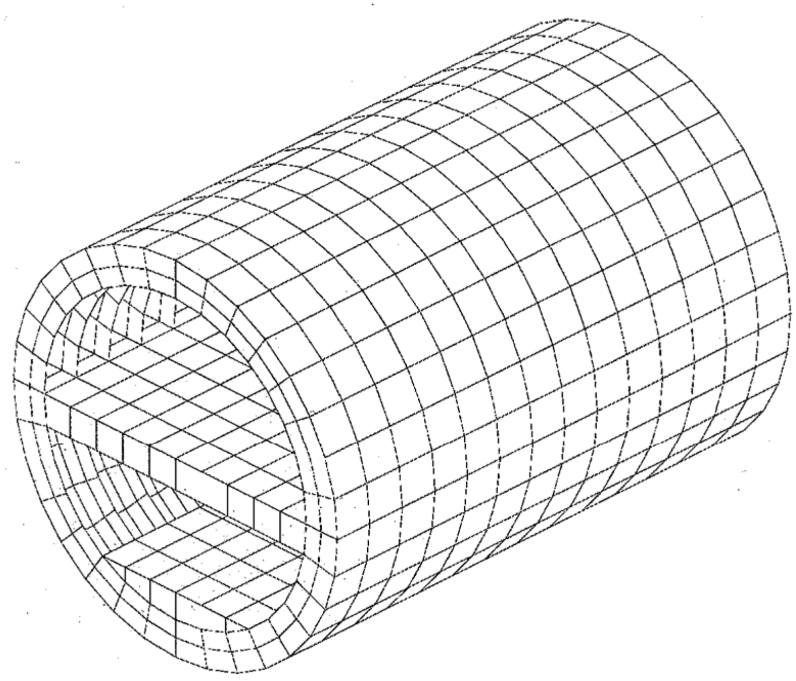
“ELFINI Aeroelastic” Using Coarse Model



- External loads calculated on coarse model
- Stiffness approximates that of the internal loads model
- CATIA-ELFINI “U-CONNECT” function used to transfer node loads
- Used on 777-200X & 777-300X

“Point Loads” Using Detailed Model

- **Hundreds of unit load cases created (represent airload, fuel, cargo, OEW, etc.)**
- **External loads group provides factors**
- **Unit cases factored and added together to create each final case on the integrated FEM**
- **Used on 767-400ER**
- **Labor intensive**



Internal loads FEM

Many Programs Can read Results From the FEM

MARGIN:	Wing stress
FEADMS:	Oracle database for body structures
Moss/Duberg:	body skin and stringer sizing
FAMOSS:	body frames
POST-ELF:	Wichita
IDTAS:	Fatigue
	Plus other IAS and Excel applications

Boeing Uses a Variety of Finite Element Codes

CATIA-ELFINI: Internal loads, stress, flutter

SAMECS: legacy internal loads

ATLAS: weights, flutter, landing gear, dynamic loads, and legacy internal loads

NASTRAN: legacy internal loads, stress, PSD, vibration

ANSYS: stress, landing gear, systems

ALGOR: systems, stress

ABAQUS: advanced nonlinear code

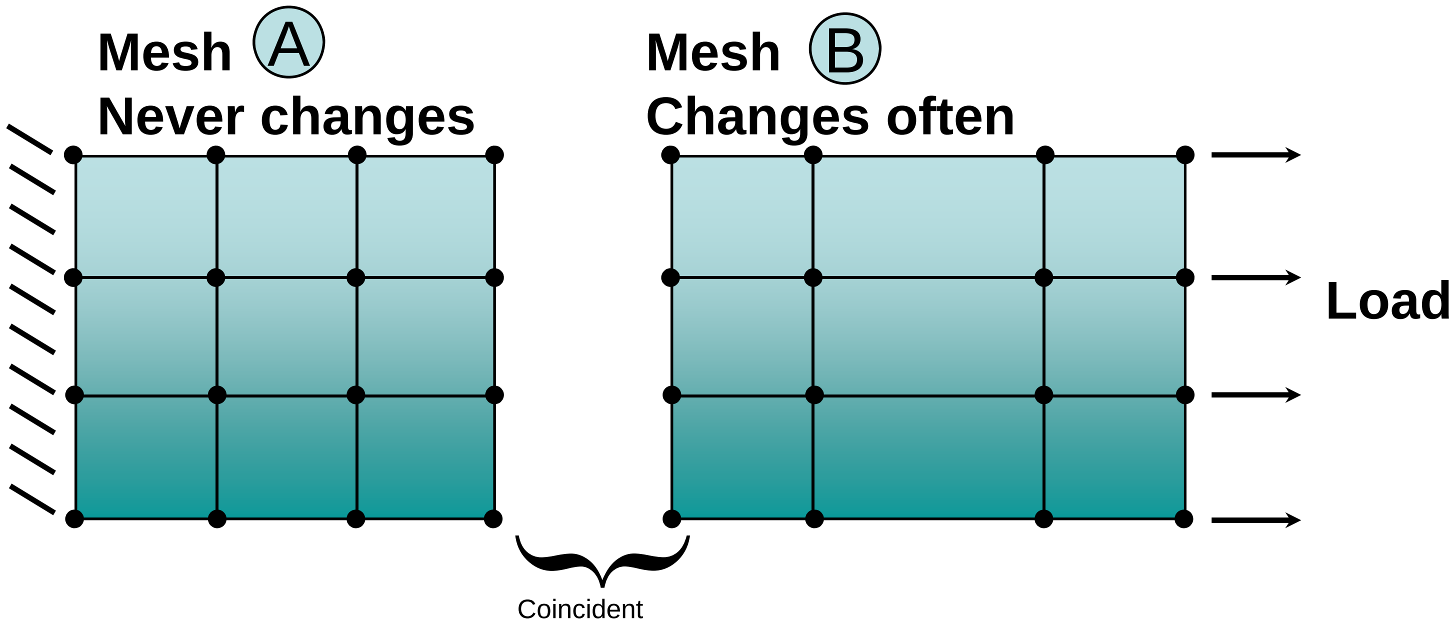
CATIA-ELFINI Has Many Differences Compare to Other Finite Element Codes

- Uses a “history” file (cutting, copying, and pasting blocks of commands)
- Uses topological meshing (10, 1, 4, 1, instead of 1001)
- Integrated into CATIA (same place as geometry)
- Sub-structuring and super-elements are very advanced
- Load and displacement transfer between meshes is easy
- Limited non-linear capability

Super-Elements Add Flexibility to the Overall Process

- **Incorporate sub-structuring**
- **Individual sections can rerun on their own**
- **Useful for fail-safe and discrete-source damage runs**

Example of Super-Elements, Step 1



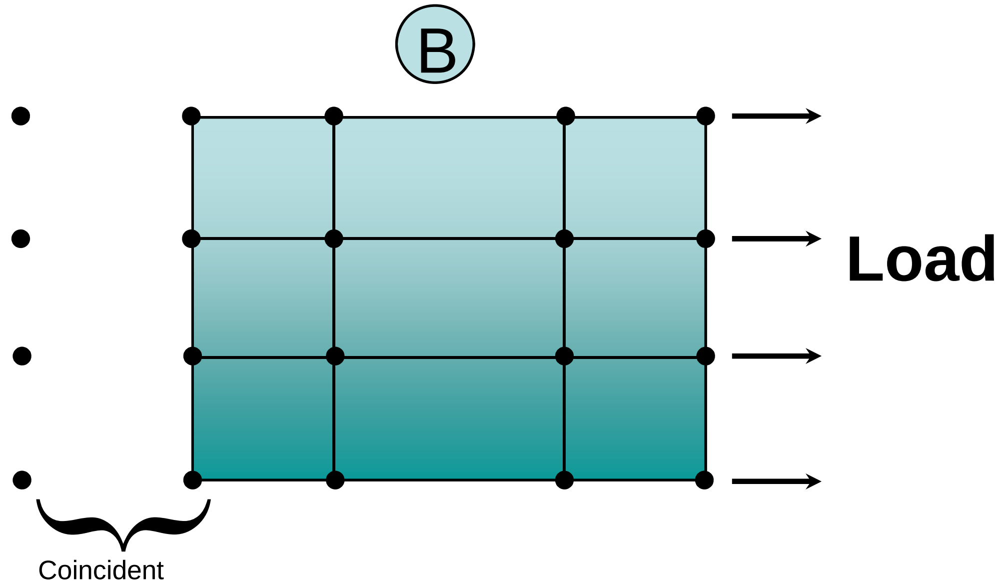
To solve (without super-elements):

1. Join Mesh A with Mesh B .
2. Assemble global stiffness matrix [K].
3. Invert global stiffness matrix [K].
4. Back-substitute to get global displacements {U}.

Note: Each time B changes, must re-solve for A .

Example of Super-Elements, Step 2

Super-elements representing stiffness of mesh A



To solve (using super-elements for Mesh A):

1. Create super-element for Mesh A
   (reduce loads and stiffness at boundary with Mesh B).
2. Join Mesh B with super-element that represents Mesh A.
3. Assemble global stiffness matrix [K].
4. Invert global stiffness matrix [K].
5. Back-substitute in Mesh B and to boundary of Mesh A.

Technical Background Summary

- Simple, easily understood elements and properties contribute to overall stiffness of the model.
- Internal Loads group uses CATIA-ELFINI to create integrated FEM.
- External loads are applied to the integrated FEM, using one of three methods.
- Many Boeing software programs use results from the FEM
- Other finite element codes are in use throughout Boeing

Agenda

Integrated FEM

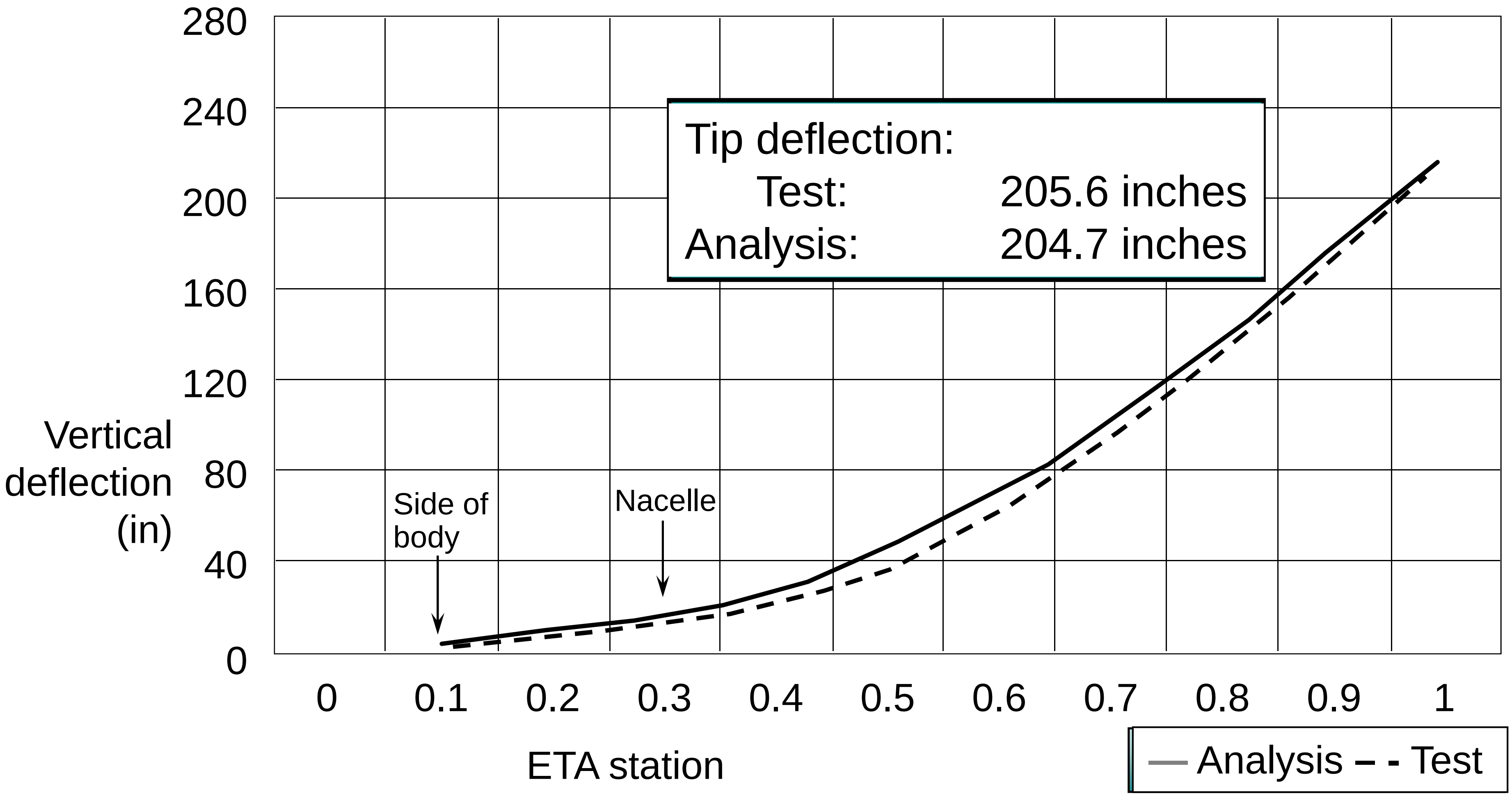
Support

Technical Background

Validation

777-200 Static Test Condition

Maximum Positive Wing Bending - 110% Limit Load



Summary

- Internal loads group develops the integrated finite element model (FEM)
- Internal loads group coordinates the overall modeling effort
- Internal loads group supports other groups by building models and providing data to the flutter, stress, and external loads groups
- The FEM uses simple, easily understood elements and properties
- FEM results correlate well with static test

Internal Loads

- **Successes**

777-200	Established many current processes
737-X	Used ELFINI Aeroelastic for external loads
767-400ER	Preliminary cycle made shorter

- **Lessons Leaned**

757-300	Two entire loads releases with composite properties in the frame webs
747-600x	Program canceled just prior to release of internal loads
777-200X/300X	Software change did not go smoothly

Why Work in the Internal Loads?

- Get to see entire airplane
- Lots of variety
- Lots of exposure to other groups
- Trips to Wichita (future: maybe Long Beach)
- Recognition lunches with upper management (in the cafeteria)

Can You Trace the Internal Load Paths?