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

Design and Analysis of Aircraft Structures
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 in 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

Web
Chord
Web
Outer chord
Stanchion (beam)
Fail-safe chord
Inner chord

Design and Analysis of Aircraft Structures
Bulkheads Use Beams and Shears

- Aft wheel well bulkhead
- Center section wing box
- Ring chord (beam elements)
- Webs (shear elements)
- Stiffeners (beam element)

Design and Analysis of Aircraft Structures
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
Design and Analysis of Aircraft Structures
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

- 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

- Wind tunnel data
- Pressure distribution
- Stability and control data
- Stiffness update
- External loads
- Balanced forces
- Internal loads model
- Stresses or internal loads
- Post-processing
- Sizing
- Update detail drawings
- Mass distribution update
### Internal Load Schedule is Critical and Highly Visible

<table>
<thead>
<tr>
<th>1997</th>
<th>1998</th>
<th>1999</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt 1</td>
<td>Qt 2</td>
<td>Qt 3</td>
<td>Qt 4</td>
</tr>
<tr>
<td><strong>Major Milestones</strong></td>
<td><strong>Configure/Requirements</strong></td>
<td><strong>Loads</strong></td>
<td><strong>Commitments &amp; Compliance</strong></td>
</tr>
</tbody>
</table>

Design and Analysis of Aircraft Structures
### Why Use the Integrated FEM?

<table>
<thead>
<tr>
<th><strong>Pros</strong></th>
<th><strong>Cons</strong></th>
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</thead>
<tbody>
<tr>
<td>Serves as a means of unifying disparate groups</td>
<td>Stress group is somewhat dependent on FEM results</td>
</tr>
<tr>
<td>Consistency of idealization and analysis</td>
<td>Requires coordination</td>
</tr>
<tr>
<td>Preserves lessons learned from previous programs</td>
<td>Idealization disagreements</td>
</tr>
<tr>
<td>Easier to find errors (debug)</td>
<td>Culture clashes</td>
</tr>
<tr>
<td>Better interface loads</td>
<td>- 767 versus 777</td>
</tr>
<tr>
<td></td>
<td>- SAMECS versus ELFINI</td>
</tr>
</tbody>
</table>

Design and Analysis of Aircraft Structures 9-23
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

Design and Analysis of Aircraft Structures
Internal Loads Group Builds Detailed Stress Models for Analysis and Verification
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
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

<table>
<thead>
<tr>
<th>Internal Loads Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Spring</td>
</tr>
<tr>
<td>• Bar</td>
</tr>
<tr>
<td>• Beam</td>
</tr>
<tr>
<td>• Shear*</td>
</tr>
<tr>
<td>• Membrane*</td>
</tr>
<tr>
<td>• Bending Plate*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solid Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 10-noded tetrahedron</td>
</tr>
<tr>
<td>• 8-noded brick</td>
</tr>
<tr>
<td>• 20-noded brick</td>
</tr>
</tbody>
</table>

* Properties for shear/membrane/bending elements

Isotropic       Composite       Honeycomb       Sandwich

More common ← ——> Less Common
Springs

- 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 $K = \infty$
- 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

Shear

• Carries shear force only

Membrane

• Adds axial capability

Bending plate

• Adds bending capability

Design and Analysis of Aircraft Structures 9-43
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.

Design and Analysis of Aircraft Structures
Finite Element Method

1. Stress/strain relationship (spring $f = Kx$)
2. Write stiffness matrix for each element
3. Assemble global stiffness matrix
4. Invert global stiffness matrix
5. Back-substitute to obtain displacements

Each element contributes to the overall stiffness of the model.

Design and Analysis of Aircraft Structures
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.

Design and Analysis of Aircraft Structures
Example of Super-Elements, Step 2

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.
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

Design and Analysis of Aircraft Structures
777-200 Static Test Condition
Maximum Positive Wing Bending - 110% Limit Load

Tip deflection:
Test: 205.6 inches
Analysis: 204.7 inches

Vertical deflection (in)

ETA station

Design and Analysis of Aircraft Structures 9-61
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 Learned**

  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?