FEM Validation and Requirements

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Airframe Breakout Session
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FEM Validation and Requirements

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What is FEA?

- **Finite Element Analysis (FEA) is not a Stress Analysis; it is an integrated part of it**
- **A computer-aided mathematical technique for obtaining approximate numerical solutions to the abstract equations of calculus that predict the response of physical systems subject to external influences**
- **This numerical procedure is used for analyzing complex problems in continuum mechanics such as structures, fluids, heat-transfer, electromagnetic**
- **A method that engineer routinely use to efficiently and accurately solve problems which are utterly intractable to solve by classical analytical methods**
- **A method of describing the response of a loaded continuum as the solution to a set of simultaneous algebraic equations**

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What is FEA? (Continued)

- **A virtually universal tool across all disciplines of engineering and throughout all engineering industries**
- **Results are rarely exact, however they could be sufficiently accurate**
- **Accuracy depend on such things as,**
  - **Element selection and mesh refinement**
  - **Physical property and dimensions**
  - **Boundary conditions (loads and constrains)**
  - **Convergence**
- **The results** *MUST ALWAYS* **be looked upon with suspicion, until they are verified and proved to be sufficiently accurate**
- **Understanding of the structure and of the FEM is a must in FEA**
- **FEA is not the end of the analysis, is only a part of the work**
- **Model validation must be part of Model development**

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Brief History of FEA

- **Concept began in France about 1850-1875 by Navier, St. Venant, Maxwell, Castgliano, Mohr, and others. Later expanded as Matrix Structural Analysis**
- **In period of 1875-1920 due to practical limitations FEA was in dormant**
- **Around 1920's Ostenfeld of Denmark and Maney of US expanded the concept to practical truss and framework analysis**
- **In 1932 Hardy Cross advanced the concept to more complex problems by introducing the method of moment distribution**
- **In 1943 Courant used piecewise continuos functions defined over a subdomain to approximate unknown functions**

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Brief History of FEA (continue)

- **In 1960 Professor Clough of UC Berkley coined the term "finite element"**
- **Since 1950 many advancements in the computer technology has occurred. Meanwhile the concept of framework and continuum analysis were combined and results were presented in matrix format.**
- **These developments were followed by a period of rather intensive developments of practical 'general purpose" software packages such as Ansys, Nastran and Abaqus.**

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- 4 minimum *required steps* for FEA process
  - Establish a clearly define goal
  - Compile and qualify the inputs
  - Solve the problem with the most appropriate means
  - Verify and document the results

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- To establish these goals ask 2 questions:

1. How accurate the results need to be?
   - Exact
   - Ballpark
   - Show trends
2. What specific data is necessary?
   - Load Distribution
   - Detail Stresses
   - Displacements
   - Reaction forces

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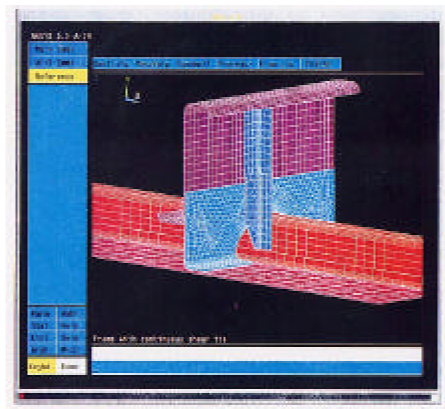
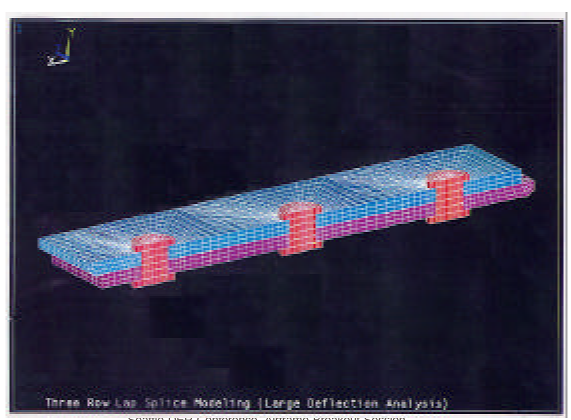
Step 1: Be Goal Oriented

- **Example: FEM to determine local stresses in a fuselage frame at stringer cutout**



Step 1: Be Goal Oriented

- **Example: FEM to determine stresses in a fuselage skin lap joint**



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Step 2: Compile and qualify the inputs

- **Compile and qualify the inputs**
  - **Geometry**
    - **Idealization (Simulation) of the geometry**
    - **Mesh: element type, shape, order**
  - **Material Properties**
    - **Scatter**
    - **Units**
  - **Boundary Conditions**
    - **Loads**
    - **Constraints**
- ***Involves assumptions and judgments***
- ***NO different than manual analysis***

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Assumptions and Judgments

- **In FEA the complex structure is partitioned into finite regions (elements) which are connected at nodes**
- **Higher node density is required for areas of rapid change; Nodes are requires where the loads and BC's are applied and where results are desired**
- **Element are mathematical representation which simulate the structure behavior**
- **So understanding of the *structural behavior* and the *element formulation* in FEA is *Fundamental***

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Assumptions and Judgments

- **In modeling the structural behavior, idealization (simulation) of the items subject to investigation is essential**
  1. **Modeling of a Seat Pan**
  2. **Effect of foreign object damage (FOD)**
     - **Modeled-In Dent**
     - **Formed Dent (Low Velocity Impact)**
- **Nonlinear geometry and plasticity**

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Assumptions and Judgments Example 1- Seat Pan

- **Actual Seat Pan- Geometry**

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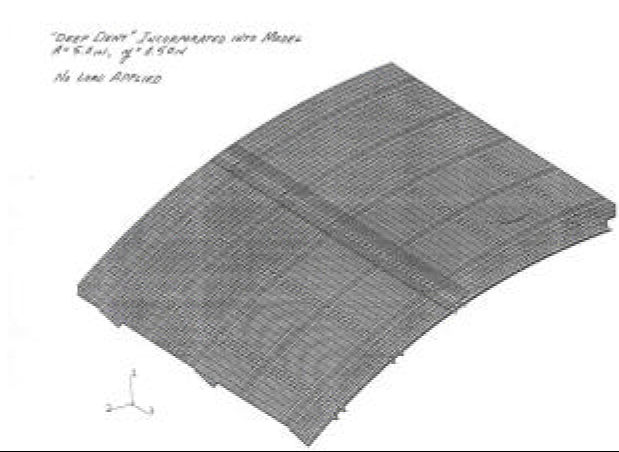
Assumptions and Judgments Example 2- Skin Dent

- **First attempt in simulating the foreign object damage (FOD) was done by "Modeled-In" dents**
  - **Most expeditious way of modeling the dent in the fuselage skin is to actually include it in the model**
  - **Stress free**
  - **One step simulations**
- **Results are *unrealistic***

Assumptions and Judgments Example 2- Skin Dent

Fuselage Skin with Modeled-In Dent



Assumptions and Judgments Example 2- Skin Dent

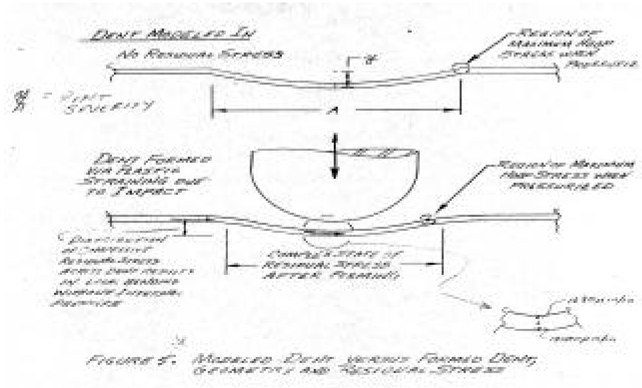
- Next attempt in simulating the FOD was done by plastic deformation of the skin
  - Low velocity impact of an object with the skin
  - Plastic Strain on the back surface of the skin is about 10x greater than than the front surface
  - Two step process
    - Impact of the object with the skin; various depths
    - Removal of the object and allowing plastic deformation to form
- Results are ***realistic***

Assumptions and Judgments Example 2- Skin Dent

- For this configuration
  - Stress levels due to cabin pressure for moderate dents (<0.20”) are lower than for similar “Modeled-In” dents
  - Stress levels due to cabin pressure for deep dents (>0.20”) are higher than for similar “Modeled-In” dents
  - Stress levels for very shallow dents are very low. The more stable formed dents resist snap through, or “oil canning” when pressurized

Assumptions and Judgments Example 2- Skin Dent

Schematic of the two simulations of dent



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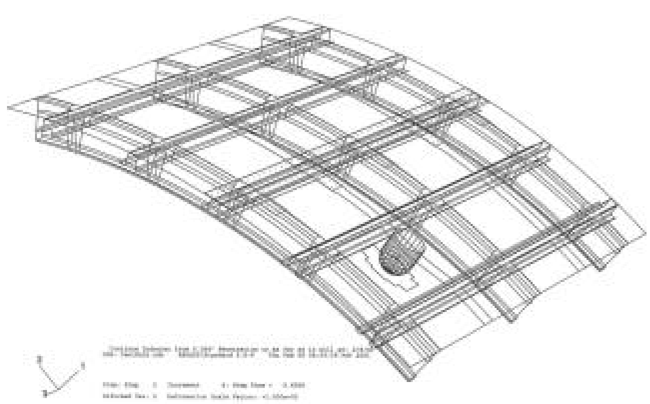
Assumptions and Judgments Example 2- Skin Dent

Skin Dent at the Formation Stage



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Assumptions and Judgments: Choice of element

- **Since the understanding of the structural behavior and the element formulation in FEA is ESSENTIAL one must be intimately familiar with:**
  - **1) Fundamentals such as Strength of Material**
  - **2) Element formulation, assumptions, capabilities, limitations and restrictions of the FEA code at hand**
- **To demonstrate this point let us examine different elements and their applications**
  - **Element *shape function***
  - **Element *shape and order***

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Assumptions and Judgments: Choice of element- Shape Function

- **In bending of thick plates where the transverse shear effect is not negligible certain shell elements, without the appropriate extra shape functions, will produce erroneous results.**
  - **Use Shell elements that have the extra shape functions**
  - **Use solid elements (Only way for very thick plates subject to bending)**
- **Let us consider a thick plate with a hole in the center, subject to pure bending**
- **Compare results to "handbook" solutions**

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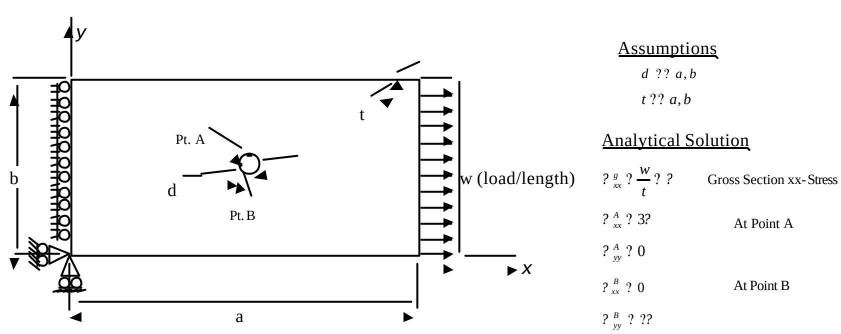
Assumptions and Judgments: Choice of element- Shape Function

Comparison of stress concentrations:

Plate Geometry				Elements without shape Functions	Elements with shape functions	Solid Elements
D	t	W	Kt			
1	0.03	8	1.65	1.615	1.595	N/A
1	0.05	8	1.65	1.615	1.605	N/A
1	0.1	8	1.65	1.615	1.605	N/A
1	1	8	2.02	1.615	2.07	2.11
1	2	8	2.23	1.615	2.31	2.3
1	4	8	2.43	1.615	2.53	2.57

Assumptions and Judgments: Choice of element- Shape / Order

- **Elements - Shape/Order - Example**
  - **Flat plate with a center hole - axial load**



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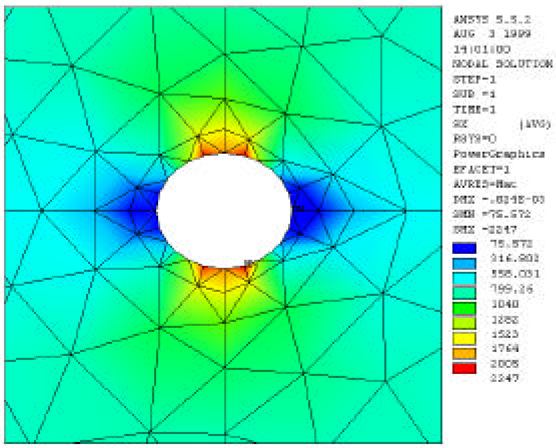
Assumptions and Judgments: Choice of element- Shape / Order

- **Elements - Order - Example**

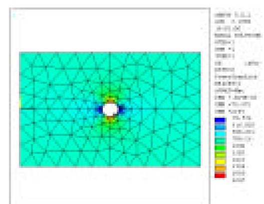


3-Node Triangle

 # Nodes: 163

 # Elems: 270

 # DOF: 318



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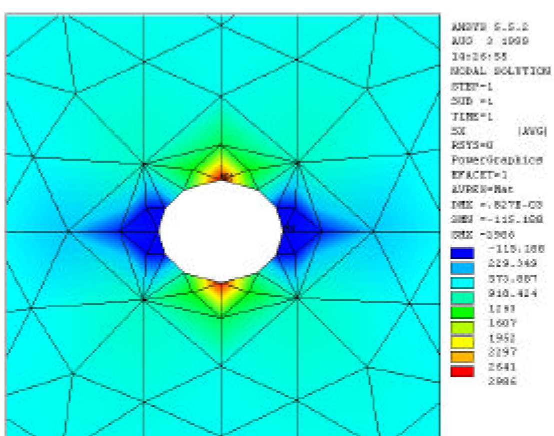
Assumptions and Judgments: Choice of element- Shape / Order

- **Elements - Order - Example**

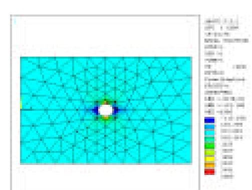


6-Node Triangle

 # Nodes: 516

 # Elems: 236

 # DOF: 1018



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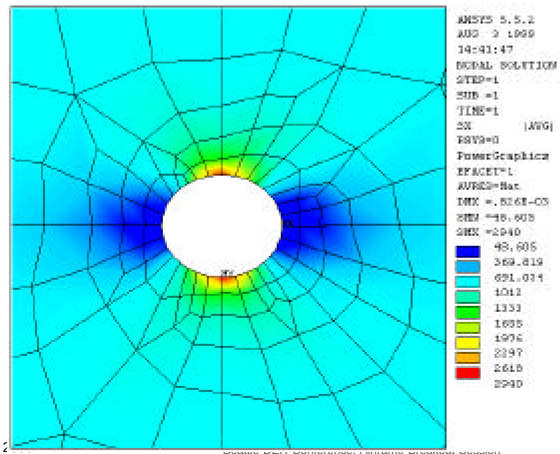
Assumptions and Judgments: Choice of element- Shape / Order

- **Elements - Shape - Example**

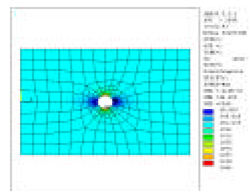


4-Node Quad

 # Nodes: 269

 # Elems: 229

 # DOF: 526



Assumptions and Judgments: Meshing Tips

- **Elements - Shape/Order - Element Checks**
  - **Element geometry affects the mathematical approximation of the problem domain**
  - **Singularities can occur**
  - **Physically impossible geometry can be generated mathematically**
  - **Tri elements should be avoided in areas of interest (much too stiff)**
    - **Performance of higher order Tri elements are comparable to Quad elements**

Assumptions and Judgments: Meshing Tips

- **Elements - Shape/Order - Element Checks**
  - **Aspect Ratio**
  - **Internal Angles**
  - **Parallel Deviation**
  - **Jacobian Ratio**
  - **Warpping Factor**
- **See Appendix A for some examples**

Assumptions and Judgments: Meshing Tips

- **Elements - Shape/Order - Element Checks**
  - **Features that inform the user of presence of any *bad quality* element(s) are available in many contemporary FEA systems**
    - **Failed elements automatic selection**
      - **Useful for mesh refinement**
    - **Failed elements plot**
    - **Specially useful in large FEA models**
  - **Ultimately the user is responsible to ensure the goodness of the elements**

Assumptions and Judgments: Meshing Tips

- **Elements - Density**
  - **Directly relates to accommodation of structural behavior**
  - **Generally more elements means more accuracy**
  - **More elements also means more resources**
  - **Regions with relatively high stress gradients require a finer mesh to resolve the peaks**
  - **Regions of the model where concentrated loads and BC's are applied show unrealistic results**
  - **For small models a simple manual convergence study using smaller and smaller elements is one easy route**
  - **For larger models automated error checking with automatic bad element selection is very useful**
- **See Appendix A for Error Estimation techniques.**

Assumptions and Judgments: Loads and Constraints

- **Constraints- Boundary Conditions**
  - **Models the remaining of the world that is not included in the model**
  - **Sets axial and rotational DOF to a set value, usually zero**
  - **Where the input loads are reacted in the model**
  - **At times it is best when symmetric characteristics of a model is utilized**
  - **If the BC is applied at discrete points the results may be incorrect in that vicinity, since the resultant reaction loads are applied at a zero area geometric entity, which results in a mathematical singularity**

Assumptions and Judgments: Loads and Constraints

- **Loads - Force**
  - Applied force or displacement
  - Applied bending moment or rotation
  - Satisfactory for beam modeling and "far field" results; Usually unsatisfactory for 2D, 3D modeling
  - Incorrect results in vicinity of load application since load is applied at a discrete point, a zero area geometric entity, which results in a mathematical singularity

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Assumptions and Judgments: Loads and Constraints

- If large displacement is anticipated the <u>load</u> and <u>boundary condition</u> applications must account for the variation in magnitude, orientation and distribution
- If accurate solution near load point is required there are two general options
  - Replace load with a pressure loading over a small representative area
    - If the stress under the force is not of interest use course mesh to distribute the resultant stress to larger neighboring elements
  - Model both parts in detail and perform contact analysis

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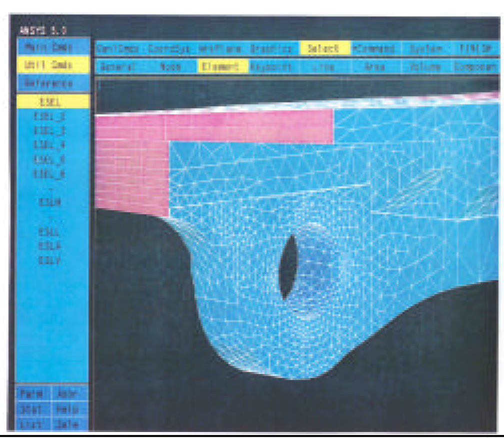
Assumptions and Judgments: Loads and Constraints

- **Loads - Pressure**
  - Discretization is based on consistency with the displacement law used in the element formulation
    - If calculating outside of FEA program, work equivalency must be considered
  - Usually more representative of actual loading
  - Many commercial FEA codes have built-in tools for applying pressure in various manners often utilizing associatively; work equivalent consistent loads are calculated as necessary
    - Parametric variation (linear, non-linear)
  - Easy to apply
    - Lines, Edges (Force/Length)
    - Faces (Force/Area)

Assumptions and Judgments: Loads and Constraints

747 Strut Midspar Fitting

- Pin load simulated by cosine distribution pressure load



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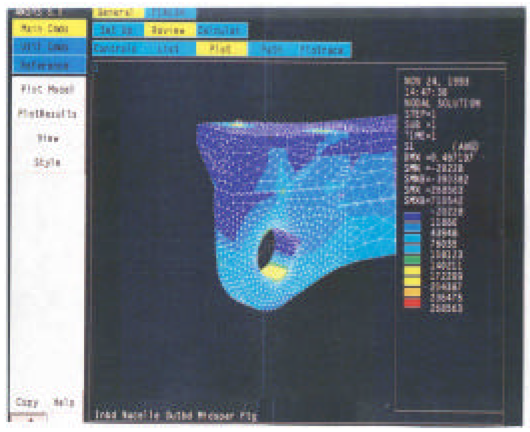
Assumptions and Judgments: Loads and Constraints

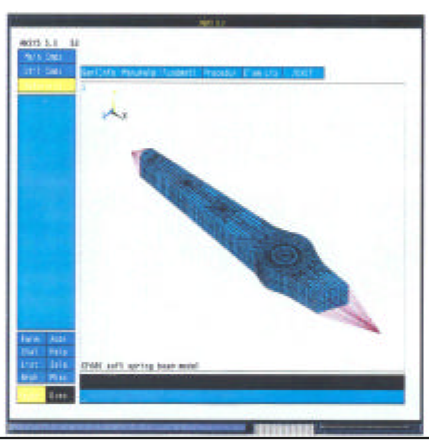
747 Strut Midspar Fitting Subject to <u>Unit Load</u>



Assumptions and Judgments: Loads and Constraints

747 Outboard Strut Spring Beam

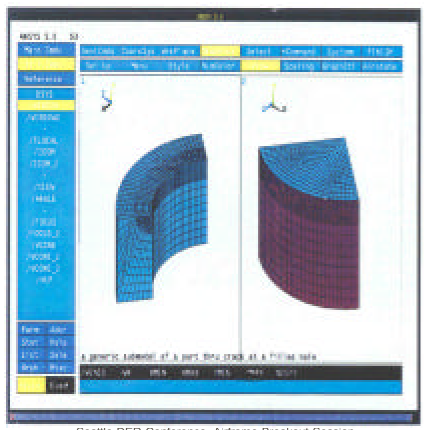
- Pin load simulated directly by use of contact elements



Test validated using strain gage

Assumptions and Judgments: Loads and Constraints

Submodel of the Spring Beam critical area with crack



Step 3: The Most Appropriate Means of Solution

- **Build in Quality- *Think ahead***
- **The simplest model is the right one**
  - **Can it be solved by manual methods?**
  - **Can the answer be found in a handbook?**
- **Analysis requirements should drive the need for the resources, not vice versa**
  - **Software, Hardware, Budget, Time, Personnel Experience ad Expertise**

The Most Appropriate Means of Solution

- Using FEA to analyze a problem requires:
  - Strong understanding of the problem and its details, and idealizing them
  - Strong understanding of the structural behavior and accommodation for it
  - Strong understanding of the analytical tool at hand such as assumptions and limitations
  - Thorough investigation of the output
- Validation of FEA is critical to its credibility?

Step 4: Verify and Document the Results

- Should NOT be the last-step in the process
- Common Misconceptions:
  - Meshing is everything
    - Resist mindless auto-meshing for everything
  - FEA replaces understanding of fundamentals such as Static and Strength of Material
  - FEA replaces testing
    - FEA augments testing and vice versa
    - Levels of uncertainty inherent in the process will almost always require that final products, at a minimum, be tested

Verify and Document the Results

- Assumptions regarding material, assembly variability, and other unpredictability need to be weighted, qualified and documented.
- No different than traditional "manual" approach where validity of analysis technique, assumptions and limitations are validated prior to application of the approach.
- Manual Post-Processing of the FEM results is an acceptable and common approach

Verify and Document the Results

- Invisible Meshing
  - Program uses appropriate *p* or *h* element refinement with minimal user intervention
  - There are FEA systems that use *p* elements to obtain quantities such as
    - Stress concentrations
    - Stress intensity factors
  - "Contemporary" stress handbook
    - Replacing the old hardbound books
    - Allow for more flexibility and variation in geometry

Verify and Document the Results

- **Basic checks of the FEA results:**
  - **Review the results**
    - **Review the reactions**
    - **Review the deflected shape**
    - **Review max/min displacement and stress locations/values**
  - **Ask questions**
    - **Can I make sense out of the results?**
    - **Are these results different from the analytical/test results?**
    - **Which results are different?**
    - **How much do they differ by? Why might this be?**
    - **What can be done to have a closer match in the results?**
    - **What level of accuracy is necessary for the design of this part?**
  - **Refine model and re-analyze if necessary**

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Verify and Document the Results

- **Components to be validated**
  - **Element Formulation**
  - **Solution Code**
  - **FEM Construction and Analysis**
- **Element Formulation and Solution Code**
  - **Generally accomplished by software provider**
  - **Generally based upon comparison of FEA Solution to theoretical solution**
    - **Theoretical problem selected to exercise element**
    - **More than 50,000 problems used as check in a certain FEA code**

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FEM Validation and Requirements

Verify and Document the Results

- Finite Element Model construction and analysis
  - Model validation to be provided by user/applicant
  - Validation plan
    - Part of the Certification Plan
    - Agreed upon
      - Measure of success
        - Ask ACO Engineers for examples
        - Many examples; Good and Bad

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Verify and Document the Results

- Verification
  - Correctness vs. Accuracy
    - A poorly posed problem can have a high degree of accuracy yet provide incorrect results
    - The solution can only be considered accurate AND correct if it is properly defined and well posed
    - The following are some important considerations in evaluating the correctness of a solution:
      - Structural idealization, mesh quality, element type, boundary conditions, material model, solution type and control parameters, method of post-processing

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Verify and Document the Results

- Verification
  - Test correlation
    - Analysis can only be as good as the test
    - A good way to verify the integrity of a finite element model
    - Can be used to help evaluate assumptions and idealizations
    - Can be used to evaluate failure theories
    - Most beneficial when used at the beginning stages of a new design type to develop a database of experimental correlation curves - once the design has matured and only minor derivatives are being designed and manufactured, testing may not be necessary

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Verify and Document the Results

- Verification
  - Test correlation
    - Pros
      - Inherently correct and accurate if conducted properly
      - Includes all real physical effects that are part of test
      - Builds confidence in analysis methodology
      - Provide insight into the limitations of the analysis
    - Cons
      - Relatively expensive (time, labor, schedule)
      - Provides only "single point" results
      - Test can only verify the analysis and possibly point to an error, it does not ensure absence of error!

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Verify and Document the Results

- **Verification**
  - **Analytical solution comparison**
    - **An alternate method of evaluating the integrity of a model**
    - **Often requires breaking the model down into smaller, simpler "pieces" in order to evaluate by hand analysis**
    - **References for analytical solutions to structural problems:**
      - "Roark's Formulas For Stress and Strain", W. C. Young
      - "Theory of Elasticity", Timoshenko & Goodier
      - "Theory of Plates and Shells", Timoshenko & Woinowsky-Krieger
      - "Analysis and Design of Flight Vehicle Structures", Bruhn
      - Government publications (ex. Mil-Handbook-XX)
      - Industry accepted design/analysis manuals
- **See Appendix B for more discussion**

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Instrumented Structural Test

There are 3 areas of consideration:

1. **Basic or gross structure**
   - **Results of FEA and test should correlate fairly closely**
     - **Within 10%?**
     - **Accuracy of model formulation**
       - **Element selection**
       - **Element, mesh size or fineness**
     - **Instrumentation**
       - **Location**
       - **Positioning precision**

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Instrumented Structural Test

2. **Areas of discontinuity or load input**
   - **Load redistribution/shear lag**
     - **The FEM should predict the pattern**
       - **Panel shear stress**
       - **Stringer/longeron loads**
     - **Effect should be obvious**
     - **Strain correlation may not be close**
       - **High strain gradients - Positioning**
       - **Complex stress fields - Orientation**

Instrumented Structural Test

3. **Areas of predicted or suspected high stress**
   - **Evaluate suitability of model to predict high stress fields**
     - **Coarse model may not always do this**
     - **Stress analysis must account for this**
   - **Verify that FEA results subject to stress analysis post-processing capture high stress areas**
   - **Sometimes difficult to correlate**
     - **Complex stress fields**
     - **High stress gradients**
     - **Local buckling or distortion**

Observation

- An Observation: Users of FEA are some
  - 1) FASCINATED
    - **Believes any problem worth meshing is worth over meshing. Rejects beam and plate elements as analytically impure. Prefers contact element algorithms over actual boundary conditions. Plots everything. Punches and keeps plots (even the ugly ones). Spends about 2-3 times more effort writing macros than the macros actually save. Reports quite colorful; heavy on graphics and FEA-speak and light on insight.**
  - 2) FRUSTRATED
    - **Refines mesh selectively; shows resignation to dealing with ambiguity. Relies less on clever elements; truly trusts only classical element types. Abandons attempts to model welds with solid elements. No longer weeps at sight of tetrahedral elements. Time spent writing and debugging macros about equals time saved by macros. Reports contain caveats and warnings about applicability.**
  - 3) HEALTHY
    - **Meshing aimed at specific problem areas; seldom models the entire airplane to find stress in the door latch. Element choice reflects engineering considerations; comfortable with approximation. Keeps obsession with computational efficiency under control, usually without medication. Makes frequent use of tabular results; understands use of numbers and text. Reports balanced between engineering issues and eye candy. Makes appropriate use of both.**
- ***Remember - There is no substitute for experience; Finite element analysis results should always be scrutinized on the basis of sound engineering judgement.***

A Simple Illustration

Example - 50” long Cantilever I-Beam
- **200 Lb/in distributed load**

- **The Cantilever Beam is idealized as**
  - ***Beam Elements***
  - ***Rod-Plate-Rod Elements***
  - ***Shell Elements***
- **All three idealizations are equally acceptable**

A Simple Illustration- Comparison of Deflections

Theoretical Solution

- **Vertical Deflection= 0.522"**

FEA Approximations

- **Beam element: 0.522"**
  - **0% difference**
- **Rod-Plate-Rod elements:0.800"**
  - **+53% difference**
- **Shell element:0.876"**
  - **+68% difference**

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A Simple Illustration- Comparison of Stresses

Theoretical Solution

- **Maximum Stress= 50.099 Ksi**

FEA Approximations

- **Beam element: 50.099 KSI**
  - **0% difference**
- **Rod-Plate-Rod elements: 52.464 KSI**
  - **+5% difference**
- **Shell element: 56.596 KSI**
  - **+13% difference**

See Appendix C for complete analysis

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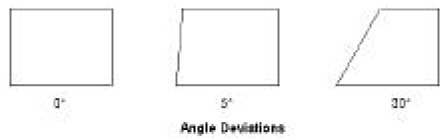
Appendix A

Assumptions and Judgments
Meshing Tips

Appendix A: Assumptions and Judgments: Meshing Tips

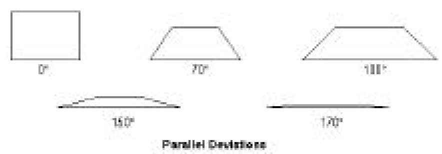
- **Elements - Shape/Order - Element Checks**
  - **Aspect Ratio**

  - **Internal Angles**



Appendix A: *Assumptions and Judgments: Meshing Tips*

- **Elements - Shape/Order - Element Checks**
  - **Parallel Deviation**



  - **Jacobian Ratio**

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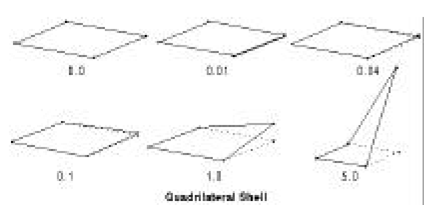
Appendix A: *Assumptions and Judgments: Meshing Tips*

- **Elements - Shape/Order - Element Checks**
  - **Warp**



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Appendix B

Verify and Document the Results

Appendix B
Verify and Document the Results

- **Element Formulation and Solution Code**
  - **Documented**
    - **Assumptions, Conditions, Limitations, Results**
    - **Quality assurance and other manuals**
      - **Available from Software Provider**
      - **Procedures, Command, Theory, Element, Verification, and Validation Manuals; Linear, Non-linear, Dynamics, Etc.**
  - **New elements, New solution algorithms or Unknown/Undocumented code**
    - **Request validation documents**

Appendix B
Verify and Document the Results

- Structure is rarely, if ever, fully tested for all loads, environments and deterioration
- Analysis is used to decide what to test
- Validation of analysis develops confidence that
  - Analysis is capable of selecting test conditions
  - Analysis is capable of identifying
    - Non-Significant Effects
    - Compensating for factors not included in test

Appendix B
Verify and Document the Results

- Instrumented structural test
  - Full sale test of actual or representative structure
  - Validation is done in combination with proof-of-structure
- Comparison to classical analysis
  - Is the classical analysis applicable to the structure?
  - Is the FEA applicable to the classical analysis?

Appendix B
Verify and Document the Results

- Building Block
  - Basic structure validated by comparison to theory
  - Detail or configuration subset models validated by:
    - Analysis
    - Test
  - Integrated structure does not invalidate model configuration
    - Detail or configuration subset model integrated into Overall structure model does not have significant changes
      - Parametric variational analysis, sensitivity studies

Appendix B
Verify and Document the Results

- Verification
  - Failure modes/theories
    - In linear analyses the program doesn't know anything about plasticity, failure modes/limits - these usually must be evaluated in manual post-processing steps
    - In non-linear analyses, the non-linearities must be defined and the associated solution controls must be properly specified
    - The analyst (in most cases) must know ahead of time what type of failure mode is to be predicted

Appendix B
Verify and Document the Results

- Verification
  - Failure modes/theories
    - One analysis can include multiple failure modes
      - All must be accounted for
      - Failed members must be eliminated (At least their stiffness)
    - Often user intervention is required during the analysis in order to drive the analysis in the expected direction

Appendix B
Verify and Document the Results

- Verification
  - Failure modes/theories
    - Most FEA systems have "built-in" theories, such as the Von-Mises equivalent stress calculation for ductile metal yield surface determination
    - The user must determine what is appropriate to use for a given analysis
    - Material properties used in this kind of analysis is different than handbook values
    - Joints must be accounted for separately if not modeled accurately- *Manual post-processing*

Appendix B
Verify and Document the Results

- Verification
  - Other failure modes/theories
    - What stress to use?
      - Ductile metals
      - Brittle materials
      - Plastics
      - Other material; e.g. Glass
    - Crack growth due to fatigue loading
    - Structural instabilities

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Appendix B
Verify and Document the Results

- Verification
  - Boundary conditions
    - Can significantly impact the solution
    - Can be difficult to determine accurately
    - Can be difficult to apply accurately
    - Require post-analysis evaluation, especially when designing "on the edge"
    - It is good validation to substantiate the BC's by test

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Appendix B
Verify and Document the Results

- Verification
  - Material models
    - Can significantly impact the solution
    - Can be difficult to obtain accurately
    - Can require significant post-analysis evaluation to become satisfied with the results
    - Always allow for reasonable variation

Appendix B
Verify and Document the Results

- Verification
  - Error estimation
    - Most contemporary FEA systems have some measures of error estimation built in
    - The most common is the "structural energy error" which is a measure of the continuity of the stress field from element to element
    - Useful for determining required level of mesh refinement
      - Valid only for linear analyses using 2D or 3D shell or solid elements

FEM Validation and Requirements

Appendix B
Verify and Document the Results

- Verification
  - Error estimation
    - For *h*-elements adaptive meshing uses error estimates internally to re-mesh a model where the error is high (higher than a user-specified tolerance)
    - These are often accompanied by a graphical display of the variation in the magnitude of the error with solution iteration for quick evaluation

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Appendix B
Verify and Document the Results

- Verification
  - Acceptance criteria
    - Each user must determine this for each particular problem
    - Should include reference to:
      - Design requirements
      - Model quality
      - Error estimation
      - Failure mode/theory
      - Solution convergence (non-linear problems)

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Appendix C

A Simple Illustration:
Modeling a Beam

Appendix C
A Simple Illustration

Example - 50” long Cantilever I-Beam
- **200 Lb/in distributed load**

- **The Cantilever Beam is idealized as**
  - ***Beam Elements***
  - ***Rod-Plate-Rod Elements***
  - ***Shell Elements***
- **All three idealizations are acceptable**
- **Theoretical solution:**
  - ***Vertical Deflection= 0.522”***
  - ***Maximum Stress= 50.099 Ksi***

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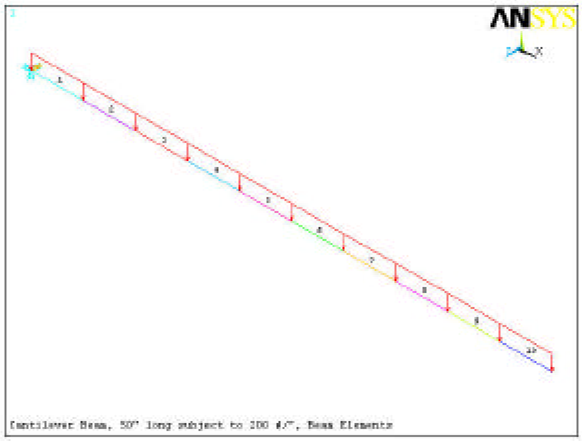
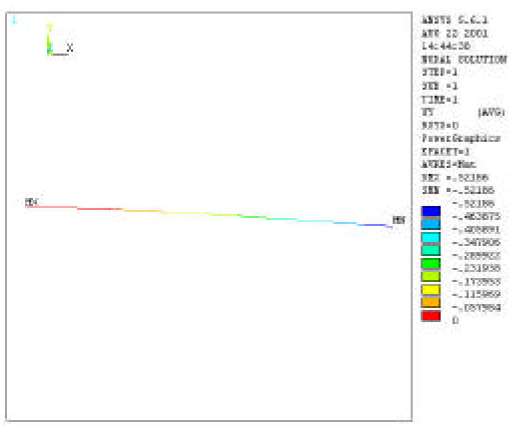
Appendix C
A Simple Illustration-
Beam Elements

Element plot of the I-Beam



Appendix C
A Simple Illustration-
Beam Elements

Deflection plot:



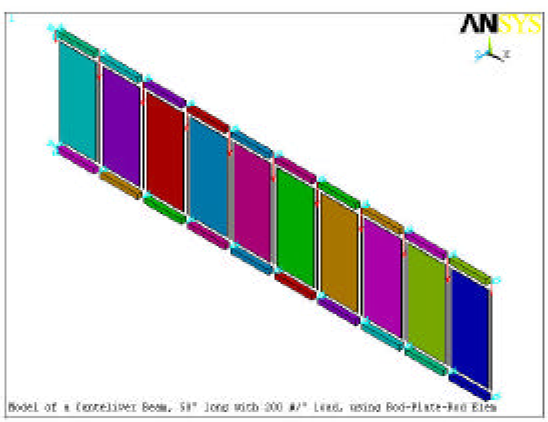
Appendix C
A Simple Illustration- Beam Elements

Stress output:

```
PRINT ELEM ELEMENT SOLUTION PER ELEMENT
***** POST1 ELEMENT SOLUTION LISTING *****
 LOAD STEP     1  SUBSTEP=     1
 TIME=    1.0000          LOAD CASE=  0

 EL=       1  NODES=       1       3  MAT=  1
BEAM3
 TEMP =    0.00    0.00    0.00    0.00
 PRES LOAD KEY = 1  FACE NODES =       1           3
               PRESSURES(F/L) =    200.00      200.00
 LOCATION   SDIR       SBYT        SBYB
  1 (I)    0.0000      50099.     -50099.
  2 (J)    0.0000      40580.     -40580.

 EL=       2  NODES=       3       4  MAT=  1
BEAM3
 TEMP =    0.00    0.00    0.00    0.00
 PRES LOAD KEY = 1  FACE NODES =       3           4
               PRESSURES(F/L) =    200.00      200.00
 LOCATION   SDIR       SBYT        SBYB
  1 (I)    0.0000      40580.     -40580.
  2 (J)    0.0000      32063.     -32063.
```


Appendix C
A Simple Illustration- Rod-Plate-Rod Elements

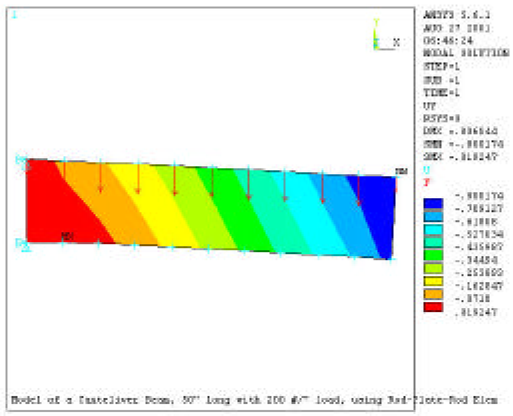
Element plot of the I-Beam



FEM Validation and Requirements

Appendix C
A Simple Illustration-
Rod-Plate-Rod Elements

Deflection plot:



Appendix C
A Simple Illustration-
Rod-Plate-Rod Elements

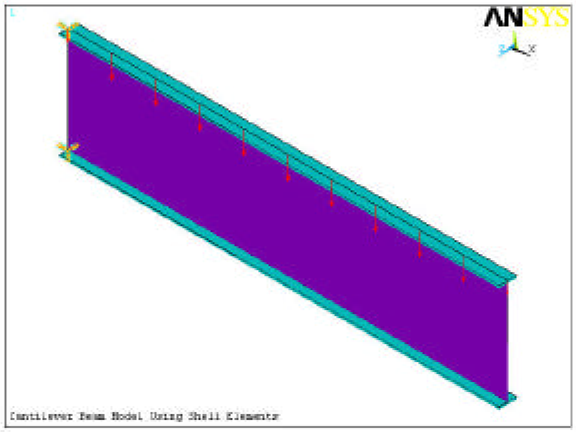
Stress output:

```
PRINT ELEM ELEMENT SOLUTION PER ELEMENT

 ***** POST1 ELEMENT SOLUTION LISTING *****

   LOAD STEP      1   SUBSTEP=      1
   TIME=    1.0000          LOAD CASE=   0

 EL=      11 NODES=       1        3 MAT=      1
LINK1
   TEMP =     0.00     0.00   FLUENCES = 0.000E+00 0.000E+00
 MFORX=  19674.
 SAXL=  52464.

EL=      30 NODES=      22       13 MAT=      1
LINK1
   TEMP =     0.00     0.00   FLUENCES = 0.000E+00 0.000E+00
 MFORX= -19674.
 SAXL= -52464.
```


Patrick Safarian, ANM-120S

Appendix C
A Simple Illustration- Shell Elements

Element plot of the I-Beam



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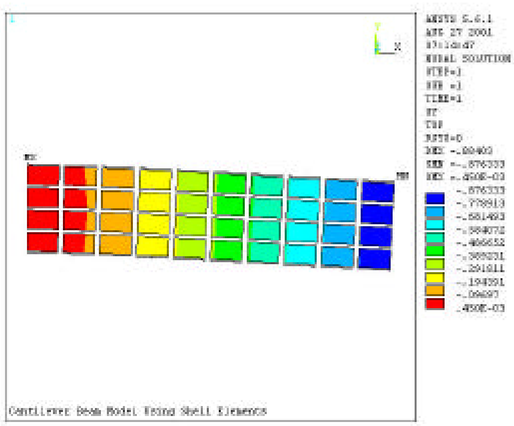
Appendix C
A Simple Illustration- Shell Elements

Deflection plot:



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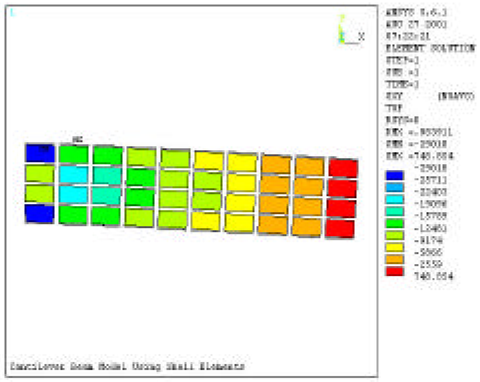
FEM Validation and Requirements

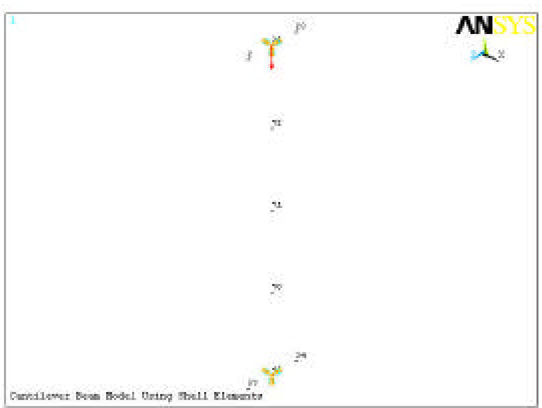
Appendix C
A Simple Illustration- Shell Elements

Shear stress plot:



Appendix C
A Simple Illustration- Shell Elements

Reaction points plots



Appendix C
A Simple Illustration-
Shell Elements

Reaction forces and moments:

```
PRINT REACTION SOLUTIONS PER NODE

  ***** POST1 TOTAL REACTION SOLUTION LISTING *****

  LOAD STEP=     1  SUBSTEP=     1
   TIME=    1.0000      LOAD CASE=   0

  THE FOLLOWING X,Y,Z SOLUTIONS ARE IN GLOBAL COORDINATES

    NODE      FX          FY          FZ          MX          MY          MZ
      12  -20808.      5180.3      0.62755E-10-0.21909E-09-0.14583E-08  158.58
      46   20808.      4819.7      0.79173E-10 0.10639E-09-0.15063E-08  141.05

 TOTAL VALUES
 VALUE   0.36016E-09  10000.     0.14193E-09-0.11270E-09-0.29645E-08  299.63
```

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Appendix C
A Simple Illustration-
Shell Elements

Stress output:

```
PRINT S     NODAL SOLUTION PER NODE

  ***** POST1 NODAL STRESS LISTING *****

  LOAD STEP=     1  SUBSTEP=     1
   TIME=    1.0000      LOAD CASE=   0
  SHELL NODAL RESULTS ARE AT TOP/BOTTOM FOR MATERIAL   1

  THE FOLLOWING X,Y,Z VALUES ARE IN GLOBAL COORDINATES

    NODE     SX          SY          SZ          SXY          SYZ          SXZ
     12   90451.      47078.     -0.38537E-23 -29018.      0.12668E-09-0.15729E-07
     46  -91288.     -46655.     -0.39952E-23 -28730.     -0.16560E-09-0.16318E-07
```

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Appendix C
A Simple Illustration-
Shell Elements

- **Revise Boundary Condition -Web**

Grid *2*		*12X*	*23*
		72X	
		71X	
		70X	
	57	*46X*	*34*

X = Constrained

Appendix C
A Simple Illustration-
Shell Elements

Reaction forces and moments:

```
PRINT REACTION SOLUTIONS PER NODE

  ***** POST1 TOTAL REACTION SOLUTION LISTING *****

  LOAD STEP=     1  SUBSTEP=     1
   TIME=    1.0000      LOAD CASE=   0

  THE FOLLOWING X,Y,Z SOLUTIONS ARE IN GLOBAL COORDINATES

    NODE       FX          FY          FZ          MX          MY          MZ
      12  -18793.      2568.4    -0.40700E-10-0.28488E-09-0.12363E-09  118.34
      46   18519.      2178.9    -0.41706E-10-0.38849E-09-0.43746E-09  103.58
      70   4400.8      1511.0     0.13642E-09-0.20379E-10-0.26982E-09 0.15732E-02
      71   106.07      2115.2    -0.67394E-10-0.73225E-11 0.50690E-10 0.28416E-02
      72  -4233.2      1626.5     0.87921E-10-0.93032E-12-0.15933E-09 0.16688E-02

 TOTAL VALUES
 VALUE   0.29740E-09  10000.     0.74539E-10-0.70200E-09-0.93955E-09  221.92
```

FEM Validation and Requirements

Appendix C
A Simple Illustration- Shell Elements

Stress output:

```
PRINT S    NODAL SOLUTION PER NODE
   ***** POST1 NODAL STRESS LISTING *****
   LOAD STEP=     1  SUBSTEP=     1
   TIME=    1.0000      LOAD CASE=   0
  SHELL NODAL RESULTS ARE AT TOP
   THE FOLLOWING X,Y,Z VALUES ARE IN GLOBAL COORDINATES
```

NODE	SX	SY	SZ	SXY	SYZ	SXZ
2	27618.	-0.78609E-13	5004.9	317.01	-7.8946	7591.0
12	76302.	5414.2	3063.9	-6495.1	-0.24406E-09	-0.18744E-07
23	27618.	0.96678E-15	5004.9	317.01	7.8946	-7591.0
34	-29283.	0.75908E-15	-4486.9	277.47	6.1986	10067.
46	-78524.	-5454.5	-3231.2	-6039.1	-0.37655E-09	-0.27518E-07
57	-29283.	-0.68718E-13	-4486.9	277.47	-6.1986	-10067.
70	-29453.	-10396.	-0.65793E-25	-19206.	-0.21778E-11	-0.27043E-09
71	-511.56	-146.73	0.16539E-24	-21690.	-0.26030E-11	0.67526E-09
72	28471.	10189.	-0.16263E-24	-20036.	-0.12320E-11	-0.66226E-09

NODE	46	70	57	71	2	57
VALUE	-78524.	-10396.	-4486.9	-21690.	-7.8946	-10067.

MINIMUM VALUES

MAXIMUM VALUES

NODE	12	72	23	23	23	34
VALUE	76302.	10189.	5004.9	317.01	7.8946	10067.

Appendix C
A Simple Illustration- Shell Elements

- **Revise Boundary Condition -Web/Flanges**

Grid			
	2X	12X	23X
		72X	
		71X	
		70X	
	57X	46X	34X

X = Constrained

Patrick Safarian, ANM-120S

Appendix C
A Simple Illustration-Shell Elements

Reaction forces and moments:

PRINT REACTION SOLUTIONS PER NODE

***** POST1 TOTAL REACTION SOLUTION LISTING *****

LOAD STEP= 1 SUBSTEP= 1
TIME= 1.0000 LOAD CASE= 0

THE FOLLOWING X,Y,Z SOLUTIONS ARE IN GLOBAL COORDINATES

NODE	FX	FY	FZ	MX	MY	MZ
2	-4087.1	15.080	3395.3	4.2405	-0.27730E-03	26.476
12	-11191.	2371.6	-0.25830E-09	-0.23387E-10	-0.51608E-11	90.292
23	-4087.1	15.080	-3395.3	-4.2405	0.27730E-03	26.476
34	4021.6	12.906	3344.1	-3.8684	-0.27242E-03	22.927
46	11027.	1984.9	-0.19806E-08	0.19600E-10	-0.19187E-11	78.175
57	4021.6	12.906	-3344.1	3.8684	0.27242E-03	22.927
70	3280.1	1801.1	0.23711E-11	0.63627E-12	-0.63500E-11	0.74169E-03
71	109.17	1863.7	0.72721E-12	-0.21000E-12	-0.40583E-11	0.35842E-02
72	-3093.9	1922.7	0.31072E-11	-0.57332E-12	-0.66728E-11	0.80487E-03

TOTAL VALUES

VALUE	0.43156E-09	10000.	0.13263E-09	-0.47127E-11	-0.24343E-10	267.28

Appendix C
A Simple Illustration-Shell Elements

Stress output:

PRINT S NODAL SOLUTION PER NODE
***** POST1 NODAL STRESS LISTING *****
LOAD STEP= 1 SUBSTEP= 1
TIME= 1.0000 LOAD CASE= 0
SHELL NODAL RESULTS ARE AT TOP

THE FOLLOWING X,Y,Z VALUES ARE IN GLOBAL COORDINATES

NODE	SX	SY	SZ	SXY	SYZ	SXZ
2	55518.	0.64393E-14	16762.	-26.291	-0.36833E-11	-1374.3
12	56596.	4139.0	11175.	-7026.6	-0.52061E-11	-0.25440E-08
23	55518.	0.57057E-27	16762.	-26.291	0.51723E-11	1374.3
34	-59146.	-0.99092E-28	-17843.	-22.036	-0.13554E-11	-1508.8
46	-59005.	-4197.3	-11896.	-6571.9	-0.46591E-11	0.18765E-08
57	-59146.	0.53970E-14	-17843.	-22.036	-0.89547E-11	1508.8
70	-26070.	-8293.8	-0.80341E-26	-19158.	-0.20563E-11	-0.34399E-10
71	-543.64	-155.94	-0.80243E-27	-19515.	-0.24228E-11	-0.33095E-11
72	25025.	8050.5	-0.61465E-26	-20014.	-0.12673E-11	-0.23563E-10

MINIMUM VALUES

NODE	34	70	34	72	57	34
VALUE	-59146.	-8293.8	-17843.	-20014.	-0.89547E-11	-1508.8

MAXIMUM VALUES

NODE	12	72	23	57	23	57