# FEM Validation

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# FEM Validation and Verification

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- Each FE model which is used to substantiate flight material must be verified
- Depending on the complexity of the model and the analysis this can be a purely simulation based verification or combined with comparisons to tests
- Focus of this presentation are the simulation based checks
- The results are documented in a FEM check sheet or a FEM validation report

# RUAG Background

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- 95% of analyses are structural linear static, remaining are eigenmodes, nonlinear static (contact / elastoplastic material / postbuckling) and dynamic
- Other analysis methods (multiphysics, nonlinear hyperelastic etc) are rarely used
- Preprocessor: MSC.Patran / Altair Hyperworks
- Solver: MSC.Nastran

# Definitions

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**Main Focus**

- Computer Aided Accuracy Checks
  - Ensure that the model represents the physical system (e.g. masses, lengths, units, loads, materials, thicknesses)
- Validity Checks
  - Ensure the model is mathematically accurate. Validity checks do *not* ensure the accuracy of the model in representing a physical system, just that the model will give mathematically correct results.
- Correlation
  - Verify that the model represents the physical system by comparing it to hand calculations, test data or other known sources. Verifies primarily the assumptions and abstractions made during modeling

# Computer Aided Accuracy Checks

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- Geometric Checks
- Boundary Conditions and Constraints
- Loading
- Material and Element Properties
- Mesh Quality
- Model Units
- Solver Type

# Computer Aided Accuracy Checks

- Geometric Checks
  - Dimensions: Check that the dimensions in the FE model correspond to the drawings, take a measurement in each dimension x,y,z. Commonly, errors are introduced when importing CAD data
  - Masses: Compare the overall mass in the model to the expected part / assembly mass
  - Coordinate systems: Describe and check the most important coordinate systems (load systems, BC systems global A/C system, material systems). Are the axes correct? Some elements (e.g. RBE in Nastran) use the node coordinate system for the different element DOFs

# Computer Aided Accuracy Checks

- Boundary Conditions and constraints
  - Make sure that constraints are in the correct positions and the correct DOFs are restrained
  - After analysis run, check that SPC forces only occur at the mount points of the model
  - Document and justify the boundary conditions in the report
- Loads
  - Check the direction, magnitude and location of applied loads. Common errors are incorrect coordinate system associated with the loads, especially when importing loads from other sources
  - Document the load cases occuring in the model and describe the loads contained therein
  - The origin of the loads must be referenced or described in the validation report

# Computer Aided Accuracy Checks

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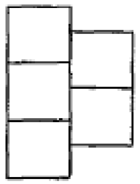
- Material and Element Properties
  - Check that the material values correspond to the in the material spec and include all the needed information (thermal expansion coefficient, reference temperature, density, etc). Check that the correct materials are assigned to the respective parts
  - Verify beam element cross sections (area, moment of inertia, offsets etc)
  - Mass and inertia properties
  - Stiffnesses of spring elements
  - Proper element use (thickness to area ratio for shell elements etc)
  - Shell Element Thickness assignments. Note the reason if thicknesses different than the blueprint thicknesses are used

# Computer Aided Accuracy Checks

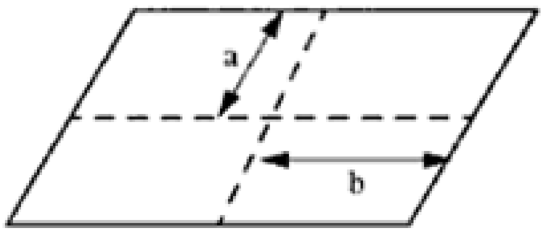
- Meshing
  - All surfaces should be appropriately covered
  - Free Edges / Faces: Appropriate Preprocessor tools should be used to show free edges. Most common error is a zipper

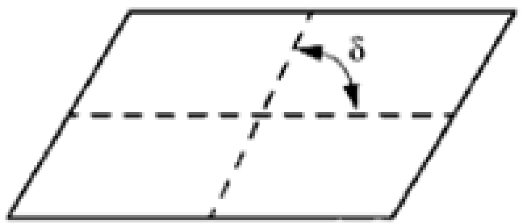


  - Duplicate nodes / elements: Free nodes can cause singularity errors while duplicate elements can change stress results
  - Element normals should be aligned consistently

# Computer Aided Accuracy Checks

- Element Quality
  - Element quality limits depend on the solver used and can differ greatly, nevertheless, warning and error limits should be established for each solver and at least the following parameters should be checked:
    - Shell Elements: Aspect Ratio, Warp, Skew Angle, Taper Ratio
    - Solid Elements: Aspect Ratio and Taper



# Computer Aided Accuracy Checks

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- Units
  - Consistent units should be used, whether in metric or in imperial
  - The table below gives consistent units where 1 force unit = 1 mass unit * 1 acceleration unit and 1 acceleration unit = 1 length unit / (1 time unit)^2
  - Nonconsistent units can lead to incorrect results e.g. when calculating eigenfrequencies

| Mass | Length | Time | Force | Stress | Energy |
|---|---|---|---|---|---|
| kg | m | s | N | Pa | J |
| ton | mm | s | N | MPa | N-mm |
| lbf $s^2$/in | in | s | lbf | psi | lbf-in |
| kg | mm | ms | KN | GPa | KN-mm |
| g | cm | s | dyne | dy/cm² | erg |
| g | cm | us | 1.0e+07 N | Mbar | 1.0e+07 Ncm |
| g | mm | s | 1.0e-06 N | Pa | |
| g | mm | ms | N | MPa | N-mm |
| slug | ft | s | lbf | psf | lbf-ft |
| kgf $s^2$/mm | mm | s | kgf | kgf/mm² | kgf-mm |
| kg | mm | s | mN | kPa | |

# Computer Aided Accuracy Checks

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- Solver / Solution type
  - Are the expected deformations small and is no contact or nonlinear material behaviour expected ?
  - Linear models use the assumption of small displacements!
  - Is the solver behaviour understood sufficiently for the model?
  - Are the solver / solution types defined correctly in the input deck and are the parameters correct (e.g. no BAILOUT, -1 parameter defined in Nastran)
  - Note the solver type and version used for verification in the report, it should be the same as for the analysis

# Mathematical Validity Checks

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- Unit Displacement
- Free-Free Eigenmodes
- Unit Temperature Increase
- Dedicated Load Case
- Unit Gravity Load Case

# Mathematical Validity Checks

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Unit enforced displacement and rotation check:

| |
|---|
| Purpose:<br><br>Verifies that no illegal grounding exists in the model. |
| Input:<br><br>Apply a unit displacement vector close to the CG of the model for each of the translational and rotational DOF of the model and calculate each resulting load case with the static solver |
| Expected Result:<br><br>Visualize the results in the postprocessor, the model should move one length unit as a rigid body. |

# Mathematical Validity Checks

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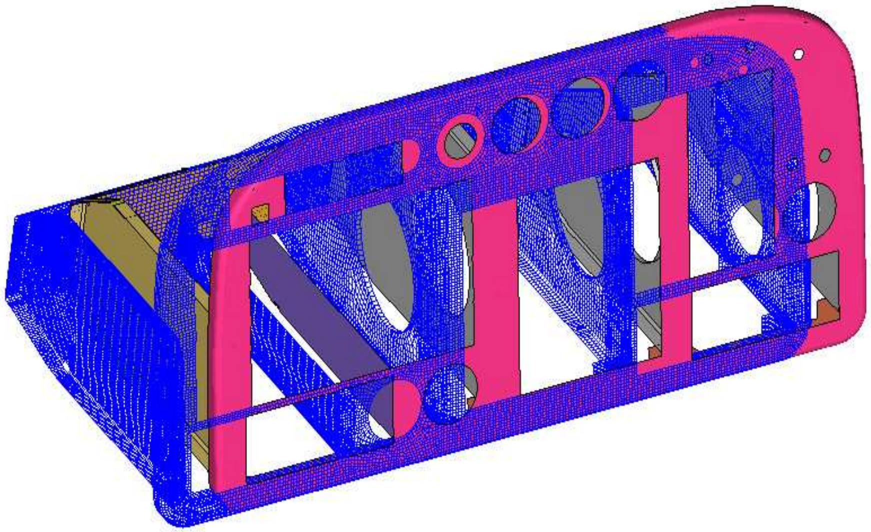

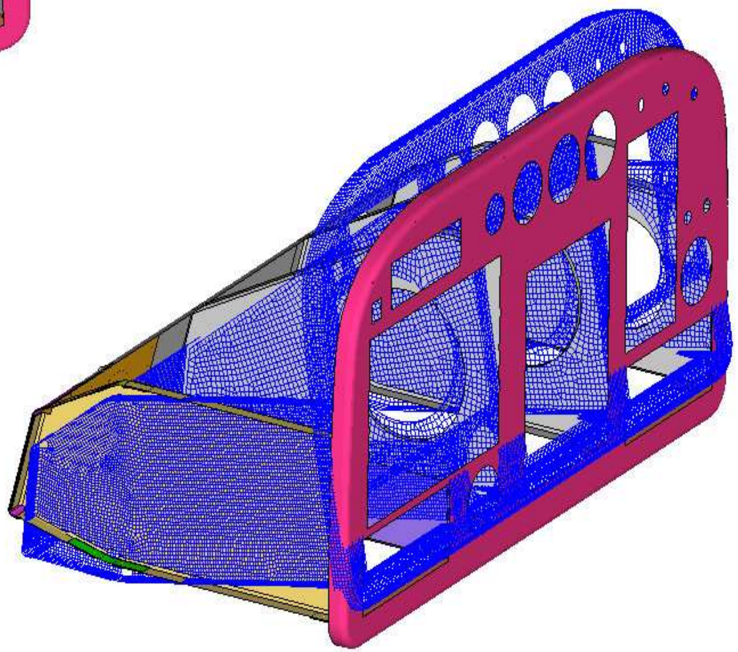

# Mathematical Validity Checks

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Free-Free Dynamic Check:

| |
|---|
| Purpose:<br><br>Show that the model behaves as a rigid body when unconstrained |
| Input:<br><br>Remove all constraints from the model and run Eigenmode solution |
| Expected Result:<br><br>Result should be 6 Eigenfrequencies close to 0 (< $10^{-2}$) with rigid body motion in each DOF. More eigenfrequencies close to 0 point to mechanisms in the model, less to illegal constraints |

# Mathematical Validity Checks

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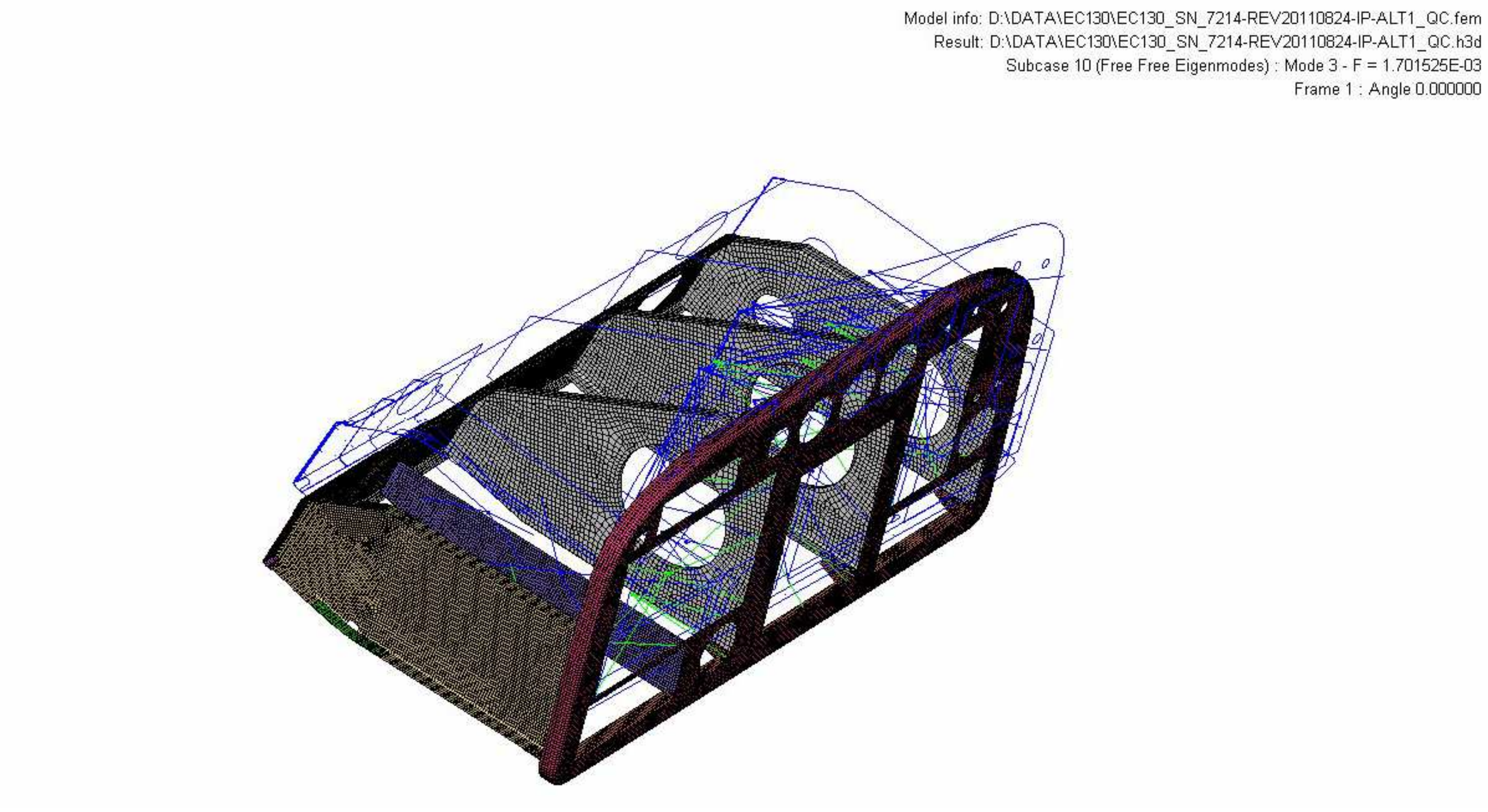

# Mathematical Validity Checks

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## Unit Gravity Loading:

| |
|---|
| Purpose:<br><br>Verify that the model provides meaningful results under inertial loading |
| Input:<br><br>Apply constraints and unit gravity loading in each translational DOF |
| Expected Result:<br><br>Result should show no large displacements for linear solutions. Additionally, forces and moments should only be obtained at the constraint locations. The forces should add up to the total weight for the model in the input loading direction and should be zero for all other directions |

# Mathematical Validity Checks

Dedicated Load Case:

| |
|---|
| Purpose:<br><br>Check the model for singularities, small deformations, force equilibrium and residuals |
| Input:<br><br>Use realistic load case and appropriate constraints |
| Expected Result:<br><br>Deformations should be small. Constraint and applied forces should be in equilibrium. No inappropriate singularities should exist in the model. The normalized value of residual loading should be small (e.g. Nastran Epsilon $< 10^{-8}$) |

# Force Equilibrium

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OLOAD Resultant

| SUBCASE/ | LOAD | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | DAREA ID | TYPE | T1 | T2 | T3 | R1 | R2 | R3 |
| 0 | 7 | FX | -1.698315E-02 | ---- | ---- | ---- | -5.081908E+06 | -9.896120E+01 |
| | | FY | ---- | -6.412354E-03 | ---- | -7.514633E+01 | ---- | 9.941594E+01 |
| | | FZ | ---- | ---- | -7.780754E-03 | 5.791170E+01 | 5.095341E+06 | ---- |
| | | MX | ---- | ---- | ---- | 9.465669E+00 | ---- | ---- |
| | | MY | ---- | ---- | ---- | ---- | -1.205979E+04 | ---- |
| | | MZ | ---- | ---- | ---- | ---- | ---- | -3.300800E+00 |
| | | TOTALS | -1.698315E-02 | -6.412354E-03 | -7.780754E-03 | -7.768963E+00 | 1.372500E+03 | -2.846062E+00 |

0 SPCFORCE RESULTANT

| SUBCASE/ | LOAD | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | DAREA ID | TYPE | T1 | T2 | T3 | R1 | R2 | R3 |
| 0 | 7 | FX | 1.698312E-02 | ---- | ---- | ---- | 1.227183E+00 | -7.131656E-01 |
| | | FY | ---- | 6.412358E-03 | ---- | -4.633506E-01 | ---- | 3.559231E+00 |
| | | FZ | ---- | ---- | 7.780789E-03 | 8.232316E+00 | -1.374047E+03 | ---- |
| | | MX | ---- | ---- | ---- | 0.000000E+00 | ---- | ---- |
| | | MY | ---- | ---- | ---- | ---- | 0.000000E+00 | ---- |
| | | MZ | ---- | ---- | ---- | ---- | ---- | 0.000000E+00 |
| | | TOTALS | 1.698312E-02 | 6.412358E-03 | 7.780789E-03 | 7.768965E+00 | -1.372819E+03 | 2.846065E+00 |

# Normalized Residual Loading

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The linear static solution solves the equation

$$Ku = P$$

The normalized Residual Loading is defined as

$$\varepsilon = \frac{u^T \cdot \delta P}{u^T \cdot P}$$

with

$$\delta P = Ku - P$$

# Singularities

- Singularities in linear analysis can stem from different sources:
  - Missing Elements
  - 2D Shells with normal rotation unconstrained (Nastran)
  - Solid model with rotational DOFs at the corners unconstrained (Nastran)
  - Incorrect beam offset modeling
  - Incorrect multipoint constraints
  - Mechanisms and free bodies
  - Low rotational stiffnesses
  - Abrupt stiffness changes
- Singularities generally decrease the accuracy of the model and should be corrected or constrained

# Mathematical Validity Checks

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Unit Temperature Increase:

| | |
|---|---|
| Purpose:<br><br>Verifies that the model provides accurate displacements due to temperature loading. | |
| Input:<br><br>Create kinematic mount for the model (one node restricted in all 6 DOF) and set all expansion coefficients and reference temperatures to the same value. Apply a one unit temperature increase. | |
| Expected Result:<br><br>Strains / stresses throughout the model should be zero. Compare distortion with hand calculation. | |

# FEM Quality Report

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- The purpose of the FEM ValidationReport is to document the checks outlined in this presentation and to describe the model in such a detail that another engineer can understand the model
- For smaller models, the model description is included in the stress analysis report and a FEM check form is filled out

# Further Reading

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1.) MSC Nastran Linear Static Analysis Users Guide, MSC, 2008

2.) Finite Element Modeling Continuous Improvement (FEMCI), Section Validity Checks, available at http://femci.gsfc.nasa.gov/validitychecks/

# Validity Checks

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Do not blindly trust the model, use common sense when evaluating the results

Thank you for your attention!