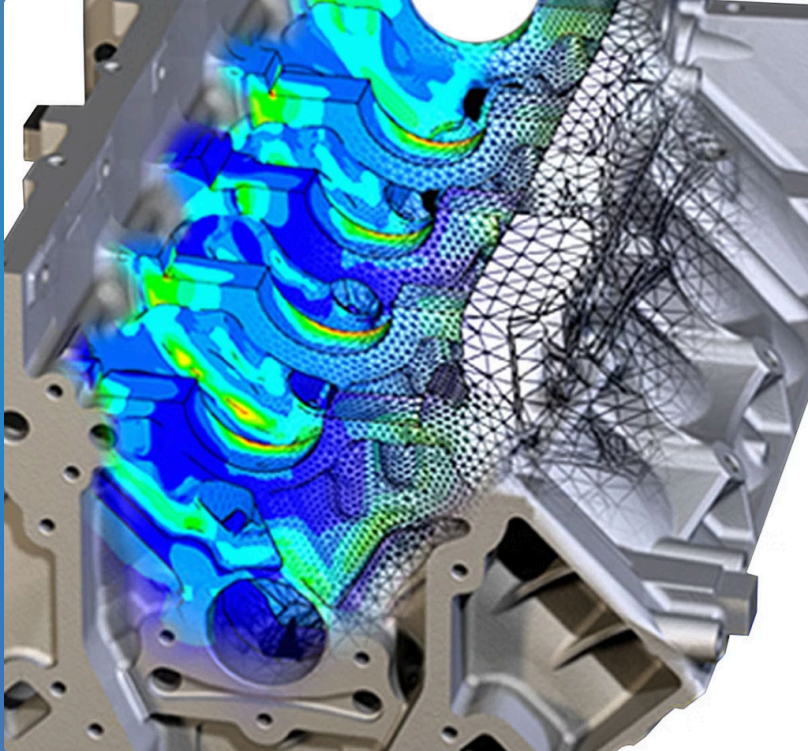


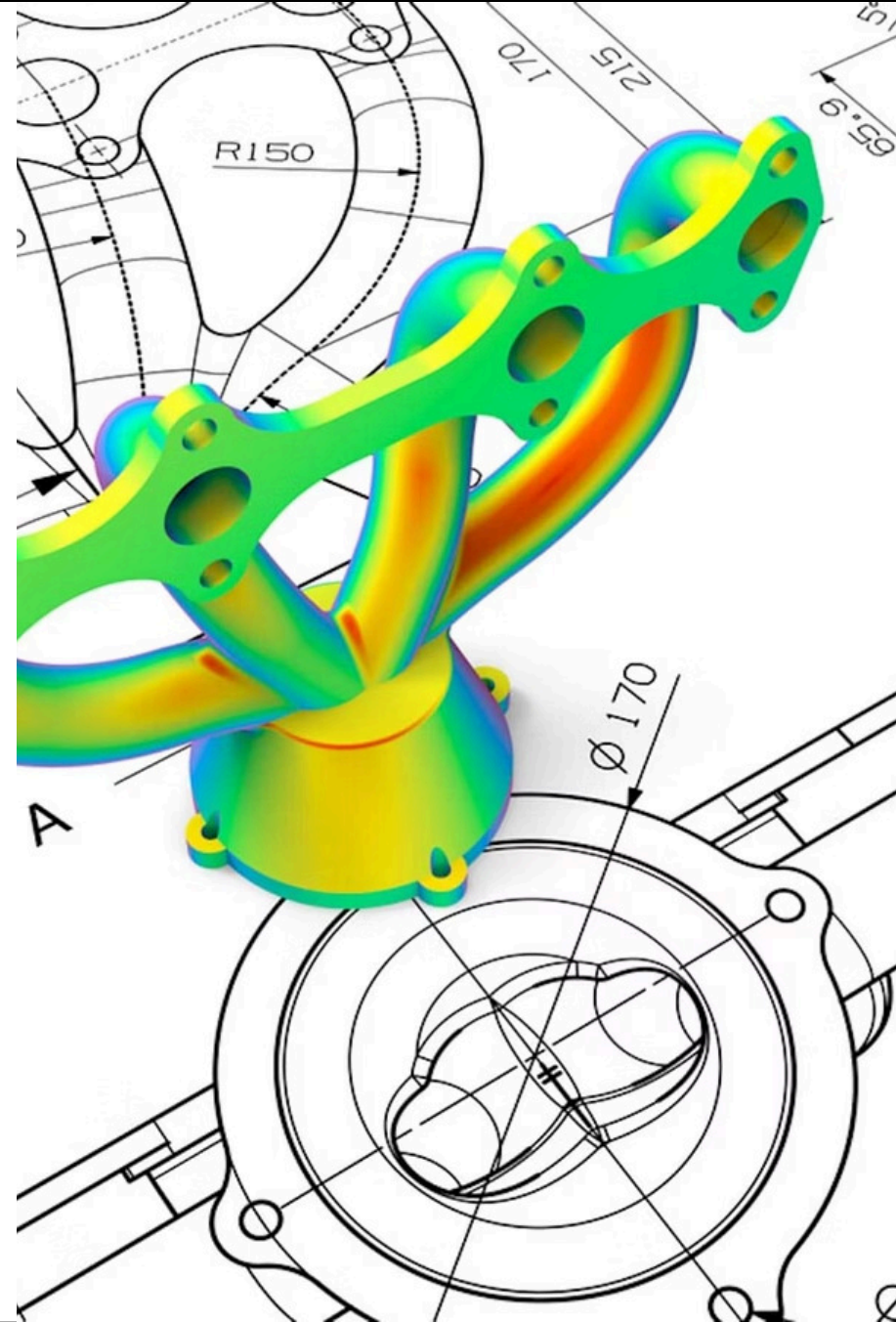


FEA Simulation Best Practices

A Comprehensive Guide to Setting Up Physics-Based Simulations

1. Project Framing & Physics Definition

Setting the foundation for accurate and meaningful simulation results starts with clear objectives and proper physics selection.



Define the Simulation Objective



Clear Objective

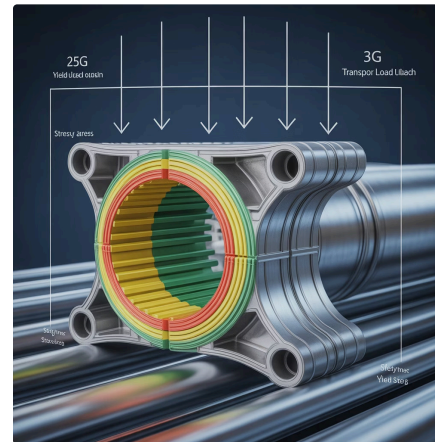
Identify what the analysis is trying to prove or predict.
Without a clear question, results can't drive decisions.



Common Pitfalls

Running FEA "to see stresses" without decision metrics, or missing critical failure modes like buckling or fatigue.

- ❏ **Example:** We need to determine if the compressor bracket will yield under a 3g transport load applied vertically downwards for 10 seconds, considering a safety factor of 1.5 against the material's yield strength of 250 MPa. If the analysis shows yielding, the bracket design must be revised to meet these criteria, otherwise, it's approved for manufacturing.



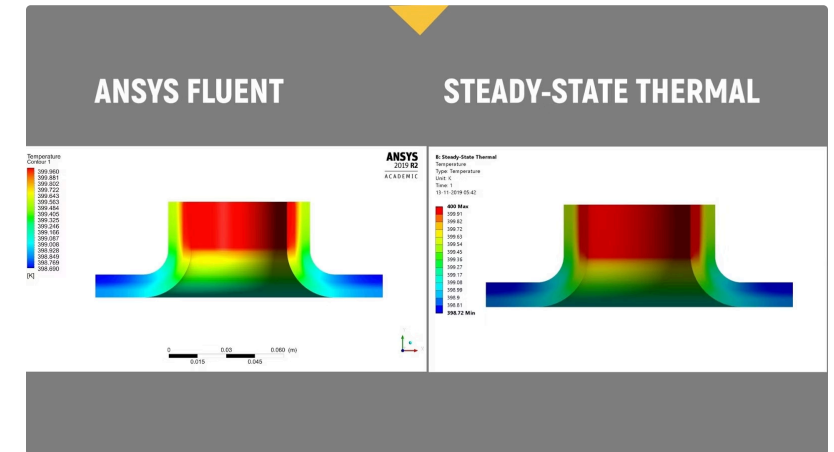
Identify Physics & Analysis Type

Select Appropriate Physics

Choose between static, dynamic, thermal, or CFD-coupled analysis.

Wrong physics selection leads to false results and wasted computational resources.

- Static analysis for steady loads
- Dynamic for time-varying forces
- Thermal-structural coupling for temperature effects
- Nonlinear for large deformations or material plasticity



Example: Thermal-structural coupling for seal leakage analysis under 300°C thermal cycling.

Define Success Criteria

Quantify Limits

Establish acceptable limits for stress, deflection, and temperature. This enables clear go/no-go engineering decisions.

Numerical Criteria

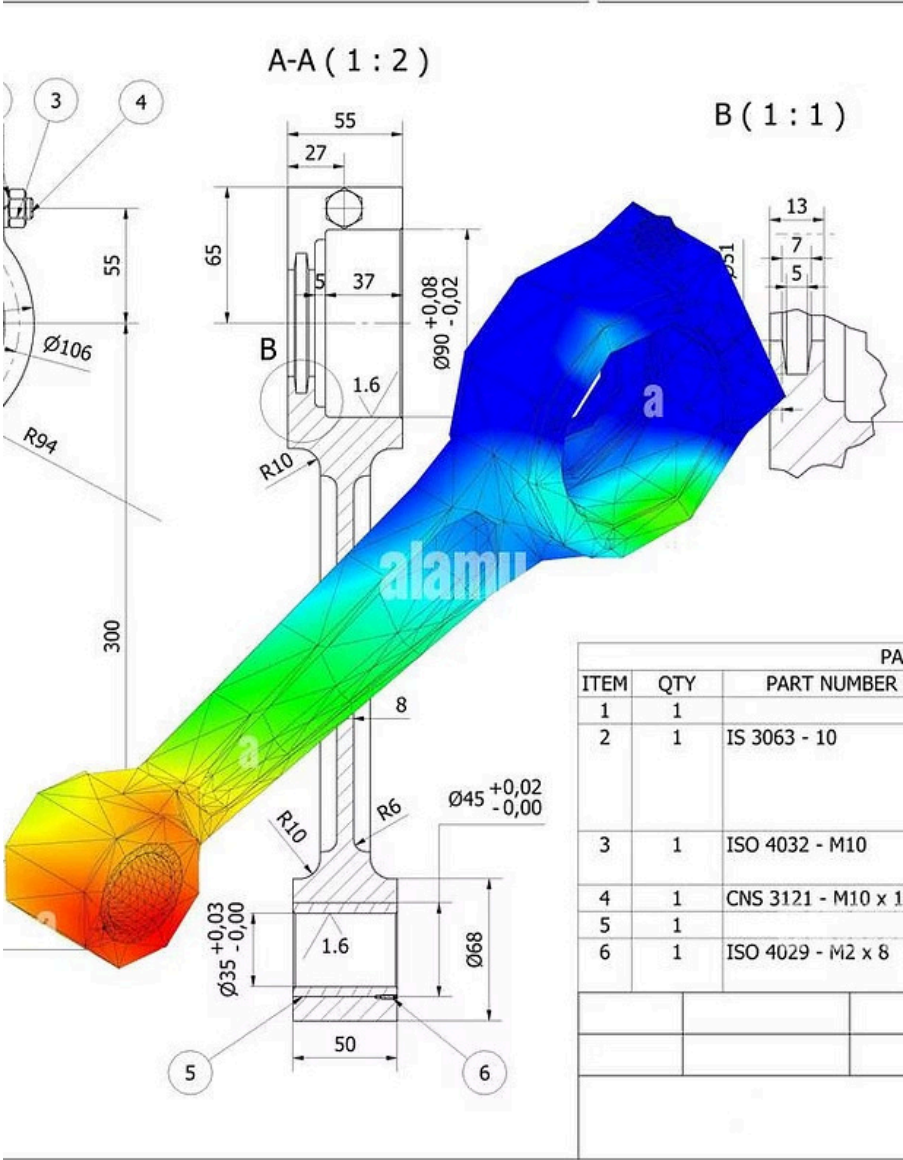
Use specific values, not subjective interpretation. Apply safety factors with documented engineering basis.

Example Criteria

Maximum stress $< 0.6 \sigma_{\text{yield}}$;
tip deflection $< 0.3 \text{ mm}$ under operational loads.

2. Geometry Preparation & Simplification

Clean, well-prepared geometry is essential for successful meshing and accurate results.



Geometry Cleanup

01

Fix Defects

Repair gaps, overlaps, and interferences that cause mesh failures.

03

Resolve Assemblies

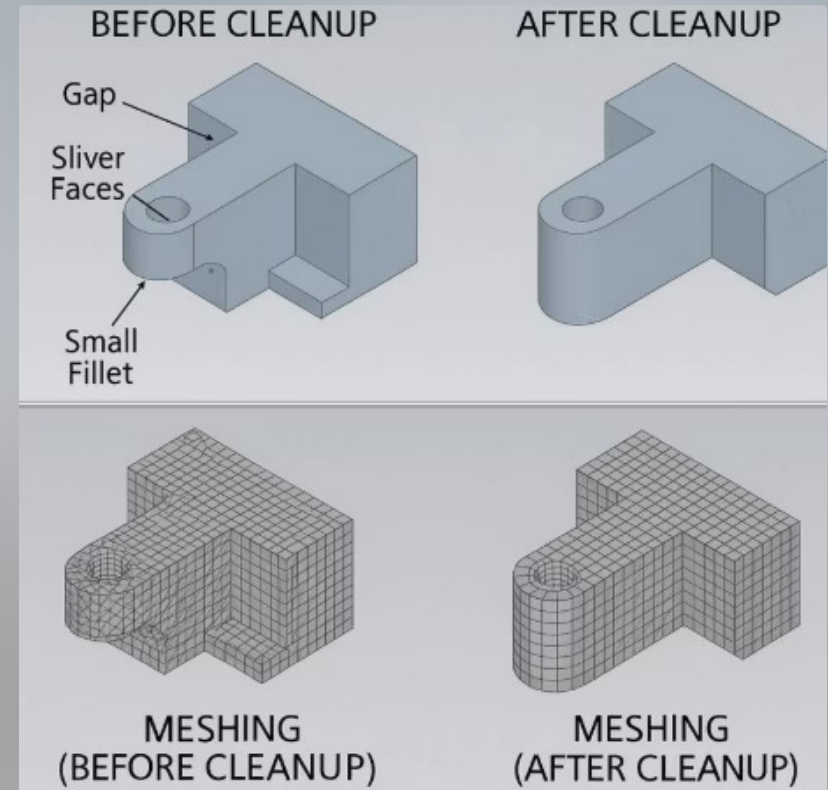
Address unresolved mates and contact interfaces.

Example: Repair 0.01 mm gap between flange and cover to ensure proper contact definition.

02

Ensure Watertight

Verify all surfaces are properly connected without gaps.

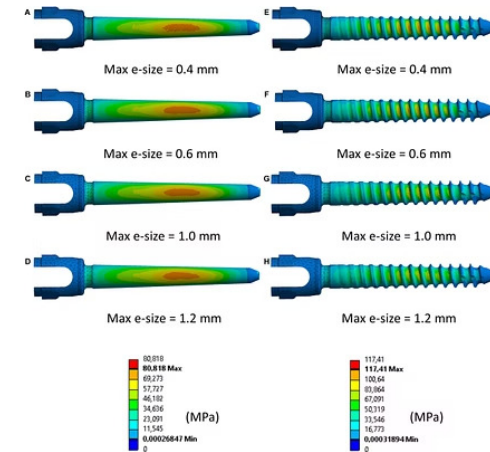


Simplification Strategy

Remove Non-Critical Features

Strategic simplification reduces computational time without sacrificing accuracy. Focus on load paths and stress concentration areas.

- Replace fastener threads with simplified connections
- Remove logos, text, and decorative features
- Suppress non-structural components



Example: Replace M6 screws with bonded contact to reduce mesh complexity while maintaining joint stiffness.

Symmetry and Idealization

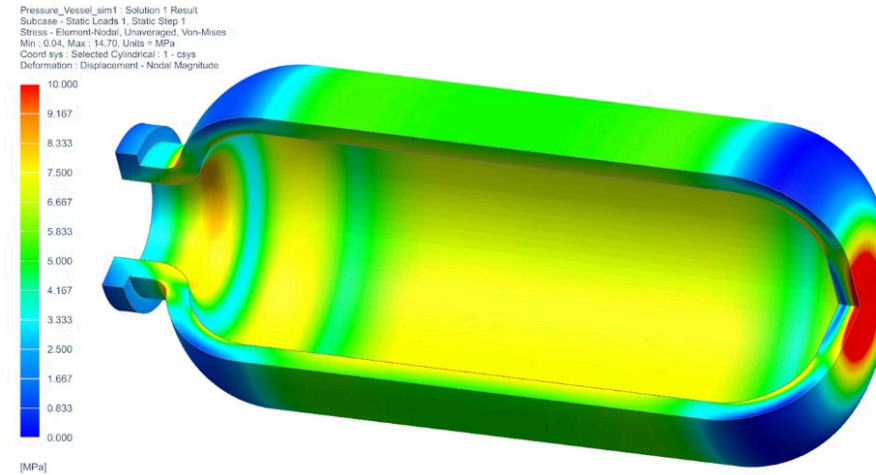
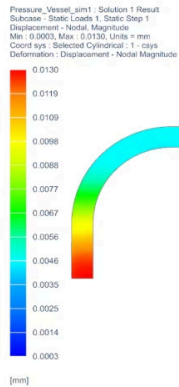
Leverage Symmetry

Use symmetry planes or 2D sections where applicable to dramatically reduce degrees of freedom and solution time.

Apply Correctly

Ensure loads and geometry are truly symmetric. Apply proper boundary constraints on symmetry planes.

Example: Axi-symmetric model of pressure vessel with symmetry boundary conditions reduces DOF by 75%.



MECHANICAL PROPERTIES



3. Material Modeling & Data Source

Accurate material properties are fundamental to simulation fidelity and reliable predictions.

Material Definition



Elastic Properties

Assign correct Young's modulus, Poisson's ratio, and thermal properties. Properties drive stiffness and stress distribution.



Temperature Dependence

Include property variation with temperature for thermal analyses. Materials weaken significantly at elevated temperatures.



Anisotropy

Consider directional properties for composites, rolled metals, and anisotropic materials.

Example: $E(T)$ for 316 stainless steel decreasing from 200 → 170 GPa across 25–600°C temperature range.

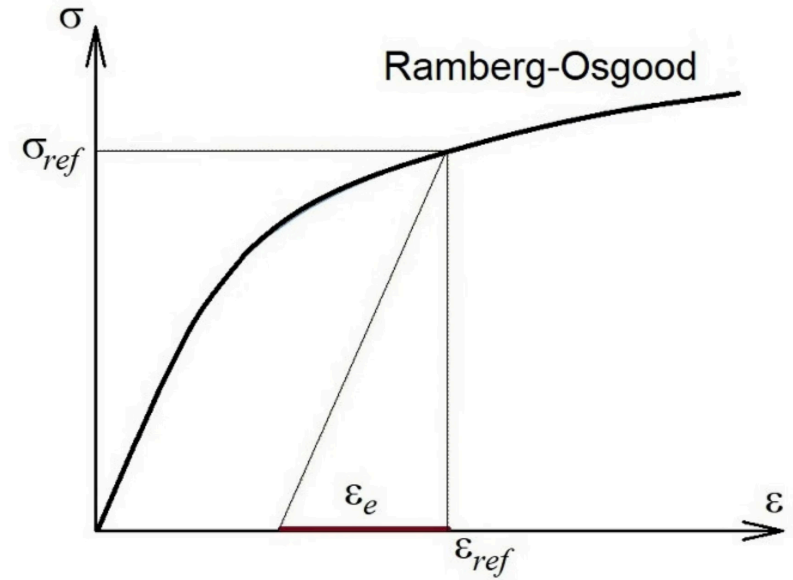
Nonlinear Material Behavior

Beyond Linear Elasticity

Include plasticity, creep, or hyperelasticity when materials exceed yield or experience time-dependent deformation.

Linear material models significantly underpredict permanent deformation and can miss critical failure modes.

- Define stress-strain curves beyond yield point
- Include isotropic or kinematic hardening
- Model creep for high-temperature applications



Example: Ramberg-Osgood model for Al 6061 with yield strength = 270 MPa and hardening behavior.

Data Source & Uncertainty

1

Document Sources

Record material data origin: vendor specs, MMPDS, internal testing, or literature.

2

Apply Tolerance

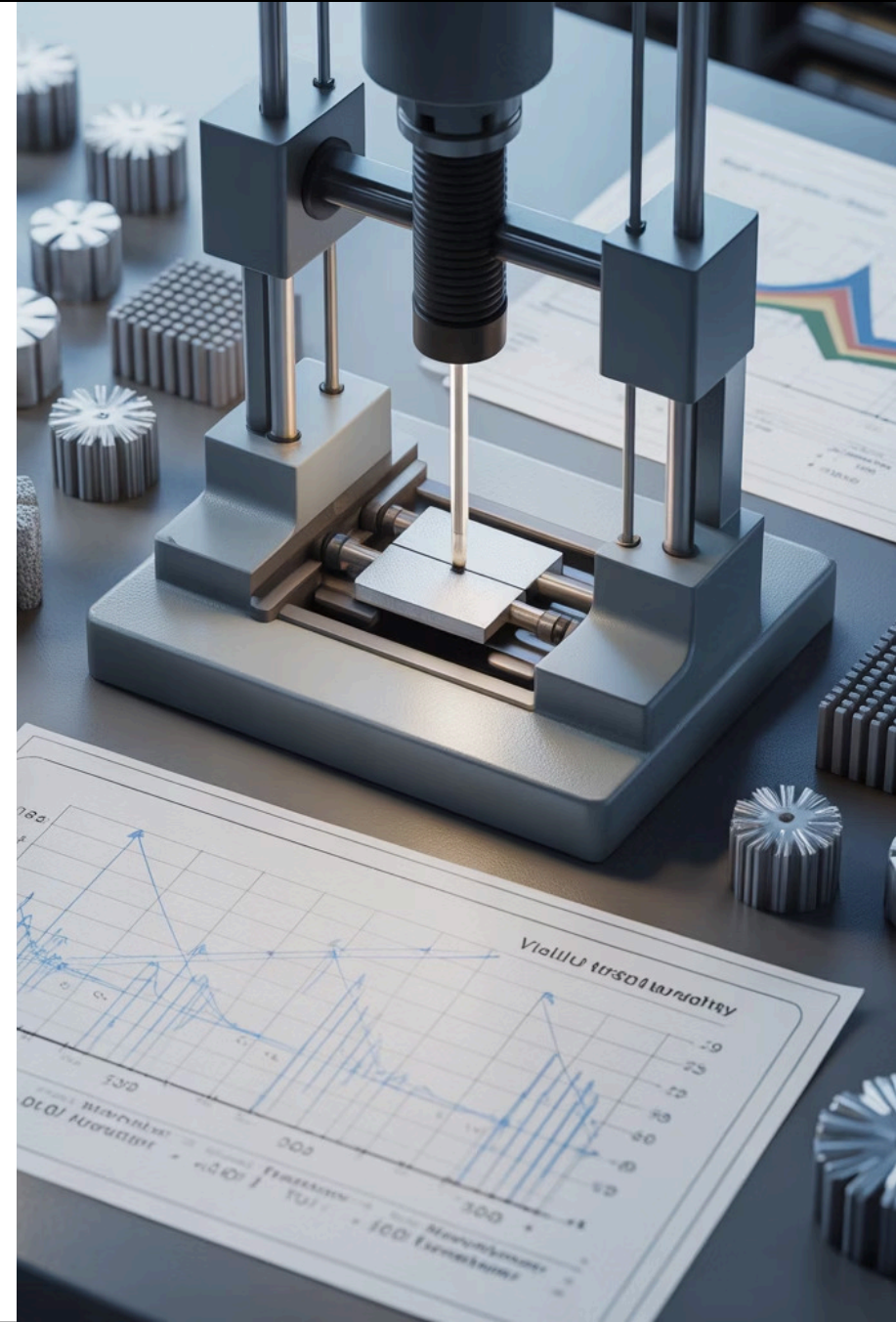
Real materials vary. Include property uncertainty in sensitivity studies.

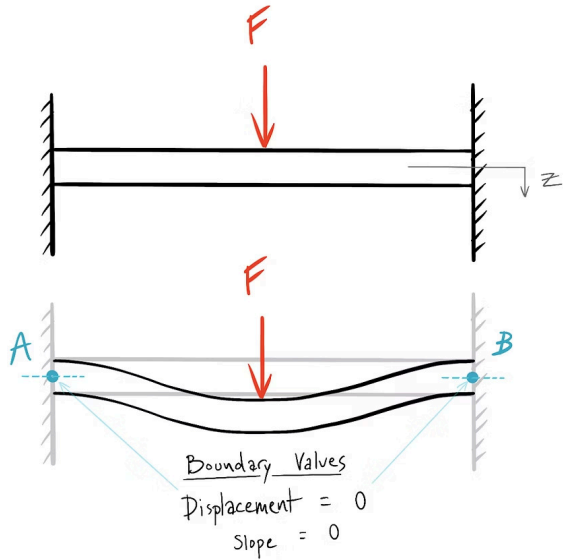
3

Validate Properties

Don't blindly trust catalog values. Verify critical properties through testing when possible.

Example: Yield strength variation captured in parametric sweep to assess design robustness.





4. Boundary Conditions, Loads & Constraints

Realistic loads and constraints are critical—inaccurate BCs dominate the error budget.

Load Identification

Define Magnitudes

Specify realistic load values and directions based on operating conditions, not estimates.

Document Basis

Record how load values were determined: measurements, calculations, or standards.

Include All Sources

Don't forget self-weight, thermal gradients, pressure, and dynamic effects.

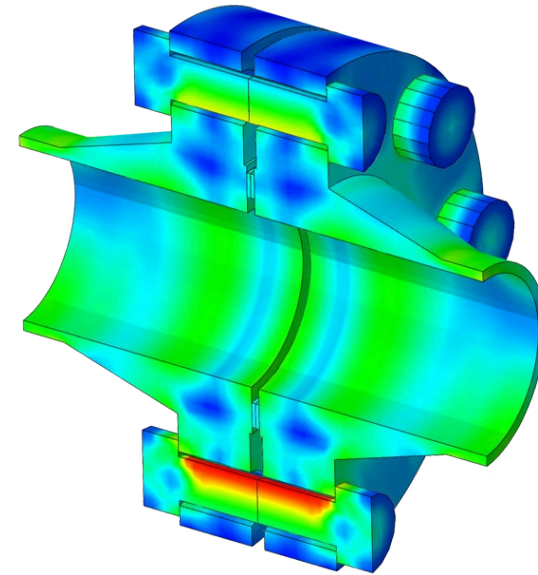
Example: 100 bar internal pressure + 5 N·m torque on shaft + thermal expansion from 350°C operating temperature.

Constraints & Supports

Represent Physical Reality

Boundary conditions must reflect how the part is actually supported. Over-constraint creates artificial stress concentrations.

- Allow appropriate degrees of freedom
- Model flexible supports, not rigid fixes
- Avoid simultaneous constraint at multiple locations
- Prevent rigid body motion without over-restraint



Example: Bolted flange with axial fixity but radial freedom to accommodate thermal expansion.

Load Sequencing

1

Preload First

Apply bolt preload or interference fits in proper sequence.

2

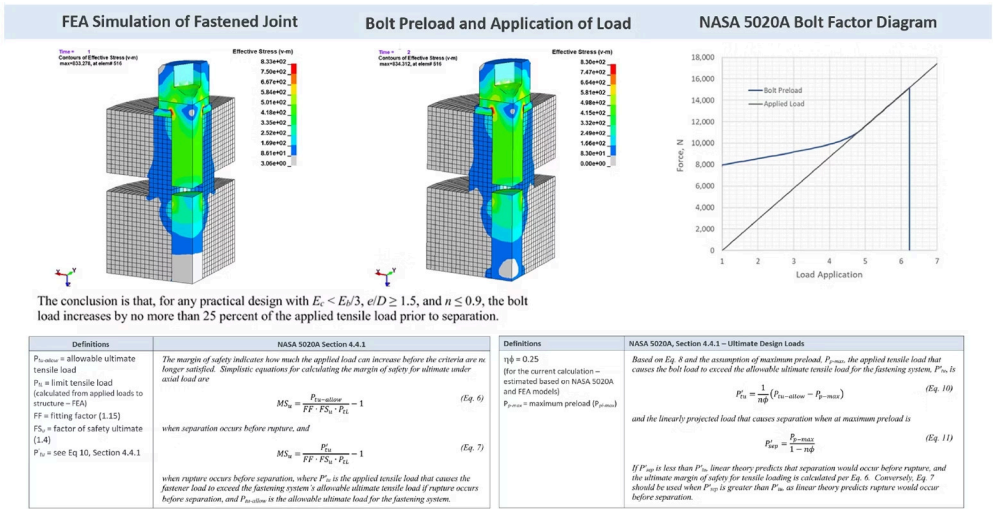
Thermal Effects

Include temperature-induced expansion or contraction.

3

Operating Loads

Apply pressure, forces, and moments in physical order.



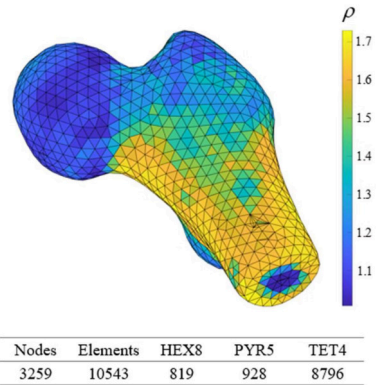
 **Example:** Thermal expansion applied before torque preload to capture residual stress correctly.

5. Meshing & Convergence Strategy

Mesh quality and refinement directly impact solution accuracy and computational efficiency.

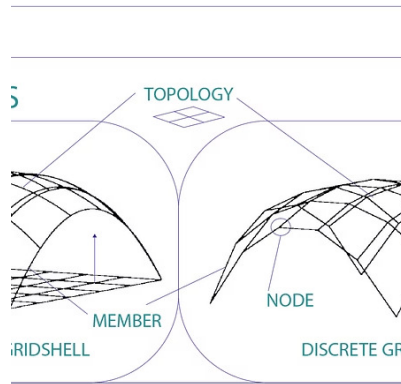


Element Type Selection



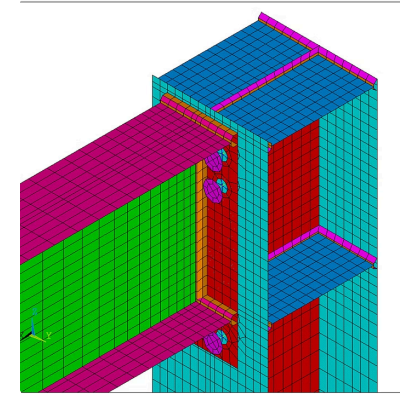
Solid Elements

Use for thick parts, complex 3D stress states, and general geometries.
Tetrahedrals for automatic meshing.



Shell Elements

Efficient for thin-walled structures where thickness $\ll$ other dimensions.
Capture bending accurately.



Beam Elements

For slender members in frames and trusses. Fast solutions for structural systems.

Example: Shell elements for 2 mm sheet metal enclosure, solid elements for crankshaft with complex geometry.

Mesh Quality & Refinement

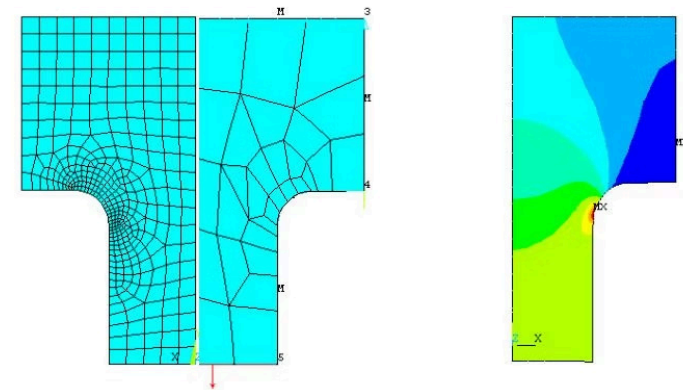
Quality Metrics

Poor element quality causes numerical instability and inaccurate results. Monitor aspect ratio, skewness, and Jacobian.

- Aspect ratio < 5:1 for most elements
- Skewness < 0.8
- Conformal mesh at contact interfaces
- Refine at stress concentrations

Example: High-skew elements near small fillets require local refinement or geometry modification.

FEA of the stress concentration in a notch

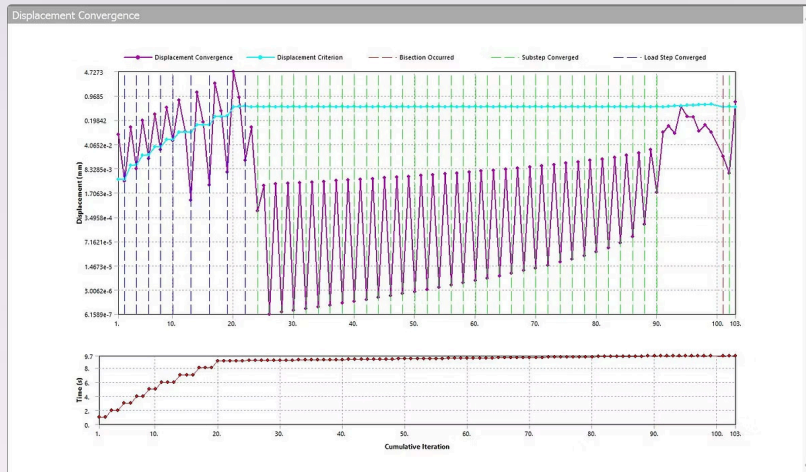


Type of element	mesh density	calculated maximum stress [MPa]
linear - four nodes	rough	1,28
linear - four nodes	fine	1,67
quadratic - eight nodes	rough	1,59
quadratic - eight nodes	fine	1,67

Convergence Study

Prove Mesh Independence

Systematically refine mesh until results change by less than 5%. This validates that discretization error is acceptable.



4

Refinement
Steps

Typical number of
mesh refinements
needed

< 5%

Convergence
Criteria

Maximum acceptable
change in critical
results

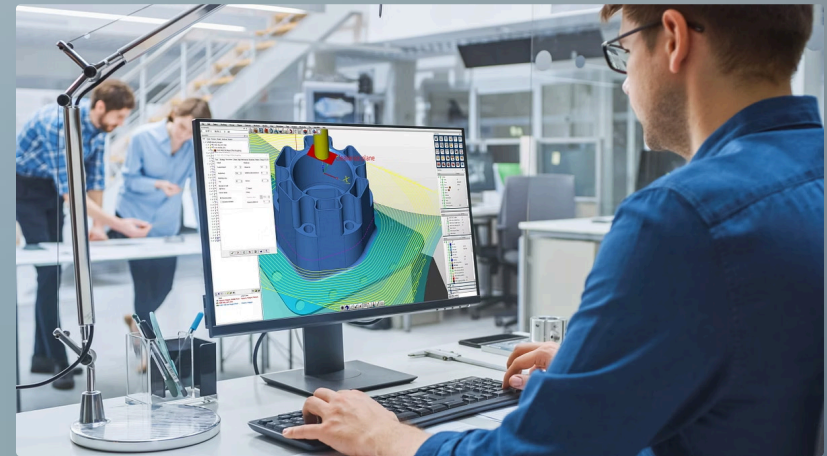
212

Final Stress
(MPa)

Converged fillet
stress value

6. Solver Setup & Numerical Controls

Proper solver configuration ensures solution stability, accuracy, and computational efficiency.



Solver Selection



Implicit Solvers

Best for static, quasi-static, and steady-state problems. Handles nonlinearity through iterative convergence.



Explicit Solvers

Required for high-speed impacts, crash, and highly nonlinear transient dynamics with large deformations.

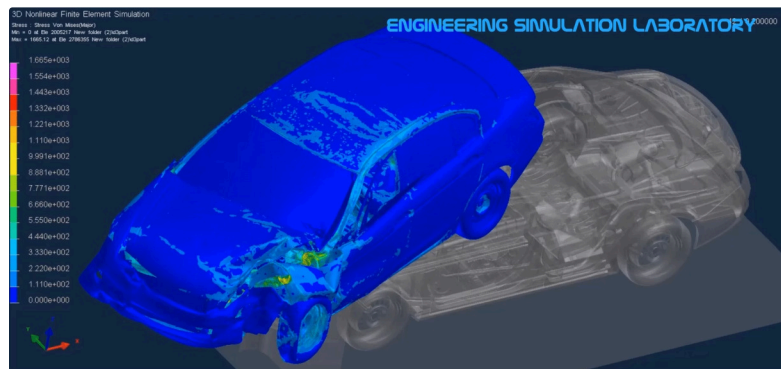


Physics-Specific

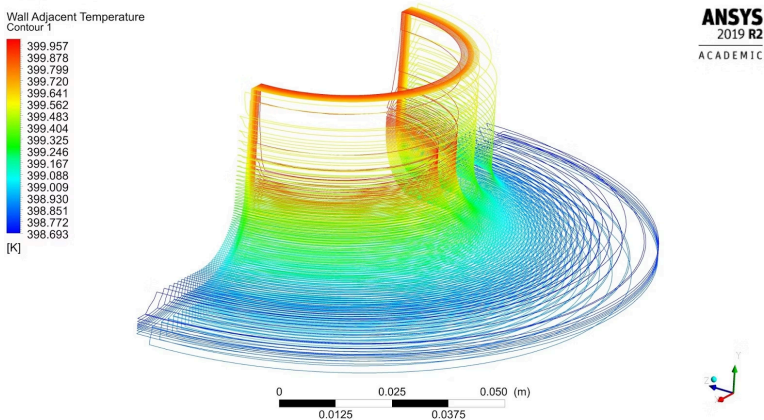
Thermal steady-state, modal analysis, and CFD coupling require specialized solution procedures.

Example: Impact analysis uses explicit solver; thermal steady-state uses implicit solver.

Explicit Solver: Impact Analysis



Implicit Solver: Thermal Analysis



Numerical Controls

Setting appropriate numerical controls is crucial for accurate and efficient simulations. This involves careful configuration of convergence settings and time stepping to ensure stability and precision without excessive runtime.

Force Residual Tolerance

Set to prevent divergence (typically 10^{-3}).

Displacement Convergence

Ensures accurate movement and deformation.

Maximum Iterations

Limits calculations per load step.

Line Search & Stabilization

Methods to enhance solution stability.

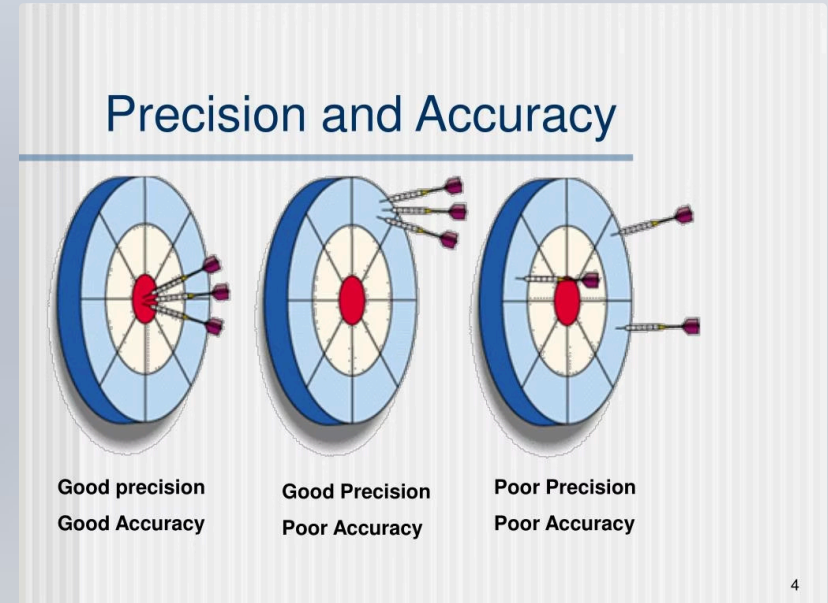
Time Stepping

Adaptive time stepping is essential for capturing rapid changes in dynamic simulations while maintaining numerical stability.

📌 **Example:** Adaptive $\Delta t = 0.001\text{--}0.01$ s with force residual $< 10^{-3}$ for nonlinear contact.

7. Verification (Numerical Accuracy)

Verification confirms the model is solved correctly—checking the math, not the physics.



Force & Moment Equilibrium

01

Sum Reactions

Total reaction forces and moments must balance applied loads.

02

Check Tolerance

Imbalance should be $< 5\%$ of applied loads.

03

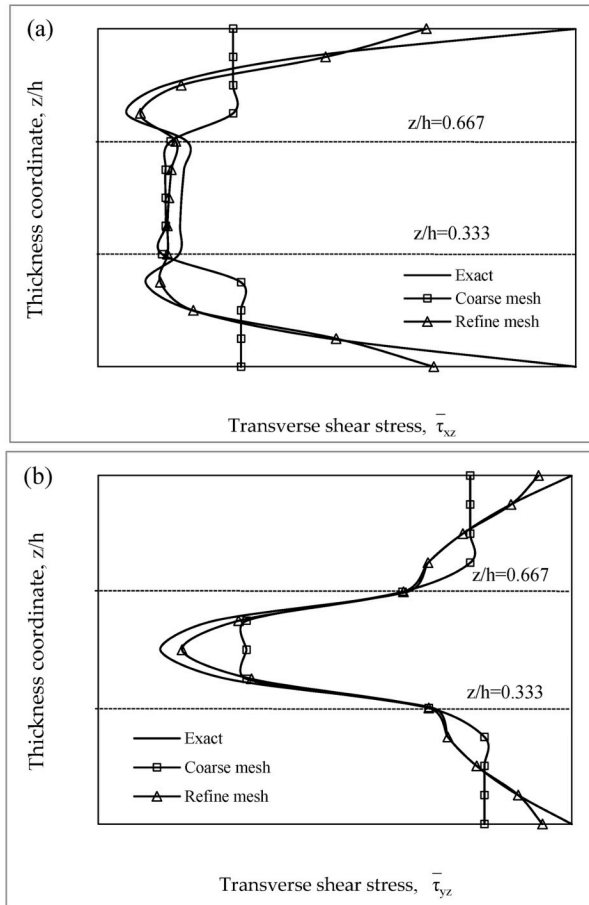
Identify Issues

Large imbalances indicate free nodes, poor constraints, or contact problems.



Example: 10 kN applied load balanced by 9.98 kN reaction force (0.2% error—excellent).

Stress Classification Line (SCL)



Separate Stress Components

Distinguish membrane stress from bending stress—critical for ASME pressure vessel and fatigue codes.

Path-averaged stress through thickness prevents singularity errors at geometric discontinuities.

Example: Membrane stress = 180 MPa, bending stress = 45 MPa at vessel nozzle junction.

Energy Balance

Internal vs. External Work

Total strain energy should equal external work done by loads.

Acceptable Error

Energy imbalance $< 2\%$ indicates good numerical accuracy.

Diagnose Problems

Large mismatch ($>10\%$) reveals contact issues, instability, or stiffness errors.



8. Validation & Correlation

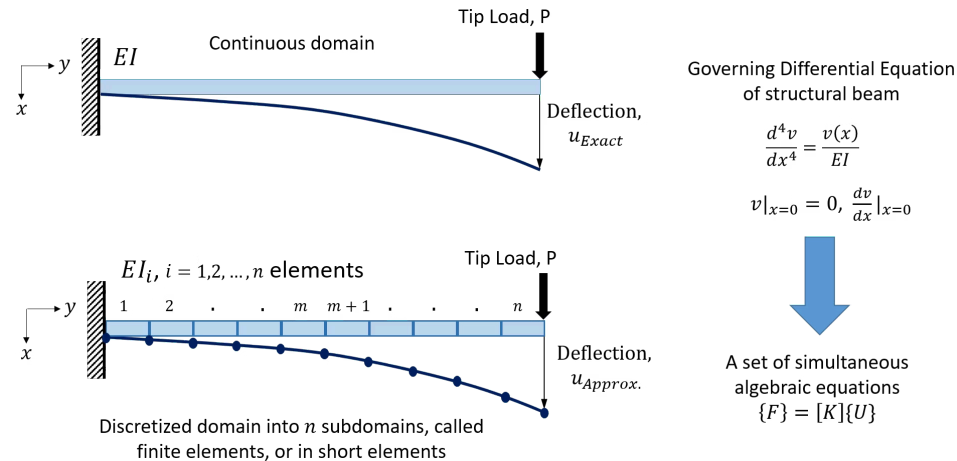
Validation confirms the model represents physical reality—checking the physics, not just the math.

Analytical Validation

Compare with Hand Calculations

Use simplified analytical solutions for beams, plates, or pressure vessels as first-level sanity check.

- Beam deflection formulas
- Thick-walled cylinder equations
- Roark's stress formulas
- Elastic foundation solutions



Detailed Example: Cantilever Beam Deflection

Scenario: A steel cantilever beam ($E=200$ GPa), 1m long with a 20x40 mm rectangular cross-section, has a 100 N point load at its free end.

1. Analytical Calculation (Beam Theory):

Deflection (δ) is calculated as 1.56 mm using beam theory formulas ($I = (\text{width} * \text{height}^3) / 12$, $\delta = (P * L^3) / (3 * E * I)$).

2. FEA Setup and Results:

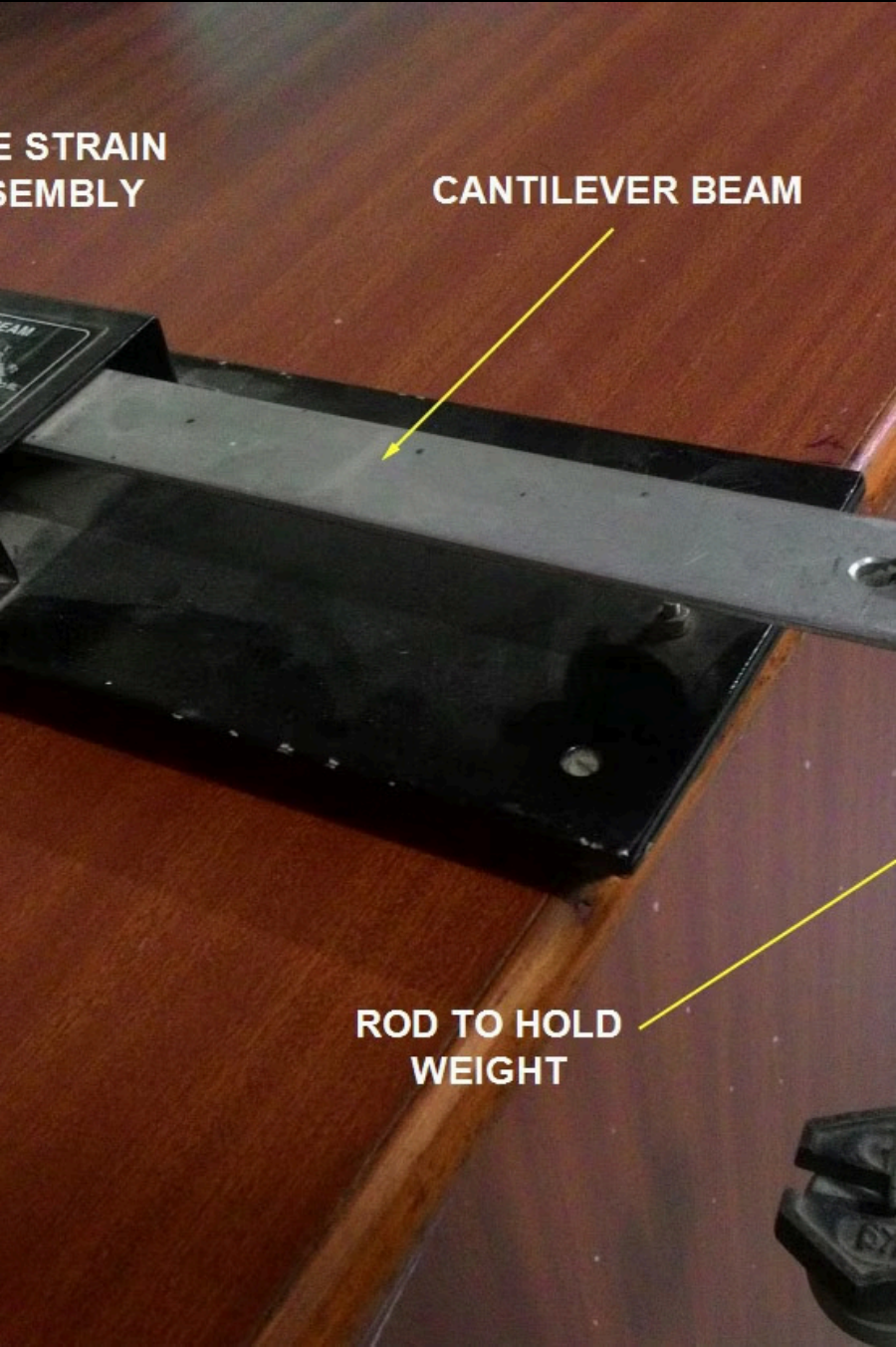
An FEA model, set up with fixed boundary conditions and the 100 N load, yielded a maximum deflection of **1.59 mm**.

3. Comparison and Validation:

The percentage difference between FEA and analytical results is $\approx 1.92\%$. This shows good correlation for this basic scenario.

4. Model Accuracy Conclusion:

The FEA model accurately captures fundamental bending behavior and material properties for simple linear-elastic conditions, building confidence in its predictions. Further validation would involve more complex scenarios or experimental data.



Experimental Correlation

The objective of experimental correlation is to match FEA results with test data, which confirms the physical accuracy of the model.

1

Objective

Match FEA with test data.

2

Importance

Confirms physical accuracy.

3

Example

Measured strain = 850 $\mu\epsilon$, FEA = 870 $\mu\epsilon$.

Common Mistakes



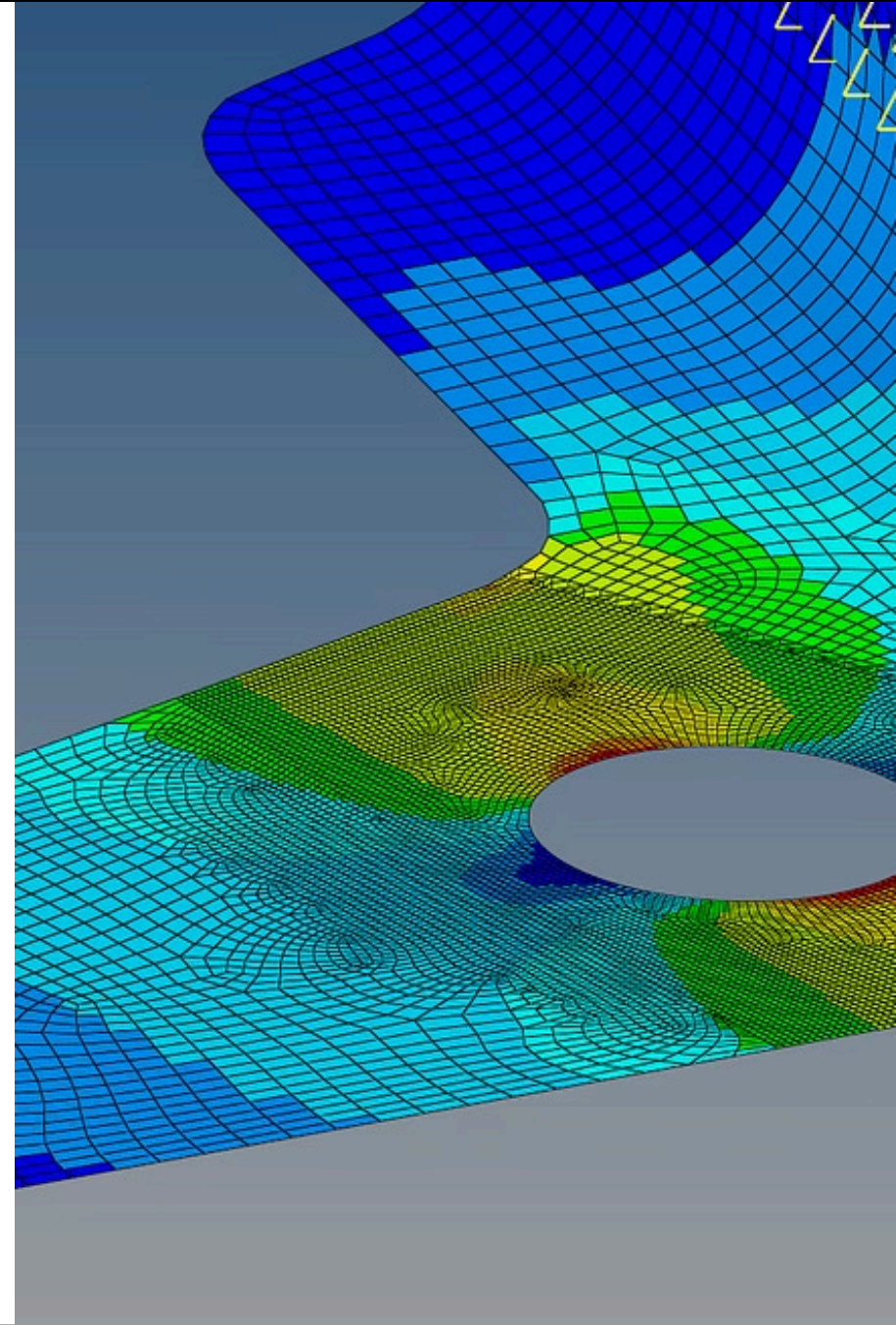
Using uncalibrated sensors/test errors.



Tuning FEA to match test ("curve-fitting") without physics basis.

9. Post-Processing & Interpretation

Extracting meaningful insights from simulation results requires careful interpretation and avoiding common visualization pitfalls.



Contour Interpretation

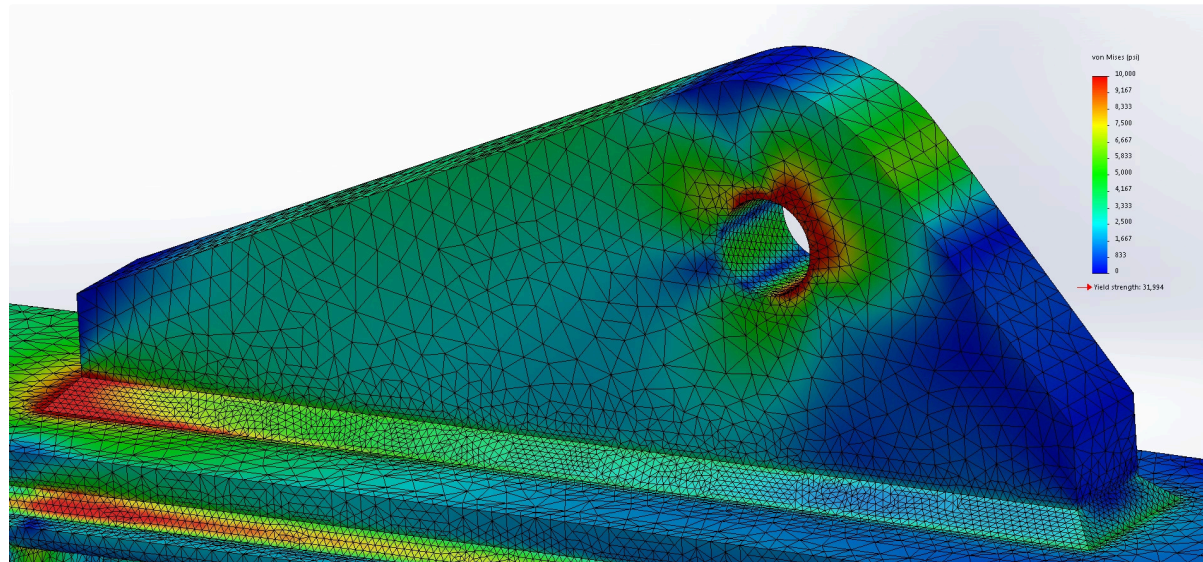
Identify Meaningful Fields

Avoid misreading color maps.

Common Mistakes

- Using max element stress blindly
- Not differentiating nodal vs elemental averaging

❏ **Example:** Ignore red spot at constraint (singularity)



Extract Key Metrics

Compute Values

Max stress, deflection, SF, temperature.

Quantitative Reporting

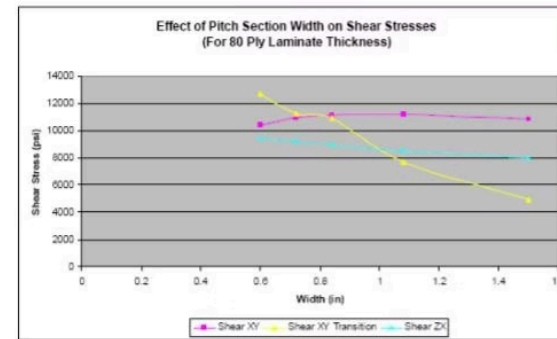
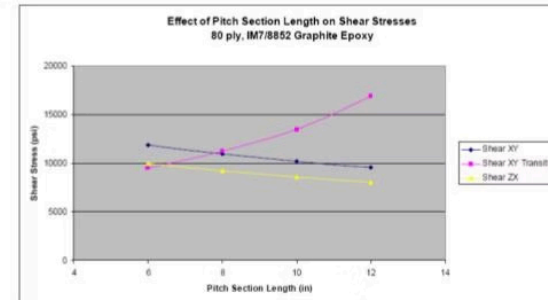
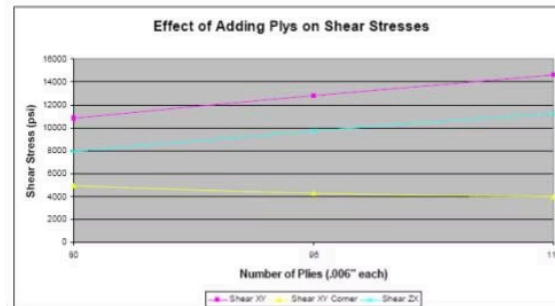
Drives design actions.

Common Mistakes

- No units or coordinate reference
- Using color scale extremes without legend check

❏ **Example:** Stress and elongation on connecting rod

FEA Results



0.4% Elongation

Design Recommendations

Translate Findings

Convert simulation results into tangible design improvements.

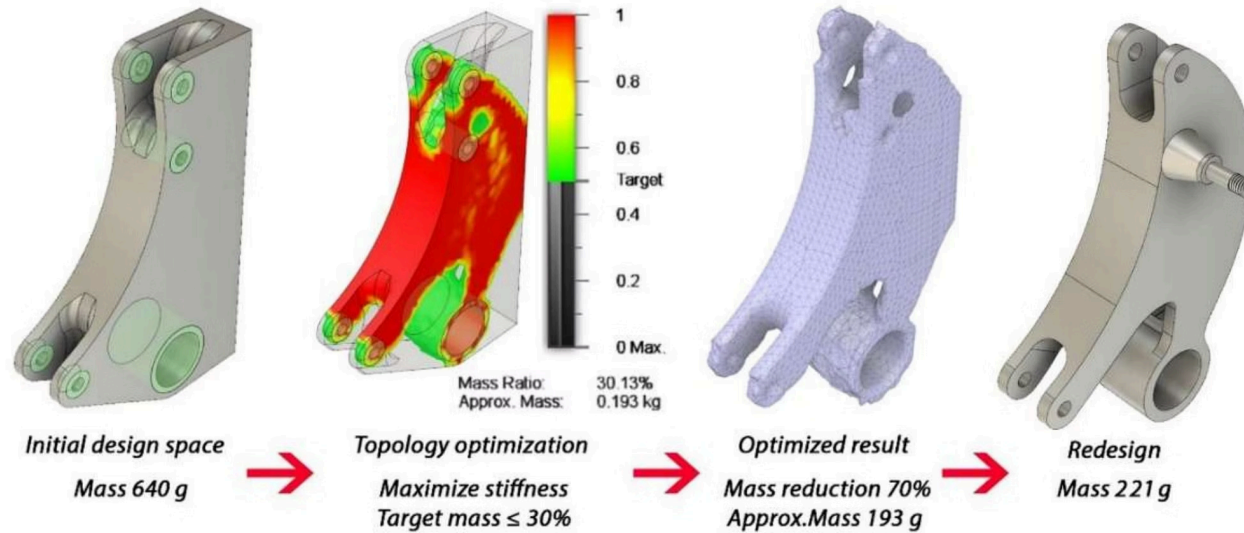
FEA to Action

Deliver actionable insights, moving beyond raw data.

Common Mistakes

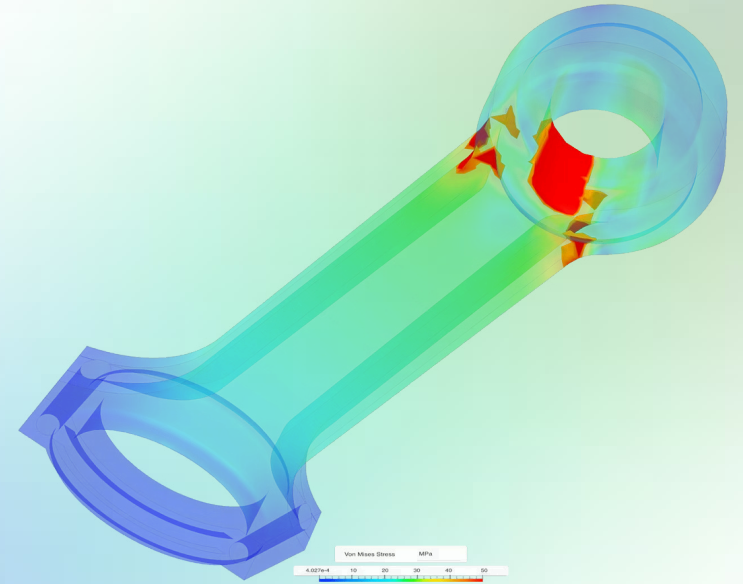
- Reporting results without conclusions.
- Suggesting changes not supported by simulation data.

❑ Example: Optimize weight of bracket using topology optimization



10. Fatigue & Life Prediction

Predicting component life under cyclic loading conditions requires specialized analysis beyond static stress evaluation.



Fatigue Analysis

Fatigue analysis is crucial for ensuring product reliability and safety under dynamic conditions. It helps engineers understand and mitigate the effects of repeated stress on components.



Predict Component Life

Determine operational lifespan under cyclic loads. Utilize S-N/ ϵ -N curves, material properties, and loading history to predict how many cycles a component can endure before failure.

- Assess material response to stress cycles.
- Incorporate various failure criteria.



Prevent Catastrophic Failure

Safeguard structural integrity against unexpected failures due to microscopic crack propagation, even when stresses are below yield strength. Design for finite or infinite life.

- Identify stress concentration points.
- Optimize geometry and material selection.

Common Pitfalls to Avoid

→ Static vs. Cyclic Stresses

Relying solely on static stress analysis overlooks the dynamic nature of fatigue, ignoring stress concentrations and residual stresses critical for accurate prediction.

→ Neglecting Environmental Factors

Surface finish, corrosion, and temperature can drastically reduce fatigue life, even for well-designed components, making environmental considerations vital.

→ Ignoring Mean Stress Correction

Failure to apply theories like Goodman or Gerber can lead to significant over or underestimation of component life, as mean stress heavily influences fatigue.

→ Inaccurate Load History

Incorrectly characterizing load amplitude, frequency, and sequence renders fatigue predictions unreliable, compromising the integrity of the analysis.

Fatigue Analysis Example: Connecting Rod

Analyzing an engine connecting rod under alternating forces to ensure reliability and prevent premature failure.

1	2
Material Properties Material: Forged Steel (AISI 4340) - Sut: 1030 MPa - Sy: 793 MPa - Se': 0.5 * Sut	Loading Conditions - Cyclic Load: 0-45 kN (tension & compression) - Mean Load: 22.5 kN - Stress Concentration Factor (Kt): 2.5

O1

FEM & Static Analysis

3D CAD meshing identified peak stress (550 MPa) at small end bearing hole.

O2

S-N Curve & Correction

Modified S-N curve established; Goodman criterion applied for mean stress effect.

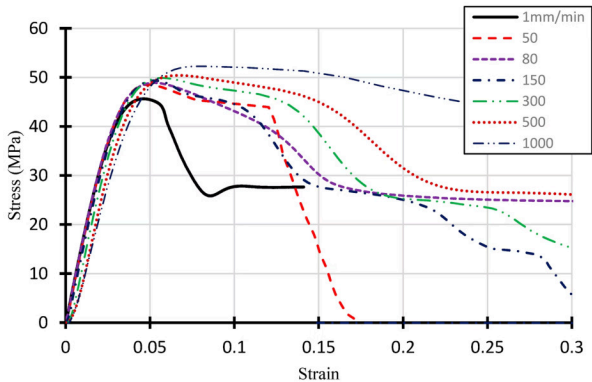
O3

Life Calculation

Predicted fatigue life using critical stress history and S-N curve.

Result:

Predicted fatigue life: 2.8×10^6 cycles. This ensures durability and guides design iterations.



Damage Accumulation

Miner's Rule

Combine multiple load cases to predict fatigue life.

Variable Amplitude

Account for real life loading scenarios with changing stress levels.

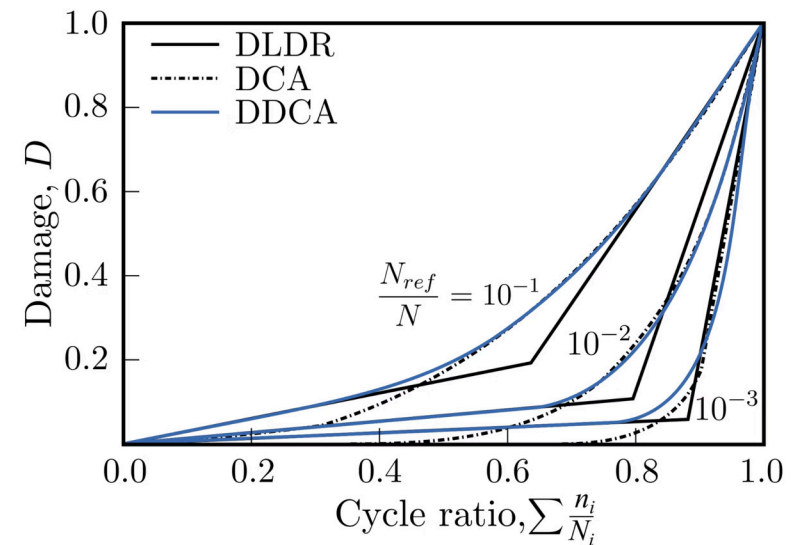
Common Mistakes

Using linear accumulation when load interaction is nonlinear, ignoring residual stresses.

Miner's Rule Methodology

Miner's Rule, also known as Palmgren-Miner linear damage hypothesis, is a foundational method for predicting fatigue life under variable amplitude loading. It assumes that each load cycle contributes a fraction of damage, and failure occurs when the sum of these damage fractions reaches 1.

The formula $\sum(n_i/N_i) = 1$ represents this, where n_i is the number of cycles applied at a specific stress level, and N_i is the number of cycles to failure at that same stress level from the S-N curve.



The accompanying diagram illustrates an S-N curve (fatigue strength vs. cycles to failure) with different stress levels. When subject to varying stress amplitudes ($\sigma_1, \sigma_2, \sigma_3$), the total damage is accumulated by summing the damage fractions from each stress level until the critical threshold (usually 1) is reached, indicating fatigue failure.

11. Documentation & Engineering Decision

Proper documentation and clear decision-making processes ensure simulation results drive effective engineering actions.

Reporting & Traceability



Capture & Document Simulation Insights

Ensure comprehensive documentation for future reference and continuous improvement.

- **Setup:** Detail initial conditions, material properties, mesh density, boundary conditions, and solver parameters.
- **Results:** Clearly present key performance indicators (e.g., stress, strain, displacement), failure modes, and design insights.
- **Learning:** Document deviations from expectations, unforeseen phenomena, and considerations for future iterations.
- **Best Practice:** Implement robust version control for all simulation models and reports.



Facilitate Rigorous Review & Repeatability

Enable independent verification and reproduction of simulation findings.

- **Peer Review:** Establish clear criteria for technical review, covering documentation, methodology, and interpretation.
- **Repeatability:** Provide detailed methodology, software versions, hardware, and file structure for exact reproduction.
- **Data Archiving:** Securely store all input, output, and post-processing files for easy access.
- **Best Practice:** Utilize standardized templates for consistent project reporting.



Avoid Common Reporting Mistakes

Proactively address oversights to maintain credibility and utility of simulation reports.

- **Missing Assumptions:** Always explicitly state all underlying assumptions, simplifications, and limitations.
- **Incomplete Solver Settings:** Document specific algorithms, convergence criteria, and time steps used.
- **Unannotated Visuals:** Include clear units, scales, legends, and labels for all screenshots and plots.
- **Best Practice:** Conduct internal quality checks for clarity, accuracy, and completeness.

Engineering Decision & Next Steps



Link Simulation to Strategy

Effectively connect simulation insights to business goals and critical test decisions.

- Quantify business impact
- Inform and refine physical testing
- Communicate strategic implications



Actionable Recommendations

Transform complex simulation data into precise, actionable engineering recommendations for design iterations.

- Propose specific design modifications
- Establish performance targets & safety margins
- Identify and mitigate risks
- Outline iterative refinement steps



Common Pitfalls to Avoid

Ensure robust decision-making by sidestepping these common errors.

- Avoid "Pretty Pictures" Syndrome
- Integrate simulation into feedback loops
- Acknowledge and manage uncertainty
- Prioritize validation with real-world data