E3B Developer's Theory Manual - M3

Double Tapered Composite Beam: Buckling Analysis

GUI User Manual (GUI Edition)

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Revision History

Version	Date	Author	Summary
v1.0	2025-11-21	HYEONSOEK HAN	Manual for CLI-only
V2.0	2026-01-06	HYEONSOEK HAN	Manual for GUI-only

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1. Overview

E3B_M3 is a GUI-based engineering tool for estimating **buckling critical load (Pcr)** and related mode characteristics for an **equivalent box-beam (E3B)** representation of a wing/beam-like structure. It supports:

- **Single Case Buckling** analysis (baseline run)
- **One-at-a-Time (OAT) Sensitivity** studies
- **Global Uncertainty Quantification (Sobol indices)**

The GUI is organized into three main tabs:

- **Buckling (Single Case)**
- **Sensitivity (OAT)**
- **Uncertainty (Sobol UQ)**

Insert Figure 1–3 in Section 4.

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2. What the Tool Solves

In early-stage design and trade studies, you often need to answer:

- “Which configuration is more buckling-resistant?”
- “Which parameter actually drives Pcr?”
- “If inputs vary ±X%, how uncertain is Pcr?”
- “Should I use a simplified model (M2) or a richer model (M3)?”

E3B_M3 is built for **rapid iteration**, not for replacing full-fidelity FE buckling analyses. It provides:

- Fast estimates of **Pcr**
- A consistent way to compare configurations
- Sensitivity ranking and Sobol-based influence measures

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3. Models: M2 vs M3

The GUI lets you select the solver model:

3.1 M2 (Simplified)

Use M2 when:

- You need **fast** sweeps and optimization loops.
- You want robust behavior over many iterations.
- Your goal is ranking / trend validation.

Typical characteristics:

- Lower computational cost
- Fewer coupling effects represented
- Often more numerically stable for broad sweeps

3.2 M3 (Enhanced)

Use M3 when:

- You want improved physics fidelity (e.g., bending–shear coupling and richer stiffness representation).
- Your design is near a boundary of validity where simplified assumptions can bias results.
- You are performing final trade studies before FE validation.

Typical characteristics:

- Higher computational cost
- More parameters “matter” because more coupling is represented
- Can be more sensitive to numerical settings (grid density, PPW)

3.3 Recommended Default

- **Start with M2** during exploration.
- Switch to **M3** for final comparative assessment, and for cases where sensitivity/UQ suggests strong coupling effects.

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4. GUI Overview

4.1 Main Layout

Each tab follows the same structure:

- **Left panel:** inputs and settings
- **Right panel:** plots, progress messages, and results summary
- **Run buttons:** execute the selected analysis mode

4.2 Tabs and Purpose

Buckling (Single Case)

Baseline run to compute:

- Pcr
- Critical mode characteristics (e.g., wavelength / dominant mode proxy)
- Output plot(s) for quick interpretation

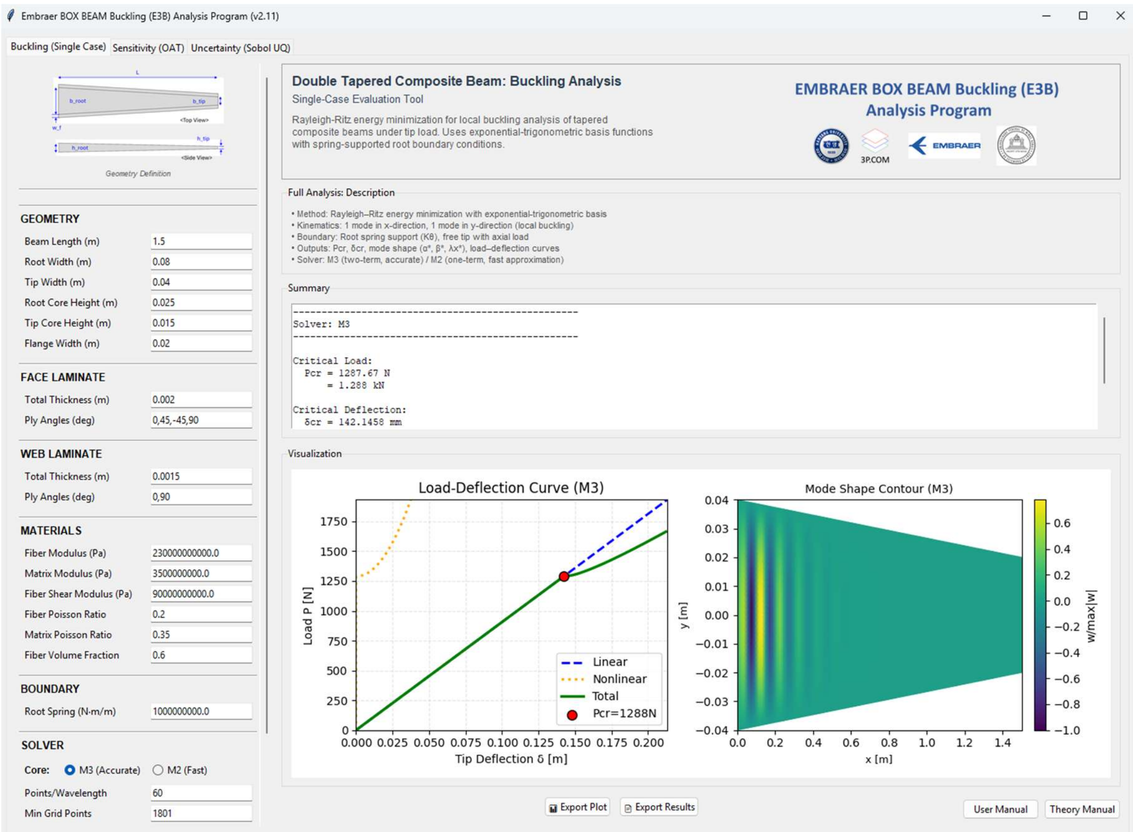

Figure 1. Buckling (Single Case) tab

Sensitivity (OAT)

Vary one parameter at a time around the baseline and record the response of Pcr.

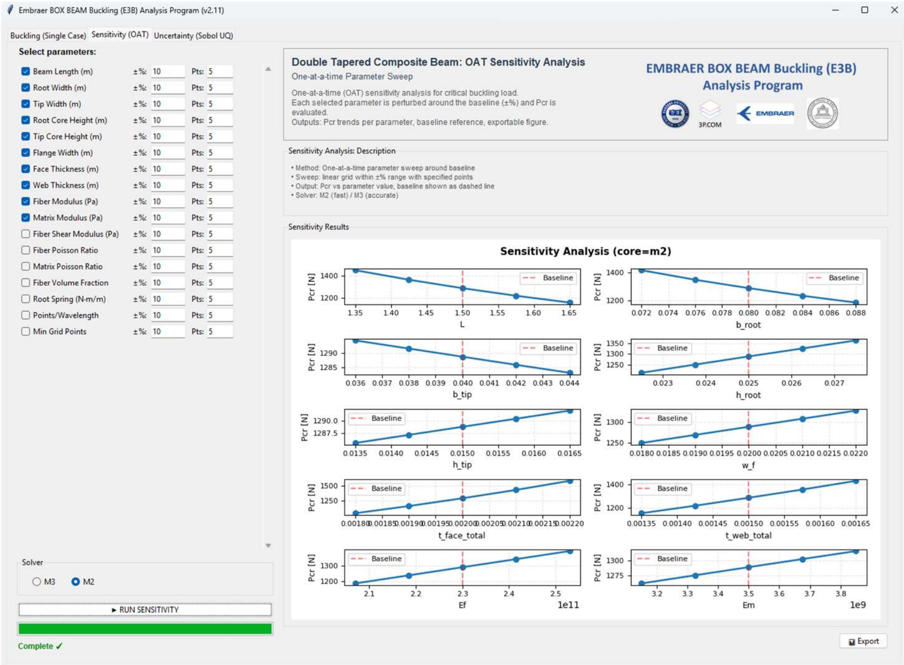

Figure 2. Sensitivity (OAT) tab

Uncertainty (Sobol UQ)

Treat selected inputs as uncertain within specified bounds and compute Sobol indices.

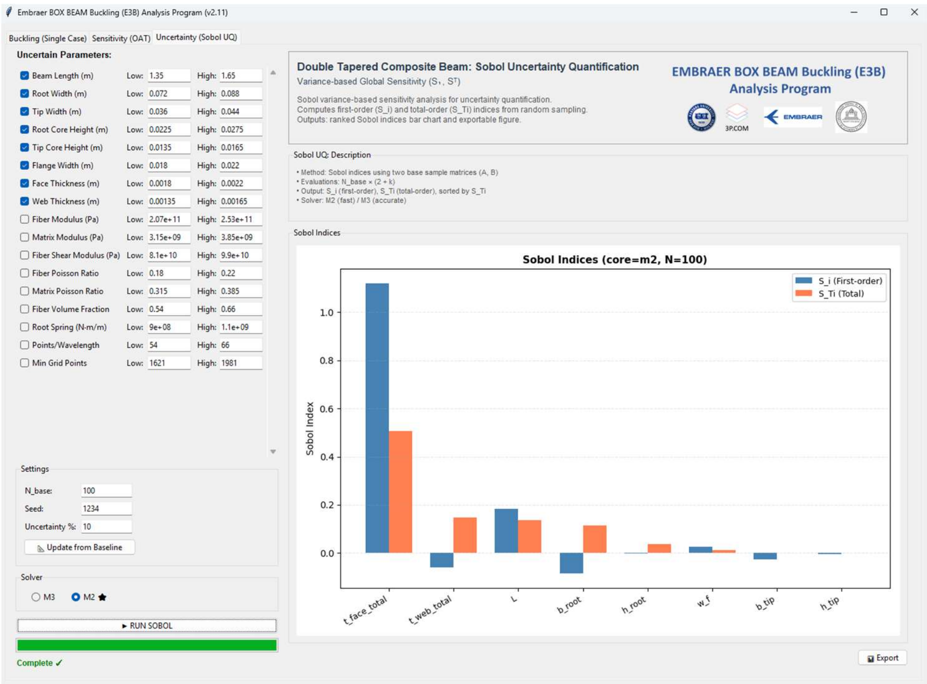

Figure 3. Uncertainty (Sobol UQ) tab

5. Quick Start (3 Minutes)

5.1 Single Case (Baseline)

1. Open **Buckling (Single Case)** tab.
2. Enter baseline geometry:
    - Beam Length, Root/Tip Width, Root/Tip Core Height, Flange Width
3. Enter laminate definitions:
    - Face thickness + ply angles
    - Web thickness + ply angles
4. Enter material parameters:
    - Fiber/Matrix modulus, shear modulus, Poisson ratios, fiber volume fraction
5. Choose model: **M2** (recommended first).
6. Click **Run Buckling**.
7. Review:
    - Pcr in results panel
    - Mode/response plot on right
8. Export or record results as needed.

5.2 Sensitivity (OAT)

1. Go to **Sensitivity (OAT)** tab.
2. Choose one or more parameters to vary (checkbox list).
3. Set:
    - Range (%): e.g., ±10%
    - Points: e.g., 5
4. Select solver: M2 or M3.
5. Click **Run Sensitivity**.
6. Read:

    - Which parameter changes Pcr the most
    - Whether response is linear or strongly nonlinear

5.3 Uncertainty (Sobol UQ)

1. Go to **Uncertainty (Sobol UQ)** tab.
2. Set uncertainty approach:
    - Either per-parameter Low/High bounds
    - Or click **Update from Baseline** then apply a uniform uncertainty %
3. Set sampling:
    - **N_base** (base sample count)
    - Seed (for reproducibility)
4. Select solver model.
5. Click **Run Sobol**.
6. Read:
    - First-order Sobol (S1): direct effect
    - Total-order Sobol (ST): direct + interactions

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6. Inputs (Baseline)

This section explains *what each input means* and *how it influences buckling*, in the same order shown in the GUI.

6.1 Geometry

Beam Length (L)

- Physical span or analysis length of the equivalent box beam.
- Strong influence on buckling: longer beams typically buckle at lower loads.

Root Width / Tip Width

- Defines chordwise dimension variation (taper).
- Influences stiffness distribution and the shape of the critical mode.

Root Core Height / Tip Core Height

- Represents box depth variation.

- Core height strongly drives bending stiffness; higher core height generally increases buckling resistance.

Flange Width

- Represents effective flange contribution (caps).
- Affects bending stiffness and coupling depending on layup.

6.2 Laminate Definitions

Face Laminate

- **Total thickness (Face)** and **Ply angles (Face)**
- Ply angles are entered as a comma-separated list of degrees. Example:
  0, 30, 60, -60, -30, 0
- The tool uses this layup to compute equivalent stiffness terms.

Web Laminate

- **Total thickness (Web)** and **Ply angles (Web)**
- Often contains ±45-dominant stacking for shear stability, but you should input your actual design layup.

Input rules (recommended):

- Angles in degrees
- Use commas to separate values
- Spaces are allowed (the tool should ignore whitespace)
- Keep the list length consistent with your stacking logic (symmetric sequences help stability)

6.3 Materials

These fields define constituent-level properties used to build an effective laminate behavior.

Fiber Modulus / Matrix Modulus

- Control axial stiffness and overall laminate stiffness.

Fiber Shear Modulus

- Controls shear behavior contribution.

Fiber Poisson Ratio / Matrix Poisson Ratio

- Influences coupling terms and lateral strain relationships.

Fiber Volume Fraction (Vf)

- Typically one of the most sensitive inputs for stiffness-driven buckling response.
- Increasing Vf generally increases stiffness (but the exact effect depends on the micromechanics model assumptions).

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7. Solver / Numerical Settings

These settings appear mainly in Sensitivity and UQ tabs but conceptually affect stability and runtime.

7.1 Root Spring (if used)

- A rotational spring stiffness at the root (or equivalent boundary compliance).
- If your real boundary is not perfectly clamped, tuning this can significantly change Pcr.

7.2 Points Per Wavelength (PPW)

- Controls how finely the solver resolves a candidate buckling wave pattern.
- Too low → inaccurate minima (missed critical mode)
- Too high → slower runtime

Recommended default: PPW = 24 (adjust if you see unstable mode jumps)

7.3 Minimum Grid Points (nx_min)

- Sets a minimum discretization density along the beam.
- Helps prevent under-resolved geometry taper or stiffness changes.

Recommended default: nx_min = 200

7.4 Sobol Sampling: N_base

- Base sample count for Sobol. Total evaluations are typically a multiple of N_base.
- Higher N_base → more stable indices, more runtime.

Recommended default: N_base = 1024 for stable reporting
Fast check: N_base = 256

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8. Outputs and How to Read Them

8.1 Core Outputs

You should treat the following as the “design-facing” outputs:

- **Pcr (Critical Load):** primary buckling metric
- **Mode indicator / wavelength proxy:** helps interpret whether the solution is physically consistent
- **Plots:** shows how the solver arrived at the critical condition (and whether minima are clean)

8.2 What "Good" Looks Like

A reliable result typically shows:

- A **clear minimum** in the response curve (not a noisy flat region)
- Consistent behavior when you slightly change PPW or nx_min
- No dramatic mode swapping unless geometry/layup truly triggers it

8.3 Exported Artifacts (General)

Depending on your build configuration, the tool typically produces:

- A **results table** (baseline + sweeps)
- **Plots** for baseline and sweep/UQ summaries
- A **run log** (warnings, parameter echo, runtime)

If your project requires strict file naming, define it in your repository "Output Convention" section and keep it version-controlled.

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9. Sensitivity (OAT)

9.1 Purpose

OAT sensitivity answers:
"If I change one parameter ±X%, how much does Pcr move?"

This is best for:

- Ranking drivers early
- Detecting nonlinearities (curvature)
- Finding parameters that cause mode switching

9.2 Recommended Setup

- Range: **±10%** (start here)
- Points: **5** (fast but informative)
- Model: **M2** for screening, **M3** for final sensitivity reporting

9.3 Interpreting Results

Common patterns:

- **Monotonic slope:** parameter has a consistent effect
- **Nonlinear curve:** parameter interacts with model physics strongly
- **Discontinuous jump:** likely mode switch (verify by rerunning with higher PPW / nx_min)

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10. Uncertainty (Sobol UQ)

10.1 Purpose

Sobol UQ answers:

- "Which parameters dominate output uncertainty?"
- "Are interactions important?"

10.2 Bounds Setup

Two safe workflows:

1. Set Low/High manually per parameter.
2. Use **Update from Baseline**, apply a global uncertainty %, then fine-tune.

10.3 Reading Sobol Indices

- **S1 (First-order):** effect of parameter alone
- **ST (Total-order):** effect of parameter plus its interactions

Rules of thumb:

- High S1 and ST → dominant, mostly independent driver
- Low S1 but high ST → interactions matter (coupling)

10.4 Reproducibility

- Fix the **Seed** if you want repeatable indices between versions.
- If indices change significantly with same seed/bounds, it may indicate numerical instability or a model change.

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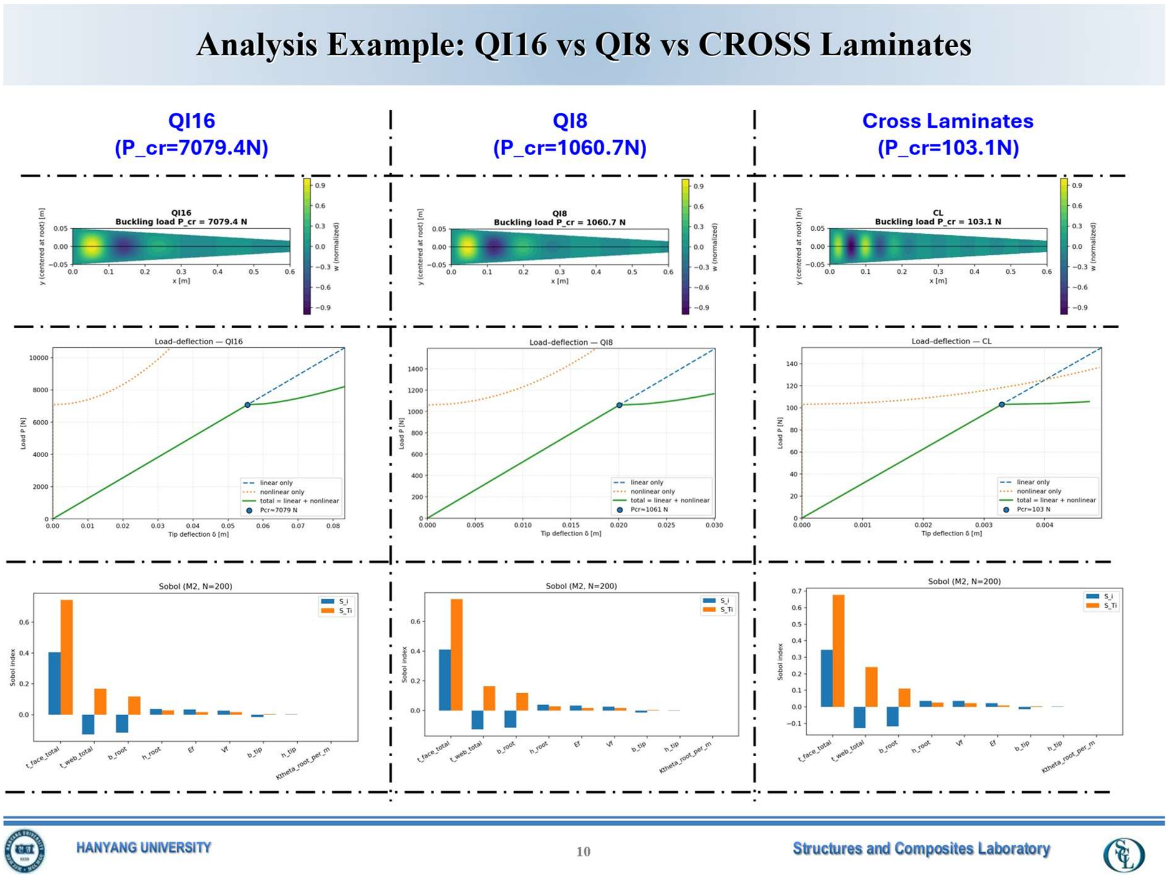
11. Verification & Example Cases (REF/QI16/QI8/CROSS)



11.1 What These Are For

These example cases are **regression checks** to ensure that:

- Pcr remains consistent between versions
- The solver does not drift due to numerical or code changes

11.2 What to Compare

- **Pcr error:** relative difference vs baseline/reference
- **Mode similarity:** qualitative consistency (shape, wavelength trend)
- **Stability:** absence of random mode swaps at same settings

11.3 Interpretation Notes (Practical)

- If REF matches but QI16/QI8 diverge, suspect **numerical integration/discretization sensitivity**.
- If CROSS behaves differently only in M3, suspect **coupling-term handling**.

Keep a small “golden results” CSV in your repo for automated comparison.

12. Limitations & Recommended Use

12.1 Modeling Limitations

- Equivalent-beam representation cannot capture all local 3D effects.
- Boundary conditions are simplified (even with root spring tuning).
- Laminate behavior is reduced to an effective representation; detailed stacking/local effects may be smeared.

12.2 Recommended Parameter Defaults

- PPW: 24
- nx_min: 200
- N_base: 1024 (UQ), 256 (quick)

12.3 When to Prefer M2 vs M3

Use **M2** when:

- High-throughput screening
- Early design ranking
- Broad sensitivity sweeps

Use **M3** when:

- Final trade study before FE validation
- Strong coupling suspected (e.g., sensitivity/UQ shows interaction-heavy behavior)
- You need improved physics representation and accept higher runtime

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Appendix A. Input Key Reference (Table)

GUI Label	Key	Unit	Description	Where Used
Beam Length	L	mm	Equivalent beam span/length	All modes
Root Width	b_root	mm	Width at root	All modes
Tip Width	b_tip	mm	Width at tip	All modes
Root Core Height	h_root	mm	Box depth at root	All modes
Tip Core Height	h_tip	mm	Box depth at tip	All modes

Flange Width	b_flange	mm	Effective flange/cap width	All modes
Face Thickness	t_face	mm	Total face laminate thickness	All modes
Face Ply Angles	theta_face	deg	Comma-separated angles	All modes
Web Thickness	t_web	mm	Total web laminate thickness	All modes
Web Ply Angles	theta_web	deg	Comma-separated angles	All modes
Fiber Modulus	E_f	(input unit)	Constituent modulus	All modes
Matrix Modulus	E_m	(input unit)	Constituent modulus	All modes
Fiber Shear Modulus	G_f	(input unit)	Constituent shear modulus	All modes
Fiber Poisson Ratio	nu_f	–	Constituent Poisson ratio	All modes
Matrix Poisson Ratio	nu_m	–	Constituent Poisson ratio	All modes
Fiber Volume Fraction	V_f	–	Fiber volume fraction	All modes
Root Spring	k_root	N·m/m	Root compliance parameter	Sensitivity/UQ (if enabled)
Points per Wavelength	PPW	–	Discretization control	Sensitivity/UQ
Min Grid Points	nx_min	–	Minimum grid density	Sensitivity/UQ
Sobol Base Samples	N_base	–	Sobol sampling base count	UQ
Seed	seed	–	Random seed	UQ

Note: If your project uses strict units (e.g., GPa/MPa), standardize them in your team template and enforce consistency.

Appendix B. Output Fields Reference (Table)

Output	**Meaning**	**Typical Use**

Pcr	Critical buckling load	Primary comparison metric
Mode/Wavelength Proxy	Indicates the dominant buckling pattern	Detect mode switching / sanity check
Baseline Plot	Solver response curve / minima visualization	Confirm clean minimum
Sensitivity Curves	Pcr vs parameter value	Rank drivers
Tornado/Ranking (if produced)	Relative influence summary	Report-ready sensitivity
Sobol S1	First-order effect	Identify direct drivers
Sobol ST	Total effect	Identify interactions

Appendix C. Key Equations Summary (High-Level)

(This section is intentionally high-level to stay readable and GUI-focused.)

- **Buckling criterion:** solve for the critical condition where stability changes and the minimum critical load is obtained over admissible mode parameters.
- **Mode parameters (concept):** the solver searches a parameter space representing candidate buckling patterns (e.g., wavelength-like behavior).
- **M2 vs M3:** both compute an effective stiffness-driven stability condition, with M3 including additional coupling/terms compared to M2.
- **Sensitivity:** OAT computes ΔPcr resulting from perturbing one input while holding others constant.
- **Sobol:** decomposes output variance into contributions from inputs (direct and interaction components).

Troubleshooting (Quick)

- **Weird discontinuity in Pcr:** increase PPW and/or nx_min and rerun; check for mode switching.
- **Sensitivity results look noisy:** increase points (e.g., 7–9) and raise nx_min.
- **Sobol indices unstable:** increase N_base, fix seed, and ensure bounds are realistic.
- **Angle list errors:** use comma-separated degrees; avoid trailing commas; keep consistent formatting.