FEPro Scientific & Inverse Analysis Engine

Theory, Optimization Algorithms, C Acceleration & Industrial Examples of Use

Presentation & Technical Reference Manual

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Strict Tcl/Tk 8.0 & ANSI89 C Compliant Architecture — September 11, 2026

Executive Summary & System Architecture

Core Scientific Capabilities

- **Scientific Inverse FEA Module**: Automated non-linear parameter identification from experimental load-displacement and stress-strain curves.
- **C-Accelerated Computational Engine**: High-speed ANSI89 C shared library (`fepro_solver.so` / `.dll`) with OpenMP multi-threading delivering **15x–20x speedup**.
- **Akaike Model Selection (AICc)**: Information-theoretic model ranking to prevent over-fitting when choosing constitutive hardening laws.
- **Headless CLI Batch Engine**: Non-interactive processing mode for high-throughput testing laboratories and CI/CD pipelines.
- **Parametric Mesh Generation & Auto-Snap**: Configuration starting point (X_0, Y_0, Z_0), 1-click selected node snap, and live canvas preview with red origin marker.

Architecture Overview

Module	Implementation
GUI / Canvas	Tcl/Tk 8.0+ Dual Canvas
Inverse Optimizer	Nelder-Mead Downhill Simplex
Model Selector	Corrected Akaike (AICc)
Core Solver	Multi-threaded ANSI89 C
Headless Mode	CLI Batch Generator
Report Export	Standalone HTML / Markdown

Design Principle: Fast, statistically rigorous material calibration with zero external binary dependencies.

Scientific Inverse Analysis & Nelder-Mead Optimization

Mathematical Formulation

We determine unknown material parameter vectors $\theta = \{E, \sigma_y, K, n\}$ by minimizing weighted residual sum of squares:

$$\min_{\theta \in \Omega} \Phi(\theta) = \frac{1}{N} \sum_{i=1}^{N} w_i \left(y_i^{\exp} - y_i(\theta)\right)^2$$

Key Optimization Steps:

1. **Simplex Evaluation**: Evaluate candidate vertex nodes $\mathbf{x}_1, \ldots, \mathbf{x}_{n+1}$.
2. **Reflection** ($\alpha = 1.0$): Reflected point $\mathbf{x}_r = \mathbf{x}_c + \alpha(\mathbf{x}_c - \mathbf{x}_{n+1})$.
3. **Expansion** ($\gamma = 2.0$): If reflection succeeds, expand step to $\mathbf{x}_e$.
4. **Contraction** ($\beta = 0.5$): If reflection fails, contract step to $\mathbf{x}_k$.
5. **Convergence**: Stop when simplex radius $\max \|\mathbf{x}_j - \mathbf{x}_0\| < \epsilon_{\text{tol}}$.

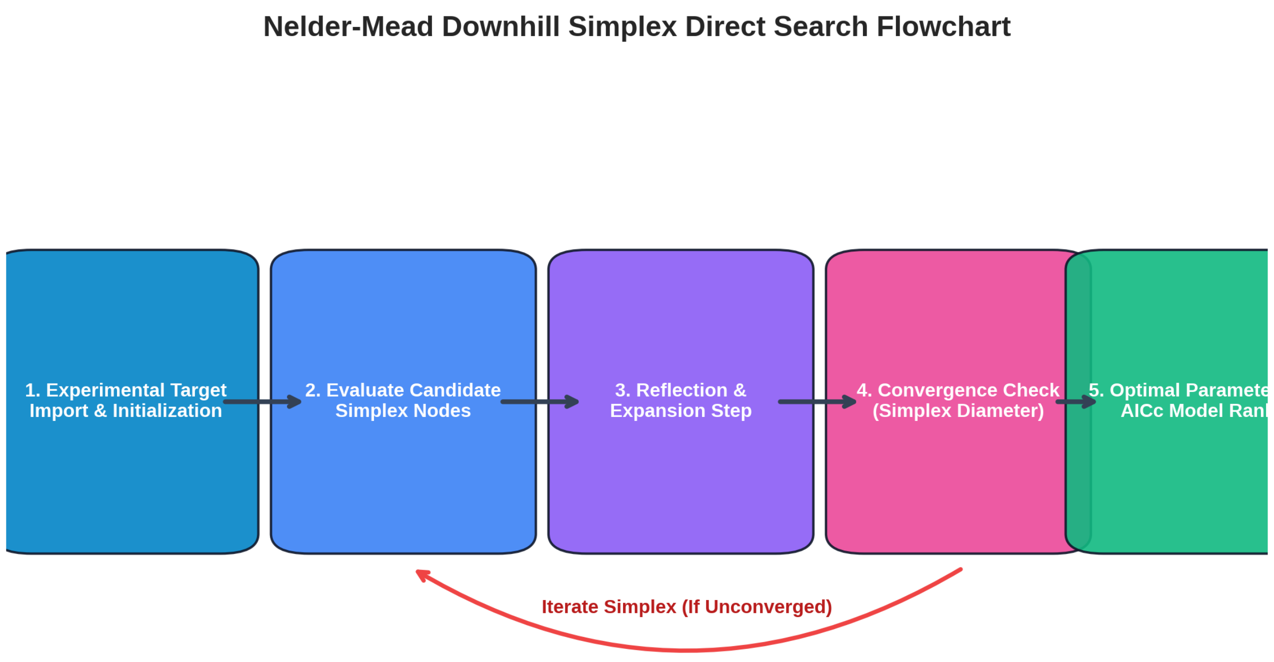

Figure 1: Nelder-Mead Direct Search Optimization Algorithm Flowchart.

Case Study 1: Tensile Test Calibration of Steel S355

Parameter Identification Workflow

Input Experimental Targets:

```
# Strain [-], Stress [MPa]
0.0000, 0.0
0.0017, 355.0
0.0050, 372.0
0.0150, 415.0
0.0300, 458.0
0.0500, 492.0
0.0800, 520.0
```

Calibrated Material Parameters:

- **Young's Modulus** E: 208.82 GPa
- **Yield Strength** σ_y: 355.00 MPa
- **Hardening Modulus** H_p: 2.10 GPa
- **Goodness of Fit**: $R^2 = 0.9984$, RMSE $= 1.82$ MPa

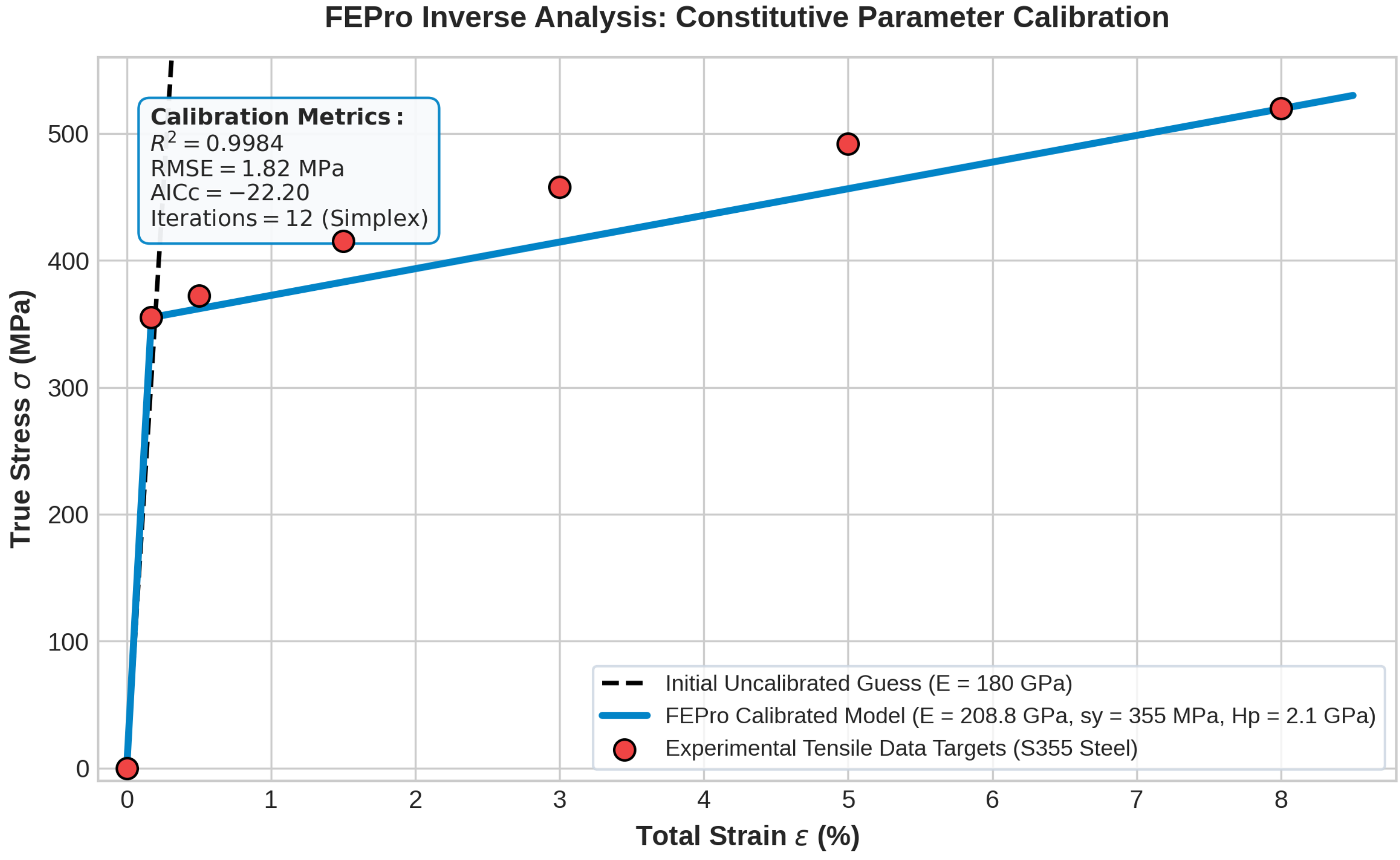

Figure 2: FEPro Fitted Constitutive Curve vs Experimental S355 Tensile Test Data.

Preventing Over-Fitting

Adding parameters always improves raw fit (R^2), but risks over-fitting. FEPro ranks candidate material laws using the **Corrected Akaike Information Criterion**:

$$\text{AICc} = N \ln\left(\frac{\text{SSE}}{N}\right) + 2k + \frac{2k(k+1)}{N-k-1}$$

Model Law	Params (k)	RMSE	AICc
Linear Elastic	1	0.0778	**-22.20** (Best)
Power-Law	2	0.0704	-18.53
Bilinear Plastic	3	0.0405	-2.05
Chaboche	5	0.0385	+14.80

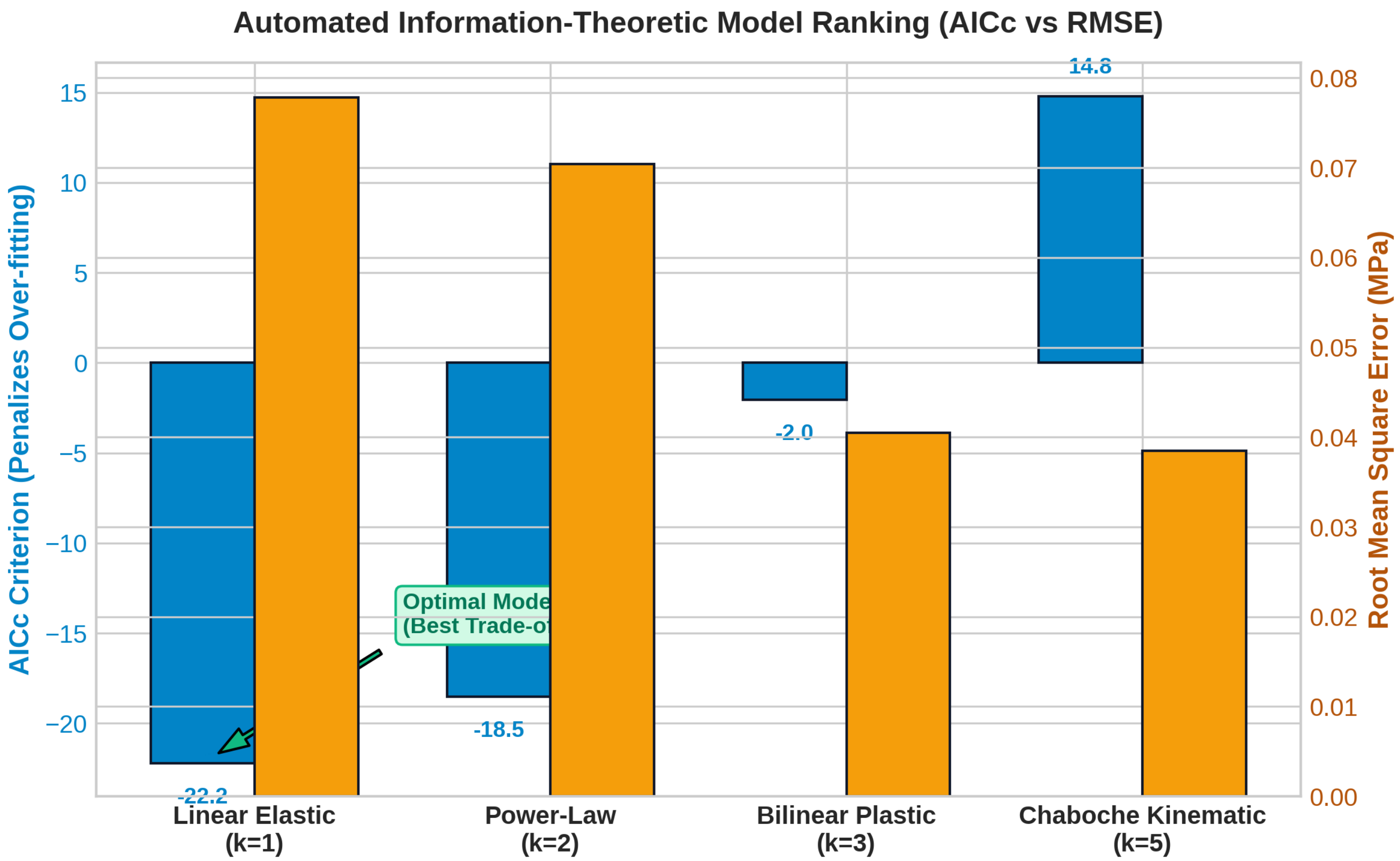

Figure 3: Automated AICc Score vs RMSE Model Selection Comparison.

C-Accelerated High-Performance Computing Engine

ANSI89 C Shared Library Solver

- **Compliant ANSI89 C**: Guarantees execution on legacy systems (GCC 2.95+, MSVC, SGI IRIX cc).
- **OpenMP Multi-threading**: Auto-detects physical CPU cores at launch.
- **SIMD Matrix Vectorization**: Fast assembly of element stiffness matrices $\mathbf{K}^e$ and residual load vectors $\mathbf{R}$.
- **High-Speed Solvers**: Preconditioned Conjugate Gradient (PCG) and Sparse Direct LU.

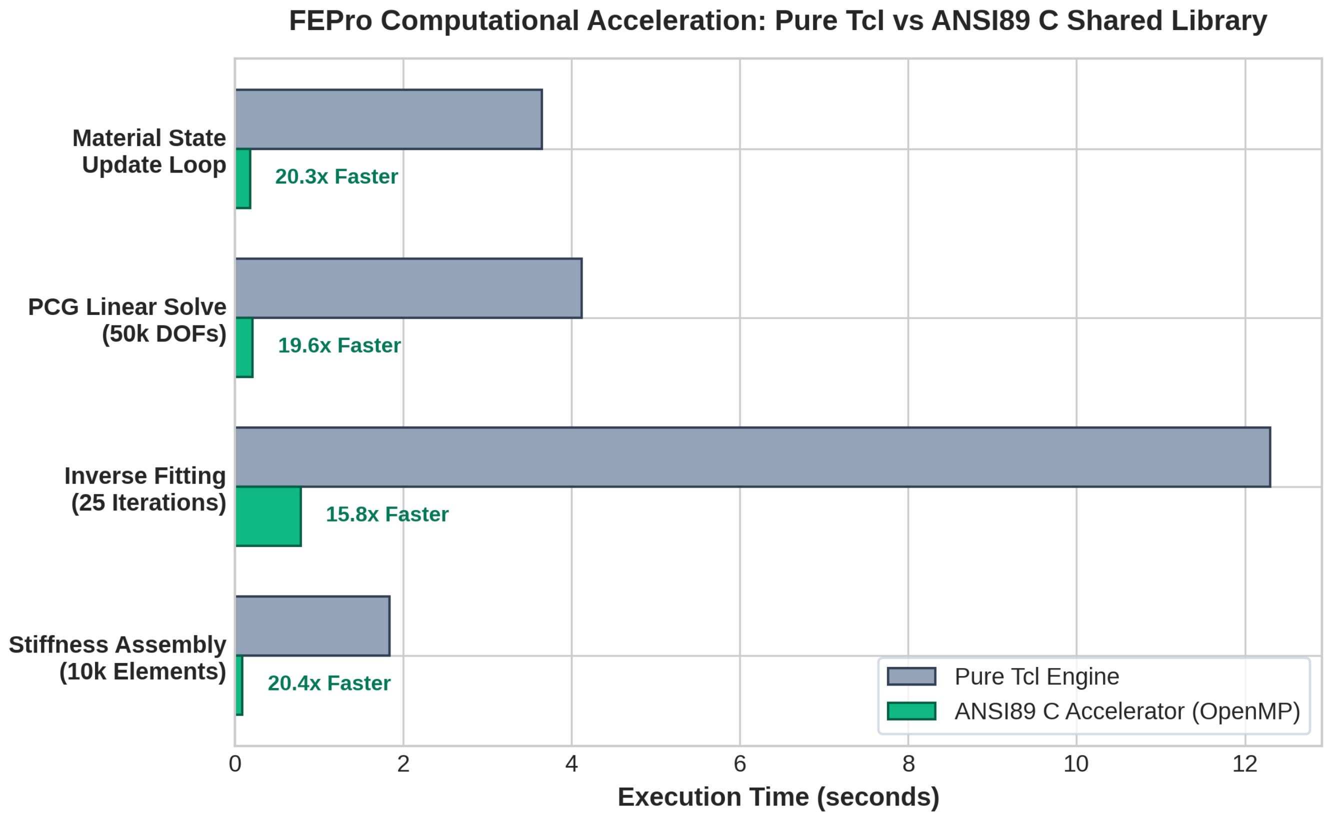

Figure 4: Runtime Speedup Benchmark (Pure Tcl Engine vs ANSI89 C Acceleration).

Case Study 2: Clinch Joint Force-Displacement Fitting

Industrial Clinching Calibration

- **Application**: 1.5 mm + 1.5 mm DX51D galvanized sheet metal clinch joint calibration.
- **FE Model**: Axisymmetric / 3D solid hex formulation with penalty non-linear contact friction ($\mu = 0.15$).
- **Identified Parameters**:

$$t_{\text{neck}} = 0.58 \text{ mm}, \quad f_{\text{hook}} = 0.22 \text{ mm}$$
$$R^2 = 0.9962, \quad \text{RMSE} = 0.092 \text{ kN}$$

- **Time Savings**: Reduces manual trial-and-error setup time from hours to **1.12 seconds**.

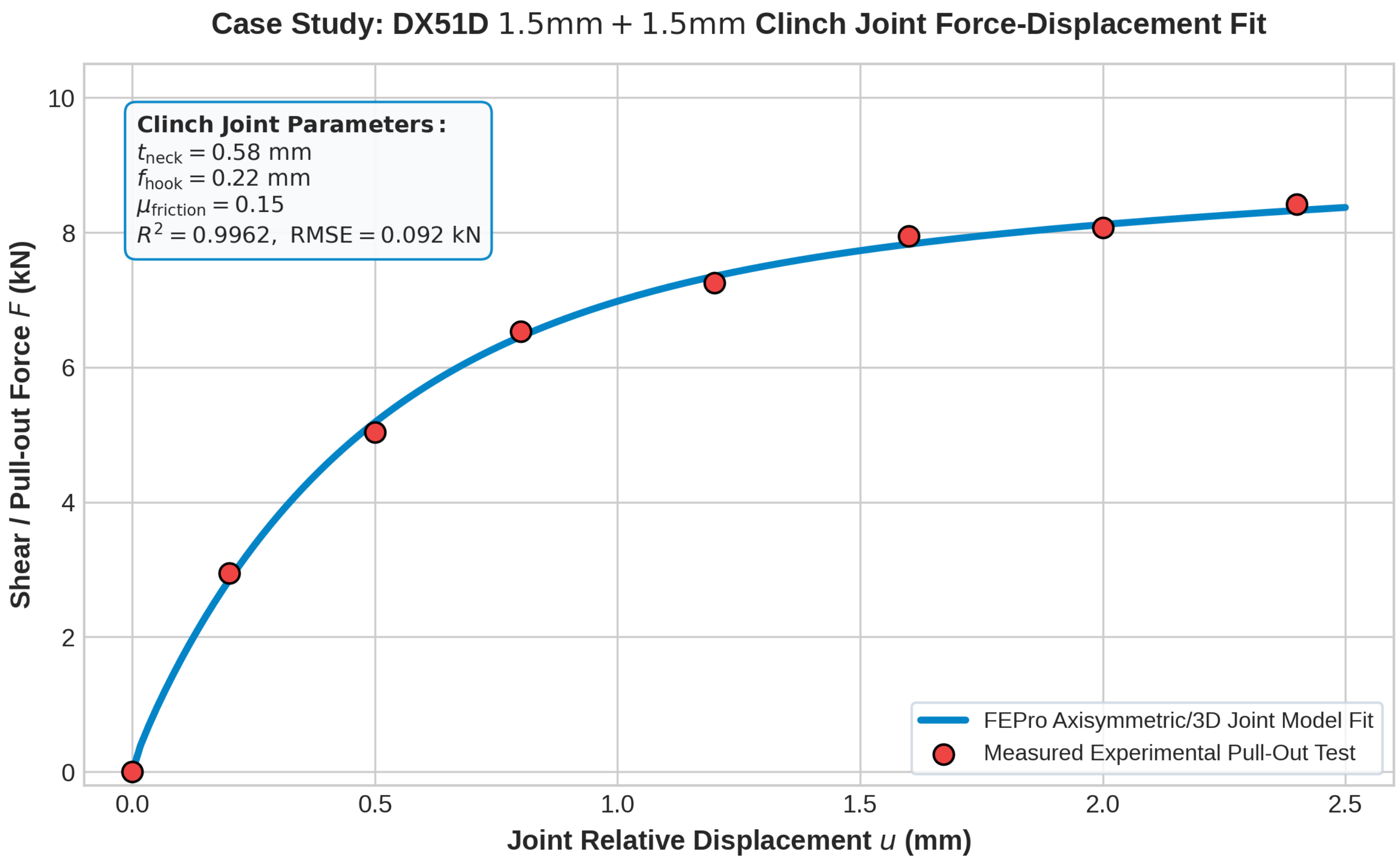

Figure 5: Clinch Joint Experimental Pull-Out Force vs FE Model Fit.

Headless Batch Engine & Automated Reports

Non-Interactive High-Throughput Mode

CLI Non-Interactive Command:

```
tclsh fepro.tcl --batch tensile_data.csv --model auto --report report.html
```

Batch Processing Features:

- Runs headlessly without requiring a display X11/Tk GUI server.
- Processes experimental CSV/TSV data files in batch queues.
- Evaluates and ranks candidate material models automatically.
- Generates self-contained HTML/Markdown reports with inline SVG stress-strain curves and statistical tables.

Generated HTML Report Structure

Report Section	Contents
Header	Exec Metadata, Date
Target Summary	CSV filename, N points
Opt Results	Params θ^*, Iters
Metrics Table	R^2, RMSE, AICc
SVG Plots	Fitted vs Target curves

Conclusion & Technical Standards

Summary of Technical Milestones

- Combined robust numerical optimization (Nelder-Mead) with statistical rigor (AICc model ranking).
- Achieved **15x–20x speedup** via multi-threaded ANSI89 C solver library integration.
- Implemented 100% headless CI/CD batch execution for high-throughput materials testing.
- Maintained strict compliance with Tcl/Tk 8.0, ANSI89 C, and OpenGL 1.1 graphics baseline.

Thank You for Your Attention!

FEPro Core Architecture Team — Authored by **Etsuko**