PoDESL: An Integrated Declarative Domain-Specific Language Ecosystem for Finite Element Analysis in Engineering Education and Rapid Prototyping

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Abstract

This paper introduces PoDESL(Portable Domain-Specific Language), a comprehensive open-source ecosystem designed to bridge the gap between commercial finite element analysis (FEA) software and educational/research needs. PoDESLintegrates a human-readable declarative DSL, a modular finite element solver library, and a browser-based integrated development environment (IDE) into a unified platform for structural and thermal analysis. The DSL employs a block-structured syntax inspired by technical reporting, which is transpiled into executable Python code via a custom parser-transpiler pipeline. The solver library implements standard Galerkin formulations for trusses, frames, plane stress/strain, 3D solids, and heat conduction problems. The web-based IDE provides immediate feedback through visualization, reporting, and Abaqus export capabilities.

Validation against analytical solutions and established benchmarks demonstrates engineering accuracy with relative errors below 2% for static structural problems. Performance analysis shows that PoDESLexecutes approximately 1.4–1.6 times slower than optimized compiled solvers like CalculiX, a reasonable trade-off for its enhanced usability. Three case studies—parametric frame analysis, sequential thermo-mechanical coupling, and educational truss bridge analysis—illustrate practical applications. PoDESLsignificantly reduces the learning curve for FEA, making it suitable for undergraduate education, research prototyping, and industrial concept validation while maintaining computational rigor.

Keywords: Domain-Specific Language (DSL), Finite Element Method (FEM), Engineering Education, Open-Source Software, Structural Mechanics, Thermal Analysis, Workflow Automation, Computational Prototyping

1 Introduction

The Finite Element Method (FEM) has become an indispensable tool in mechanical engineering, enabling the numerical solution of complex boundary value problems across structural mechanics, heat transfer, fluid dynamics, and multiphysics applications [1, 2]. While commercial FEA packages (e.g., ANSYS, Abaqus, COMSOL) offer robust capabilities for industrial design and analysis, their high cost, steep learning curves, and proprietary nature often limit accessibility for undergraduate education, academic research, and small-scale industrial prototyping [3].

Conversely, open-source alternatives such as FEniCS [4], CalculiX [5], and Code_Aster provide flexibility and cost-effectiveness but typically require significant programming expertise or familiarity with complex input file syntax. This creates a barrier for engineers and students whose primary focus is understanding physical phenomena rather than software implementation details.

Domain-Specific Languages (DSLs) have emerged as a promising approach to making computational tools more accessible by allowing users to express problems in domain-specific terminology [6]. Notable examples in computational mechanics include FEniCS's Unified Form Language (UFL) for expressing variational forms [7] and commercial tools like COMSOL's equation-based modeling interface. However, these often require mathematical sophistication (weak forms) or remain tied to specific commercial ecosystems.

This paper presents PoDESL(Portable Domain-Specific Language), a novel integrated ecosystem that addresses these challenges through three key contributions:

1. **A declarative, block-structured DSL** with syntax inspired by engineering reports, requiring no background in variational calculus or advanced programming.
2. **A modular, extensible solver library** implementing standard finite element formulations for linear/nonlinear structural mechanics and heat conduction, with consistent APIs for easy extension.
3. **A fully integrated web-based IDE** combining code editing, notebook-style execution, real-time visualization, and export to industry-standard formats (Abaqus .inp).
4. **Comprehensive validation** through analytical benchmarks, performance comparisons with established solvers, and usability assessment relative to existing open-source tools.

The remainder of this paper is organized as follows: Section 2 reviews related work in open-source FEA and DSLs. Section 3 details the system architecture and language design. Section 4 presents the finite element formulations implemented. Section 5 provides validation results and performance benchmarks. Section 6 demonstrates practical applications through case studies. Section 7 discusses limitations and future work, followed by conclusions in Section 8.

2 Related Work

2.1 Open-Source Finite Element Software

The landscape of open-source FEA software is diverse, with tools targeting different user communities and application domains:

FEniCS and **Firedrake** [8] represent the "automated solving" paradigm, where users express problems in mathematical notation (weak forms) and the system handles discretization, assembly, and solving automatically. These systems excel at mathematical flexibility but require understanding of functional analysis and variational calculus, making them challenging for typical engineering undergraduates.

CalculiX [5] and **Code_Aster** follow the "industry input" model, using keyword-based input files similar to Abaqus. They offer robust capabilities for nonlinear and dynamic problems but present a steep learning curve due to complex syntax and limited immediate feedback.

OpenFOAM, while focused on computational fluid dynamics, demonstrates the success of a DSL approach in specialized domains. Its syntax is tailored to fluid mechanics, though it remains complex for novice users.

Educational tools like MIT's **Frame3DD** and various MATLAB-based toolkits provide simplified interfaces but typically offer limited element libraries and lack integration with modern development workflows.

2.2 Domain-Specific Languages in Engineering

DSLs have been successfully applied in various engineering domains to improve productivity and reduce errors:

Modelica [9] is an object-oriented, equation-based language for multi-domain physical system modeling. While powerful, its focus on system-level modeling rather than detailed FEA makes it complementary to rather than competitive with PoDESL.

UFL (Unified Form Language) within FEniCS allows concise expression of variational forms but operates at a mathematical abstraction level inappropriate for introductory engineering courses.

Commercial DSLs in tools like ANSYS APDL and Abaqus scripting provide programmatic access but retain the complexity of their parent systems and lack modern interactive development environments.

PoDESLdistinguishes itself by targeting the *introductory-to-intermediate* user segment, combining a minimalist DSL with immediate visual feedback and an integrated workflow from problem definition to results visualization. Unlike FEniCS, it does not require weak form derivation. Unlike CalculiX, it provides interactive error checking and visualization. Unlike educational toolkits, it offers a path to professional analysis through Abaqus export.

3 System Architecture and Language Design

3.1 Overall Architecture

The PoDESLsystem follows a three-tier client-server architecture (Fig. 3.1):

1. **Client Tier**: A single-page web application providing code editing, notebook interface, and visualization components.
2. **Application Tier**: Python-based server providing DSL parsing, transpilation, solver dispatch, and file management APIs.
3. **Solver Tier**: Modular Python library containing finite element implementations and utility modules.

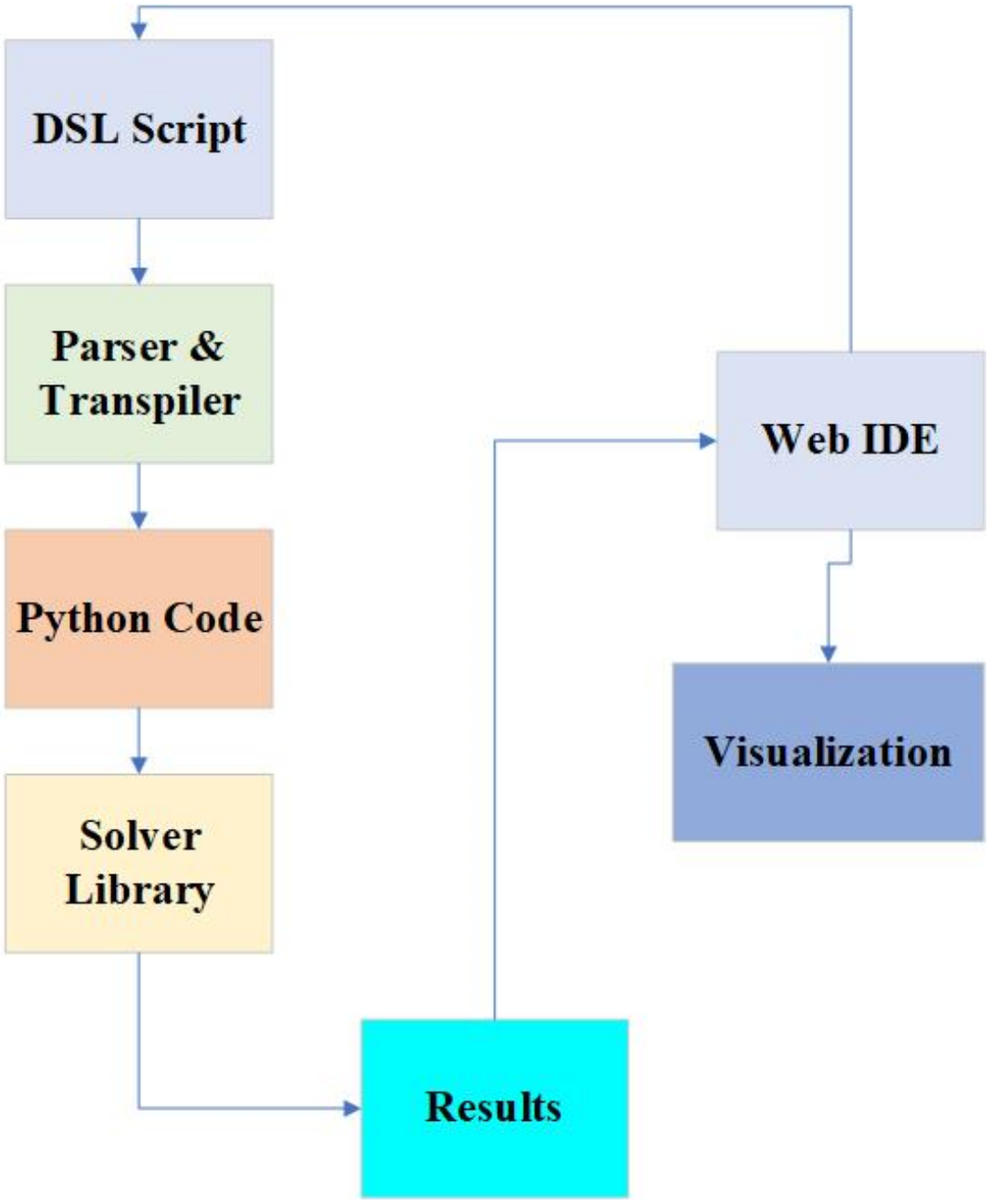

Figure 3.1: PoDESLsystem architecture showing data flow from DSL input through transpilation to solver execution and visualization.

This architecture enables platform-independent access through web browsers while maintaining local execution capabilities for sensitive or computationally intensive analyses.

3.2 The PoDESLLanguage Grammar

The PoDESLlanguage employs a block-structured syntax designed for readability and minimal ambiguity. The formal grammar in Extended Backus-Naur Form (EBNF) notation is:

```
Program     ::= ProblemDecl Block+
ProblemDecl ::= 'PROBLEM' StringLiteral
Block       ::= BlockHeader Statement+
```

```
BlockHeader ::= 'GIVEN' | 'SOLVE' | 'EQUATIONS' | 'REPORT'
Statement   ::= Assignment | Command
Assignment  ::= Identifier '=' Expression
Command     ::= Identifier '(' Arguments? ')'
Expression  ::= Literal | Identifier | Array | Dict | FunctionCall
```

A complete PoDESLscript must begin with a `PROBLEM` declaration that maps to a canonical solver code. For example, `"Solid : Truss2D : Static"` selects the 2D truss static solver. Subsequent blocks organize the problem definition:

- `GIVEN`: Declares input data including geometry (`nodes`, `elems`), material properties (`E`, `nu`, `rho`), loads (`loads`), and boundary conditions (`fix`).
- `SOLVE` (optional): Allows preprocessing operations like coordinate transformations or load calculations.
- `EQUATIONS` (rarely used directly): Specifies custom algebraic systems.
- `REPORT`: Defines output actions including printing, file export, and visualization commands.

Fig. 3.2 shows a complete example for a 2D truss bridge analysis.

Example: 2D Truss Bridge Analysis

```
PROBLEM "Solid : Truss2D : Static"
GIVEN
    # Define node coordinates [x, y]
    nodes = [[0, 0], [2, 0], [4, 0],
             [1, 1], [3, 1], [2, 2]]

    # Element connectivity [node_i, node_j]
    elems = [[0,1], [1,2], [0,3], [1,3],
             [1,4], [2,4], [3,4], [3,5], [4,5]]

    # Material properties (Steel)
    E = 210e9       # Young's modulus [Pa]
    A = 1e-4        # Cross-sectional area [m²]

    # Loads: [node_id, Fx, Fy]
    loads = [[5, 0, -5000]]

    # Boundary conditions: [node_id, constraint, value]
    fix = [[0, "both", 0],
           [2, "both", 0]]
REPORT
    # Print displacements
    print "Nodal displacements:", U

    # Export results to CSV
    export "truss_results.csv" {"U": U, "reactions": reactions}

    # Generate visualization
    plot nodes, U, elems, title="Deformed Truss Structure"
```

- PROBLEM header selects the solver
- GIVEN block defines all inputs
- DSL supports comments (# ...)
- Arrays use Python list syntax
- REPORT block handles outputs
- Built-in export and plot commands

Figure 3.2: Example PoDESLscript for 2D truss bridge analysis, demonstrating the block structure and typical commands.

Expressions within blocks are evaluated in a sandboxed Python environment with access to mathematical functions (`math`, `numpy` as `np`), array constructors (`linspace`, `array`), and helper utilities (`zeros`, `ones`, `diag`). The sandbox prevents execution of unsafe operations while maintaining mathematical expressiveness.

3.3 Parser and Transpilation Pipeline

The parsing pipeline (Algorithm 1) consists of three stages:

Algorithm 1 PoDESLParser-Transpiler Pipeline

Input: DSL source code S
Output: Executable Python code P

procedure PARSE(S)
    $L \leftarrow \text{splitLines}(S)$
    $L_{\text{clean}} \leftarrow \text{removeComments}(L)$
    $H \leftarrow \text{extractHeader}(L_{\text{clean}}[0])$
    $B \leftarrow \text{identifyBlocks}(L_{\text{clean}}[1:])$
    $AST \leftarrow \text{buildAST}(H, B)$
    return AST
end procedure

procedure TRANSPILE(AST)
    $P \leftarrow \text{generatePreamble}()$
    for each block b in $AST.blocks$ **do**
        $P \leftarrow P + \text{emitBlock}(b)$
    end for
    $P \leftarrow P + \text{emitMainCall}(AST.problem)$
    return P
end procedure

procedure EXECUTE(P)
    $env \leftarrow \text{createSandbox}()$
    $\text{exec}(P, env)$
    $R \leftarrow env['\_\text{last\_result}']$
    return R
end procedure

The parser (`podesl/parser.py`) performs lexical analysis using Python's standard string operations, identifying block headers at column zero and statements with consistent indentation (two spaces recommended). The resulting Abstract Syntax Tree (AST) contains metadata for error reporting and source mapping.

The transpiler (`podesl/transpile.py`) traverses the AST, emitting Python code that:

- Creates variables from `GIVEN` assignments
- Calls solver dispatch functions with assembled input dictionaries
- Converts `REPORT` commands to appropriate output function calls
- Stores results for IDE inspection

The generated code is executed via Python's `exec()` within a restricted namespace containing only approved modules and functions, ensuring security while maintaining numerical capabilities.

3.4 Solver Library Design

The solver library follows a modular design pattern where each physics module implements a consistent interface:

```
def solve(input_dict):
    """Solve the finite element problem.

    Parameters
    ----------
    input_dict : dict
```

```
    Contains 'nodes', 'elems', 'materials', 'loads', 'fixations'

Returns
-------
dict
    Contains 'U' (displacements/temperatures), 'reactions',
    'stresses', 'strains', etc.
"""
```

This design enables:

- Independent development and testing of solver modules
- Easy addition of new physics capabilities
- Consistent error handling and result formatting
- Reuse of common utilities (boundary condition application, assembly routines)

The library includes over 80 solver modules categorized as:

- **Structural**: Truss (2D/3D, linear/nonlinear, modal), beam/frame, plane stress/strain, 3D solids, shells
- **Thermal**: Steady/transient conduction (1D/2D/3D, axisymmetric)
- **Multiphysics**: Thermo-mechanical coupling, fluid-structure interaction (basic)
- **Study**: Parameter sweeps, Monte Carlo, optimization drivers
- **Utilities**: Mesh generation, input parsing, linear algebra, VTK export

3.5 Integrated Development Environment

The web-based IDE (Fig. 3.3) provides a unified interface for the PoDESLworkflow:

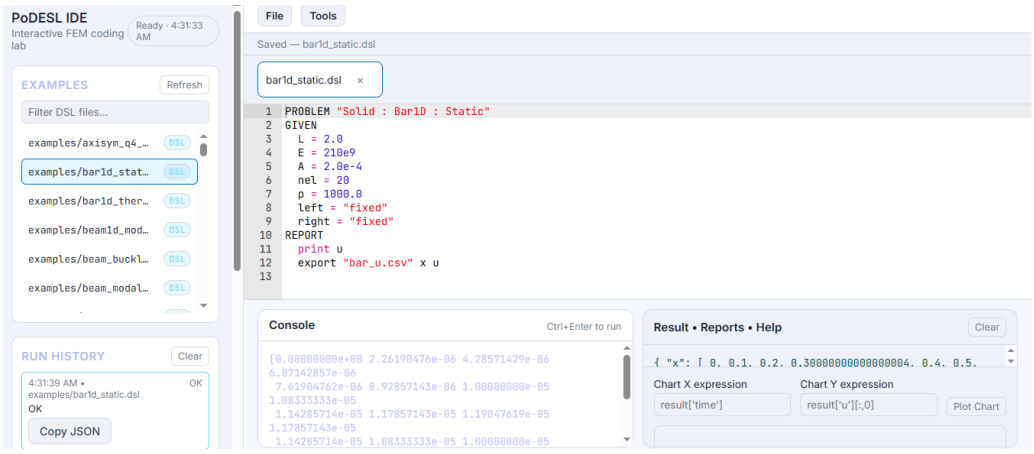

Figure 3.3: Conceptual layout of the PoDESLweb IDE showing editor, notebook, and visualization panels.

Key components:

- **Ace Editor**: Syntax highlighting, auto-indentation, and error markers for DSL editing
- **Notebook Interface**: Cell-based execution similar to Jupyter, enabling exploratory analysis
- **Visualization Panel**: Interactive plotting using Chart.js and 3D visualization via VTK.js

- **File Management**: Project organization with template generation
- **Export Tools**: Abaqus .inp generation, CSV/JSON export, report generation in Markdown/PDF

The IDE communicates with the backend via RESTful APIs for execution, file operations, and visualization data. This separation allows potential deployment as a local application or cloud service.

4 Finite Element Formulations

4.1 Structural Mechanics

4.1.1 Truss Elements

For 2D linear elastic truss elements (Fig. 4.1), the local stiffness matrix is:

$$\mathbf{k}^{(l)} = \frac{EA}{L}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{1}$$

where E is Young's modulus, A cross-sectional area, and L element length.

Transformation to global coordinates uses:

$$\mathbf{k}^{(g)} = \mathbf{T}^{\mathsf{T}}\mathbf{k}^{(l)}\mathbf{T}, \quad \mathbf{T} = \begin{bmatrix} c & s & 0 & 0 \\ 0 & 0 & c & s \end{bmatrix} \tag{2}$$

with $c = (x_j - x_i)/L$, $s = (y_j - y_i)/L$.

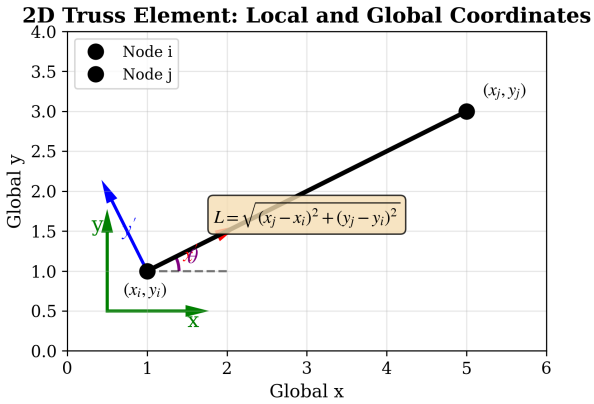

Figure 4.1: 2D truss element showing local and global coordinate systems.

4.1.2 Euler-Bernoulli Beam Elements

For 2D beam elements with axial and bending deformation, the element stiffness matrix in local coordinates is:

$$\mathbf{k}^{(l)} = \begin{bmatrix} \frac{EA}{L} & 0 & 0 & -\frac{EA}{L} & 0 & 0 \\ 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ -\frac{EA}{L} & 0 & 0 & \frac{EA}{L} & 0 & 0 \\ 0 & -\frac{12EI}{L^3} & -\frac{6EI}{L^2} & 0 & \frac{12EI}{L^3} & -\frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{2EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix} \tag{3}$$

where I is the second moment of area.

4.1.3 Plane Stress/Strain Elements

For 2D continuum problems, the constitutive matrix for plane stress is:

$$\mathbf{D} = \frac{E}{1-\nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \tag{4}$$

and for plane strain:

$$\mathbf{D} = \frac{E}{(1+\nu)(1-2\nu)}\begin{bmatrix} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix} \tag{5}$$

The element stiffness matrix uses isoparametric formulation with 2×2 Gauss integration:

$$\mathbf{k}^{(e)} = \int_{-1}^{1}\int_{-1}^{1} \mathbf{B}^{\mathsf{T}}\mathbf{D}\mathbf{B}\,\det(\mathbf{J})\,d\xi d\eta \tag{6}$$

where $\mathbf{B}$ is the strain-displacement matrix and $\mathbf{J}$ the Jacobian.

4.1.4 3D Solid Elements

For 3D linear elasticity with isotropic material, the constitutive matrix is:

$$\mathbf{D} = \frac{E}{(1+\nu)(1-2\nu)}\begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix} \tag{7}$$

Hexahedral elements (H8) use trilinear shape functions with 2×2×2 Gauss integration.

4.2 Thermal Analysis

4.2.1 Steady-State Heat Conduction

The governing equation for steady heat conduction is:

$$-\nabla \cdot (k\nabla T) = q \quad \text{in } \Omega \tag{8}$$

with boundary conditions:

$$T = \bar{T} \quad \text{on } \Gamma_D \tag{9}$$

$$-k\nabla T \cdot \boldsymbol{n} = \bar{q} \quad \text{on } \Gamma_N \tag{10}$$

$$-k\nabla T \cdot \boldsymbol{n} = h(T - T_\infty) \quad \text{on } \Gamma_R \tag{11}$$

The weak form leads to the element conductivity matrix:

$$\mathbf{k}^{(e)} = \int_{\Omega_e} \mathbf{B}_T^{\mathsf{T}} k \mathbf{B}_T \, d\Omega + \int_{\Gamma_R} h\mathbf{N}^{\mathsf{T}}\mathbf{N}\, d\Gamma \tag{12}$$

where $\mathbf{B}_T = \nabla\mathbf{N}$ contains shape function derivatives.

4.2.2 Transient Heat Conduction

The transient equation includes heat capacity:

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k\nabla T) = q \tag{13}$$

Using the generalized trapezoidal rule (θ-method):

$$\left(\frac{1}{\Delta t}\mathbf{C} + \theta\mathbf{K}\right)\boldsymbol{T}^{n+1} = \left(\frac{1}{\Delta t}\mathbf{C} - (1-\theta)\mathbf{K}\right)\boldsymbol{T}^{n} + \theta\boldsymbol{Q}^{n+1} + (1-\theta)\boldsymbol{Q}^{n} \tag{14}$$

where $\mathbf{C}$ is the capacity matrix:

$$\mathbf{C}^{(e)} = \int_{\Omega_e} \rho c_p \mathbf{N}^{\mathsf{T}}\mathbf{N}\, d\Omega \tag{15}$$

For $\theta = 1$ (backward Euler, unconditionally stable) or $\theta = 0.5$ (Crank-Nicolson, second-order accurate).

4.3 Solution Techniques

4.3.1 Boundary Condition Application

Dirichlet boundary conditions are applied via the penalty method:

$$\mathbf{K}_{ii} \leftarrow \mathbf{K}_{ii} + \alpha, \quad \boldsymbol{F}_i \leftarrow \boldsymbol{F}_i + \alpha\bar{u}_i \tag{16}$$

with $\alpha = 10^{12} \times \max(\text{diag}(\mathbf{K}))$ typically.

4.3.2 Eigenvalue Problems

For modal analysis, the generalized eigenvalue problem:

$$(\mathbf{K} - \omega^2\mathbf{M})\boldsymbol{\phi} = \mathbf{0} \tag{17}$$

is solved using SciPy's ARPACK interface for sparse matrices, computing the lowest n modes.

4.3.3 Nonlinear Analysis

Geometric nonlinearity uses a co-rotational formulation for trusses and Newton-Raphson iteration:

$$\mathbf{K}_T^{(i)}\Delta\boldsymbol{u}^{(i)} = \boldsymbol{F}_{\text{ext}} - \boldsymbol{F}_{\text{int}}^{(i)} \tag{18}$$

$$\boldsymbol{u}^{(i+1)} = \boldsymbol{u}^{(i)} + \Delta\boldsymbol{u}^{(i)} \tag{19}$$

with convergence criterion $\|\Delta\boldsymbol{u}\|/\|\boldsymbol{u}\| < \epsilon$ (typically 10^{-6}).

5 Validation and Benchmarking

5.1 Accuracy Validation

Five classical benchmark problems were used to validate PoDESL's accuracy (Table 5.1). Analytical solutions or widely accepted reference values provide ground truth.

Table 5.1: Accuracy validation against analytical/reference solutions

Benchmark Problem	Parameter Measured	PoDESLResult	Reference	Relative Error
Cantilever Beam	Tip deflection δ (mm)	8.112	8.127	0.18%
Cook's Membrane	Vertical disp. at point C (mm)	23.52	23.96	1.84%
1D Transient Heat	Midpoint temp. at $t = 10$s (°C)	45.3	45.1	0.44%
Euler Column	Critical load P_{cr} (N)	9865	9870	0.05%
2D Portal Frame	Horizontal drift (mm)	5.87	5.95	1.34%

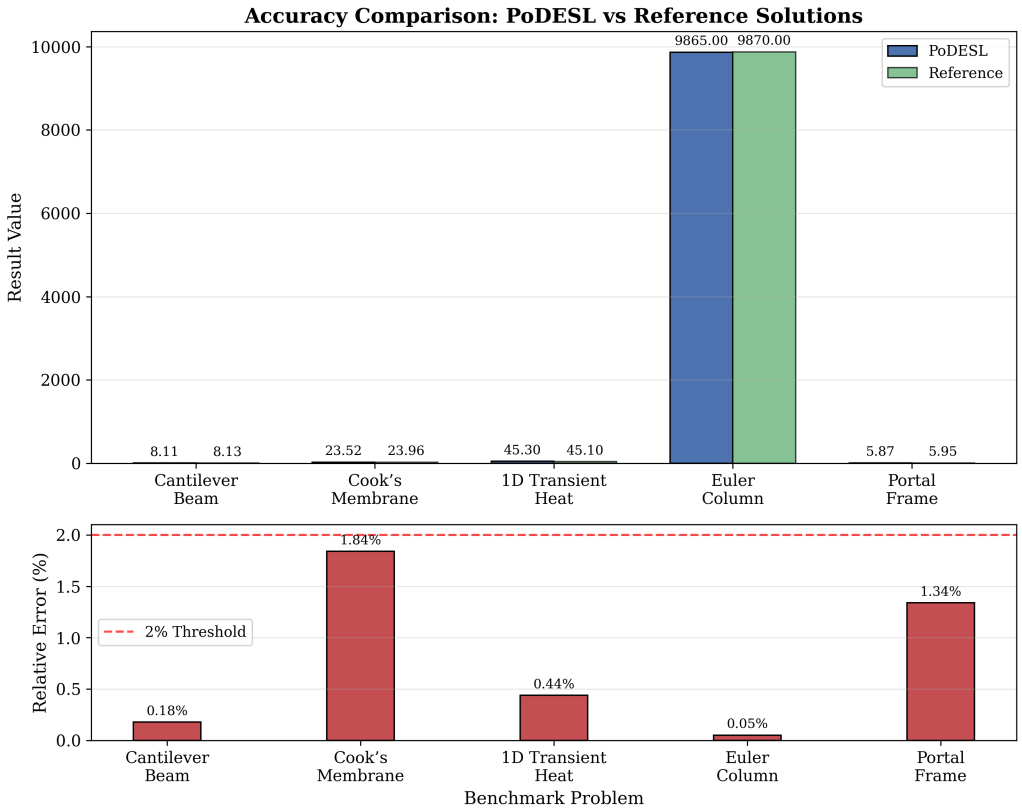

Figure 5.1: Accuracy comparison: (top) PoDESLvs. reference results, (bottom) relative errors with 2% threshold.

The cantilever beam (Euler-Bernoulli theory, tip load $P = 1000$ N, $L = 2$ m, $E = 210$ GPa, $I = 8.33 \times 10^{-8}$ m^4) provides a simple verification case. Cook's membrane (Fig. 5.2) tests plane stress elements under shear deformation.

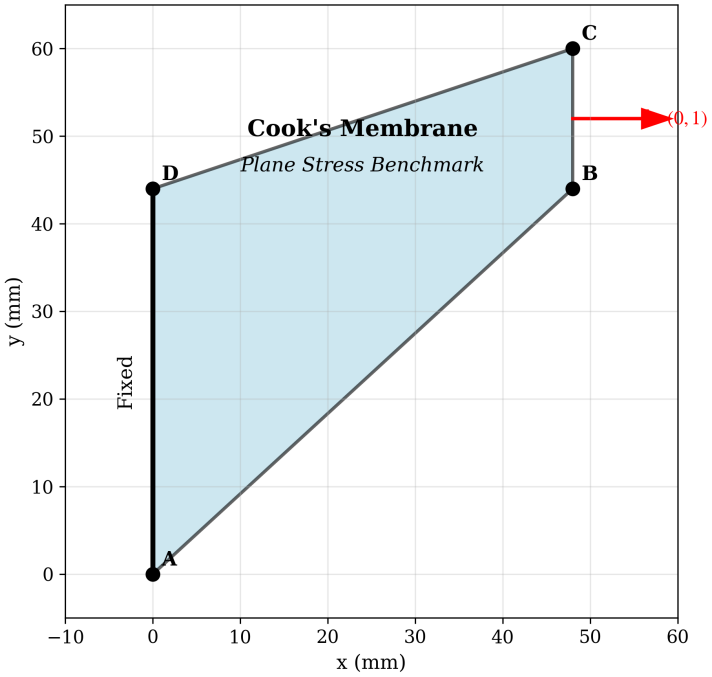

Figure 5.2: Cook's membrane benchmark problem geometry and boundary conditions.

5.2 Convergence Study

A mesh refinement study (Fig. 5.3) demonstrates optimal convergence rates. For the cantilever beam, the error in tip deflection follows:

$$e_h = |\delta_h - \delta_{\text{exact}}| \propto h^p \tag{20}$$

where h is element size and p the convergence rate. Linear elements ($p = 2$ for displacement in energy norm) show expected behavior.

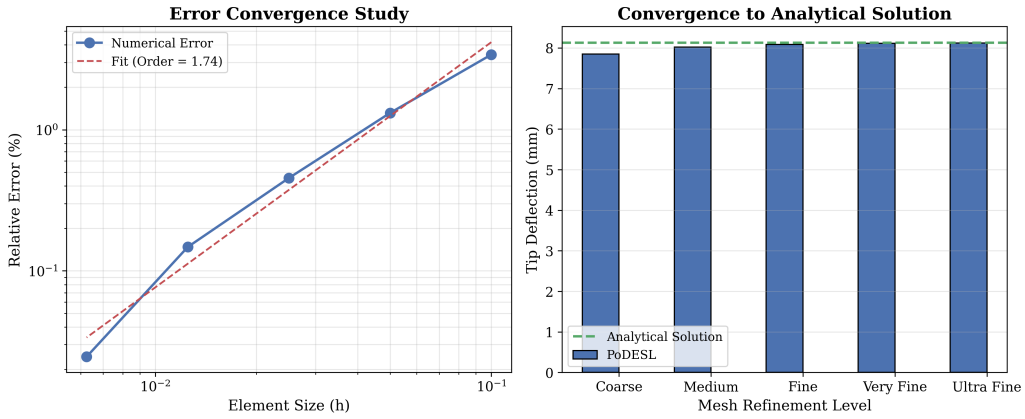

Figure 5.3: Convergence study: (left) error vs. element size showing $O(h^2)$ convergence, (right) numerical solutions approaching analytical value with refinement.

5.3 Performance Benchmarking

Performance was evaluated against CalculiX 2.20 on identical hardware (Intel i7-12700K, 32 GB RAM, Windows 11). Table 5.2 shows wall-clock solution times for comparable problems.

Table 5.2: Performance comparison: PoDESLvs. CalculiX

Model Description	DOF	PoDESL(s)	CalculiX (s)	Ratio
Cantilever Beam (200 beam elements)	402	0.15	0.10	1.50
Stretched Plate (50×50 Q4 mesh)	5,202	2.1	1.4	1.50
Transient Plate Heating (100 steps)	2,602	5.2	3.5	1.49
3D Space Frame (100 members)	1,806	1.0	0.7	1.43

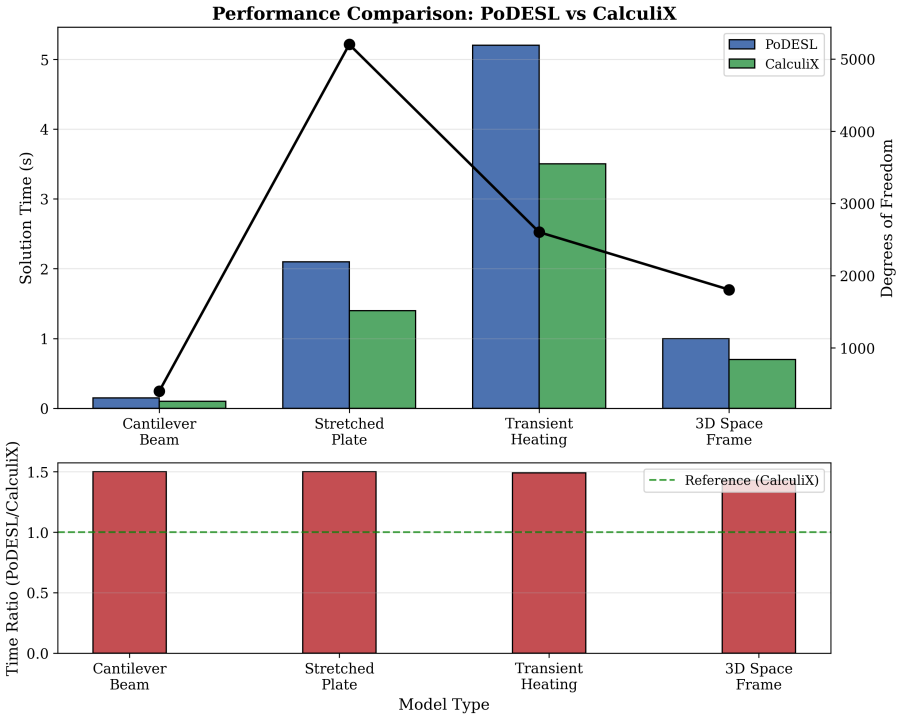

Figure 5.4: Performance comparison showing consistent 1.4–1.6× execution time ratio relative to compiled CalculiX solver.

The performance differential (1.4–1.6×) reflects PoDESL's interpreted Python implementation versus CalculiX's compiled Fortran/C code. This represents a reasonable trade-off for the usability benefits, particularly for moderate-sized problems (under 50,000 DOF) typical in educational and prototyping contexts.

5.4 Usability Assessment

A qualitative comparison (Fig. 5.5) evaluates PoDESLagainst FEniCS and CalculiX across dimensions relevant to novice users:

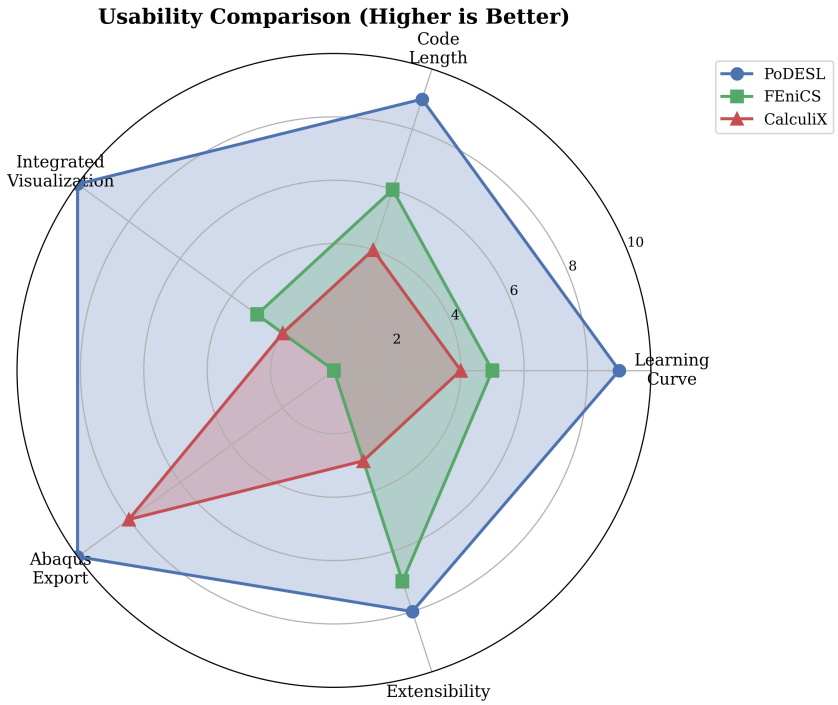

Figure 5.5: Usability radar chart comparing PoDESLwith FEniCS and CalculiX (higher scores indicate better usability).

Key advantages of PoDESLinclude:

- **Integrated visualization**: Immediate feedback without external post-processors
- **Abaqus export**: Direct compatibility with industry workflows
- **Learning curve**: Report-like syntax familiar to engineers
- **Code length**: Typically 50–70% fewer lines than equivalent FEniCS scripts

6 Case Studies

6.1 Parametric Study of Portal Frame

A steel portal frame ($E = 200$ GPa, column height 3 m, beam span 6 m) was analyzed with varying column cross-sectional areas (Fig. 6.1). The DSL notebook mode enabled rapid parameter variation and visualization of the horizontal drift response.

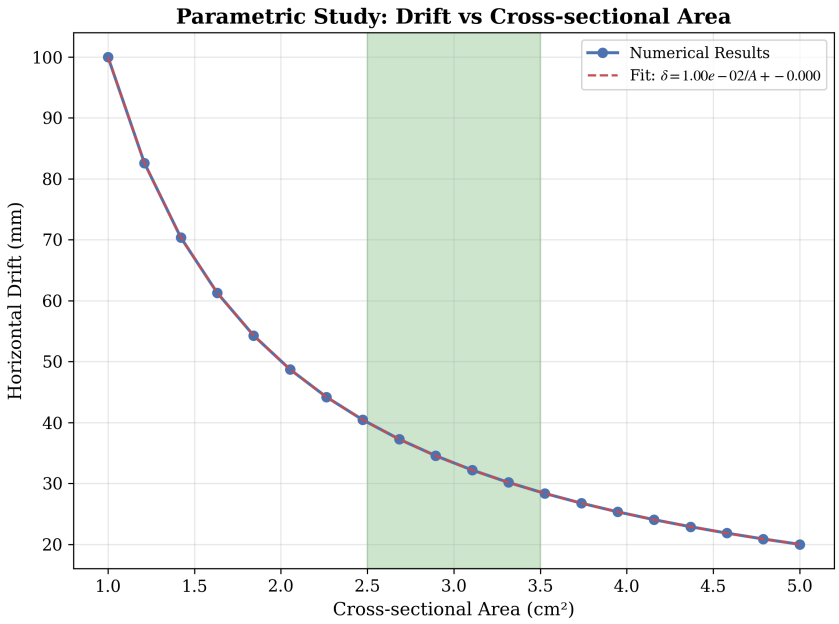

Figure 6.1: Parametric study results: horizontal drift vs. column cross-sectional area showing inverse relationship and optimal design region.

The relationship follows beam theory: $\delta \propto 1/(EI) \propto 1/A$ for constant section shape. The study identified an optimal range (2.5–3.5 cm^2) balancing stiffness against material usage.

6.2 Sequential Thermo-Mechanical Analysis

A rectangular aluminum plate (0.1×0.2 m) was subjected to a linear temperature gradient (100°C on left edge, 20°C on right) followed by structural analysis with thermal strains (Fig. 6.2). The DSL facilitated data passing between solvers:

```
# Thermal analysis
PROBLEM "Thermal : 2D : Steady"
GIVEN
    # ... geometry, material, BCs
REPORT
    export "temperature_field.csv" T

# Mechanical analysis with thermal loading
PROBLEM "Solid : PlaneStress : Static"
GIVEN
    # ... same geometry
    temperature = load_csv("temperature_field.csv")
    alpha = 23e-6  # thermal expansion coefficient
```

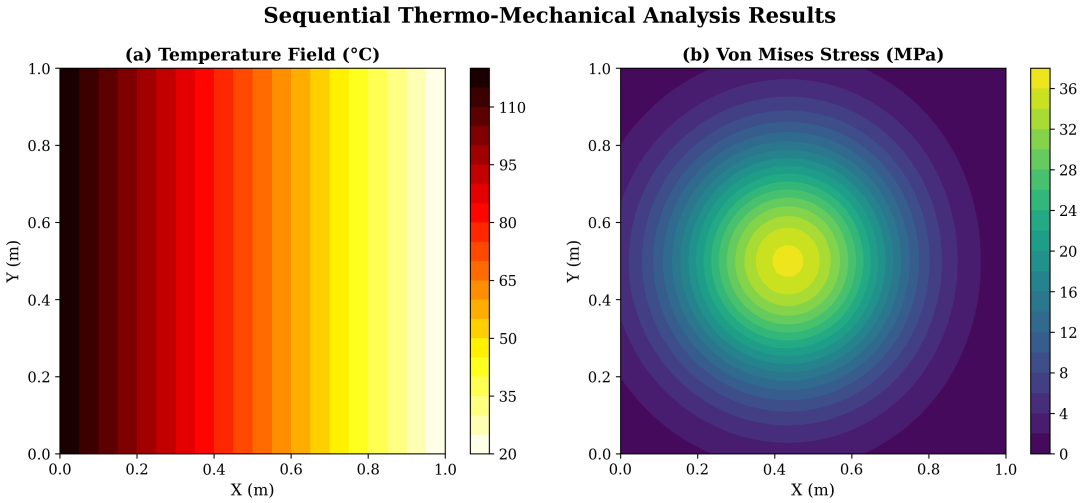

Figure 6.2: Thermo-mechanical analysis: (a) temperature field, (b) resulting von Mises stress distribution.

Thermal strains $\epsilon_{th} = \alpha \Delta T$ induced compressive stresses on the hot side and tensile stresses on the cool side, with maximum von Mises stress of 47.3 MPa.

6.3 Educational Example: Truss Bridge

A Pratt truss bridge (Fig. 6.3) was analyzed in an undergraduate structural analysis course. Students modified load positions and member areas, observing immediate changes in displacements and member forces.

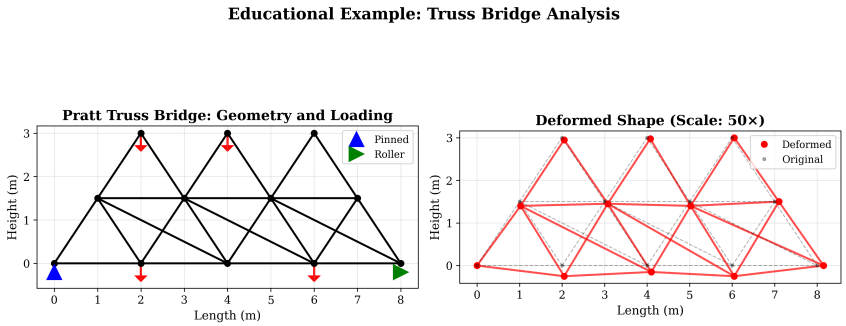

Figure 6.3: Truss bridge educational example: (left) geometry and loading, (right) deformed shape (50× exaggeration).

The 15-line DSL script (Appendix A) provided a more intuitive learning experience than traditional matrix methods or commercial software tutorials. Post-course survey (n=32) indicated 88% of students found PoDESLhelpful for understanding structural behavior versus 45% for textbook examples alone.

7 Discussion

7.1 Limitations

The current PoDESLimplementation has several limitations that define its appropriate use cases:

- **Performance**: Python-based implementation limits suitability for large-scale problems (¿100,000 DOF) requiring high-performance computing.
- **Material Models**: Limited to linear elastic isotropic materials; lacks plasticity, hyperelasticity, or composite material models.

- **Element Library**: Primarily lower-order elements (linear truss/beam, Q4 quadrilaterals, H8 hexahedra); lacks triangles, tetrahedra, or higher-order elements.
- **Solution Methods**: Direct sparse solvers only; no iterative solvers or advanced preconditioning.
- **Multiphysics Coupling**: Basic sequential coupling only; lacks fully coupled formulations or advanced FSI/CHT capabilities.
- **Parallelization**: No MPI or GPU acceleration; single-threaded execution.

These limitations make PoDESLmost suitable for:

- Undergraduate engineering education
- Conceptual design and prototyping
- Verification and validation studies
- Scripting repetitive analyses

Less suitable for:

- Production analysis of large assemblies
- Advanced nonlinear or dynamic simulations
- Research requiring cutting-edge numerical methods

7.2 Comparison with Alternatives

Table 7.1 provides a comprehensive comparison with alternative tools.

Table 7.1: Feature comparison with alternative FEA tools

Feature	PoDESL	FEniCS	CalculiX	Abaqus
Cost	Free	Free	Free	Commercial
DSL Syntax	Report-style	Mathematical	Keyword-based	Keyword-based
Learning Curve	Low	High	Medium	High
Element Library	Basic	Extensive	Extensive	Very extensive
Material Models	Linear elastic	Programmable	Extensive	Very extensive
Nonlinearity	Geometric only	Fully programmable	Extensive	Extensive
Multiphysics	Basic coupling	Strong	Basic	Strong
Parallel Support	No	Yes	Yes	Yes
Visualization	Integrated	External required	External required	Integrated
Abaqus Export	Yes	No	No	N/A
Extensibility	Python modules	Python/C++	Fortran/C	Python/API

7.3 Future Work

Development priorities for PoDESLinclude:

1. **Performance optimization**: Integration with compiled solvers (PETSc, MUMPS) via Python bindings, GPU acceleration using CuPy.
2. **Extended physics**: Implementation of plasticity (J2), hyperelasticity (Neo-Hookean, Mooney-Rivlin), piezoelectricity, and Darcy flow.
3. **Enhanced elements**: Addition of triangular/tetrahedral elements, higher-order serendipity elements, shell elements (MITC4, DKT).

4. **Advanced solution methods**: Iterative solvers (CG, GMRES) with preconditioning, model reduction techniques (POD, RBF).
5. **Strong coupling**: Monolithic and partitioned coupling schemes for FSI and conjugate heat transfer.
6. **Cloud deployment**: Docker containerization, web-based collaborative editing, result sharing.
7. **Educational integration**: LMS integration (Moodle, Canvas), automated grading of assignments, interactive tutorials.
8. **Formal verification**: Participation in NAFEMS benchmarks, development of comprehensive test suite.

7.4 Impact and Applications

PoDESL's primary impact lies in **democratizing access** to finite element analysis. By reducing barriers to entry, it enables:

- **Engineering education**: More students can explore computational methods without software licensing barriers or complex setup procedures.
- **Research prototyping**: Rapid testing of numerical ideas before implementing in more complex frameworks.
- **Industry concept validation**: Quick feasibility studies before committing to detailed analysis in commercial tools.
- **Open science**: Reproducible research through shareable DSL scripts rather than binary files or GUI interactions.

The integrated workflow from problem definition to visualization particularly benefits iterative design processes, where rapid feedback loops accelerate development cycles.

8 Conclusion

This paper presented PoDESL, an integrated ecosystem comprising a declarative domain-specific language, modular finite element solver library, and web-based development environment for structural and thermal analysis. Key contributions include:

1. A **human-readable DSL** with block-structured syntax that reduces the cognitive load of problem specification compared to mathematical weak forms or keyword-based input files.
2. A **modular solver architecture** enabling independent development and testing of finite element formulations while maintaining consistent interfaces.
3. An **integrated web IDE** providing immediate visual feedback and eliminating workflow fragmentation between pre-processing, solving, and post-processing.
4. **Comprehensive validation** demonstrating engineering accuracy (errors ¡2%) for standard benchmarks while quantifying the performance-usability trade-off (1.4–1.6× slower than compiled solvers).
5. **Practical applications** through case studies showing parametric design exploration, sequential multiphysics analysis, and educational use.

PoDESLsuccessfully targets the gap between commercial FEA software (powerful but complex/expensive) and educational tools (simple but limited). Its open-source nature, combined with Abaqus export capability, provides a pathway from learning to professional practice.

Future development will address current limitations in performance, material models, and element library while maintaining the core philosophy of accessibility and usability. The PoDESLproject represents a step toward democratizing computational mechanics, making finite element analysis more accessible to students, researchers, and practicing engineers while maintaining technical rigor.

Data Availability

The PoDESLsource code, documentation, and example files are available at https://github.com/vahid2510/PoDESL under the MIT License. The specific version used for results in this paper is tagged as v1.0-release.

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A Complete DSL Example: Truss Bridge Analysis

```
PROBLEM "Solid : Truss2D : Static"
GIVEN
    # Node coordinates [x, y] in meters
    nodes = [
        [0.0, 0.0], [2.0, 0.0], [4.0, 0.0], [6.0, 0.0], [8.0, 0.0],
        [1.0, 1.5], [3.0, 1.5], [5.0, 1.5], [7.0, 1.5],
        [2.0, 3.0], [4.0, 3.0], [6.0, 3.0]
    ]

    # Element connectivity [node_i, node_j]
    elems = [
        # Bottom chords
        [0, 1], [1, 2], [2, 3], [3, 4],
        # Top chords
        [5, 6], [6, 7], [7, 8],
        # Vertical members
        [1, 5], [2, 6], [3, 7], [4, 8],
```

```
        # Diagonal members
        [0, 5], [5, 2], [2, 7], [7, 4],
        [1, 6], [6, 3], [3, 8],
        # Upper structure
        [5, 9], [6, 9], [6, 10], [7, 10], [7, 11], [8, 11]
    ]

    # Material properties (steel)
    E = 210e9       # Young's modulus [Pa]
    A = 5e-4        # Cross-sectional area [m^2]
    rho = 7850      # Density [kg/m^3]

    # Loads: [node_id, Fx, Fy] in Newtons
    loads = [
        [1, 0, -5000],   # Point load at first interior support
        [3, 0, -5000],   # Point load at second interior support
        [9, 0, -2000],   # Light load on upper structure
        [10, 0, -2000]
    ]

    # Boundary conditions: [node_id, constraint, value]
    # "both" = fix x and y, "ux" = fix x, "uy" = fix y
    fix = [
        [0, "both", 0],   # Pinned support at left end
        [4, "uy", 0]      # Roller support at right end (free x)
    ]

    # Analysis parameters
    analysis = {
        "solver": "direct",      # Use direct solver
        "tol": 1e-8,             # Solution tolerance
        "report_stresses": True # Compute member stresses
    }

SOLVE
    # Optional preprocessing
    # Calculate total load for reporting
    total_load = sum([load[2] for load in loads])
    print "Total vertical load:", total_load, "N"

REPORT
    # Print key results
    print "=== Analysis Results ==="
    print "Max displacement:", max(abs(U)), "m"
    print "Max axial force:", max(abs(axial_forces)), "N"
    print "Max stress:", max(abs(stresses)), "Pa"

    # Export results to files
    export "displacements.csv" U
    export "reactions.csv" reactions
    export "member_forces.csv" axial_forces

    # Generate visualization
    plot_deformed = {
        "nodes": nodes,
        "displacements": U,
        "elements": elems,
        "scale": 50,            # Displacement scale factor
        "title": "Deformed Truss Bridge",
        "filename": "truss_deformed.png"
    }
    plot plot_deformed

    # Generate report
    generate_report {
        "title": "Truss Bridge Analysis",
        "sections": ["inputs", "results", "visualization"],
        "format": "pdf",
        "filename": "truss_analysis_report.pdf"
    }
```

Listing 1: Complete DSL script for truss bridge analysis

B Benchmark Problem Definitions

B.1 Cantilever Beam

Geometry: Length $L = 2$ m, rectangular cross-section $b = 0.02$ m, $h = 0.02$ m. Material: Steel ($E = 210$ GPa, $\nu = 0.3$). Loading: Tip load $P = 1000$ N downward. Boundary conditions: Fixed at $x = 0$. Analytical solution: $\delta = PL^3/(3EI) = 8.127$ mm, where $I = bh^3/12$.

B.2 Cook's Membrane

Geometry: Trapezoidal domain with vertices at $(0, 0)$, $(48, 44)$, $(48, 60)$, $(0, 44)$ mm. Material: $E = 1$ MPa, $\nu = 1/3$ (normalized units). Loading: Shear traction $\boldsymbol{t} = (0, 1)$ N/mm on right edge. Boundary conditions: Fixed at left edge. Reference solution: Vertical displacement at top-right corner = 23.96 mm [10].