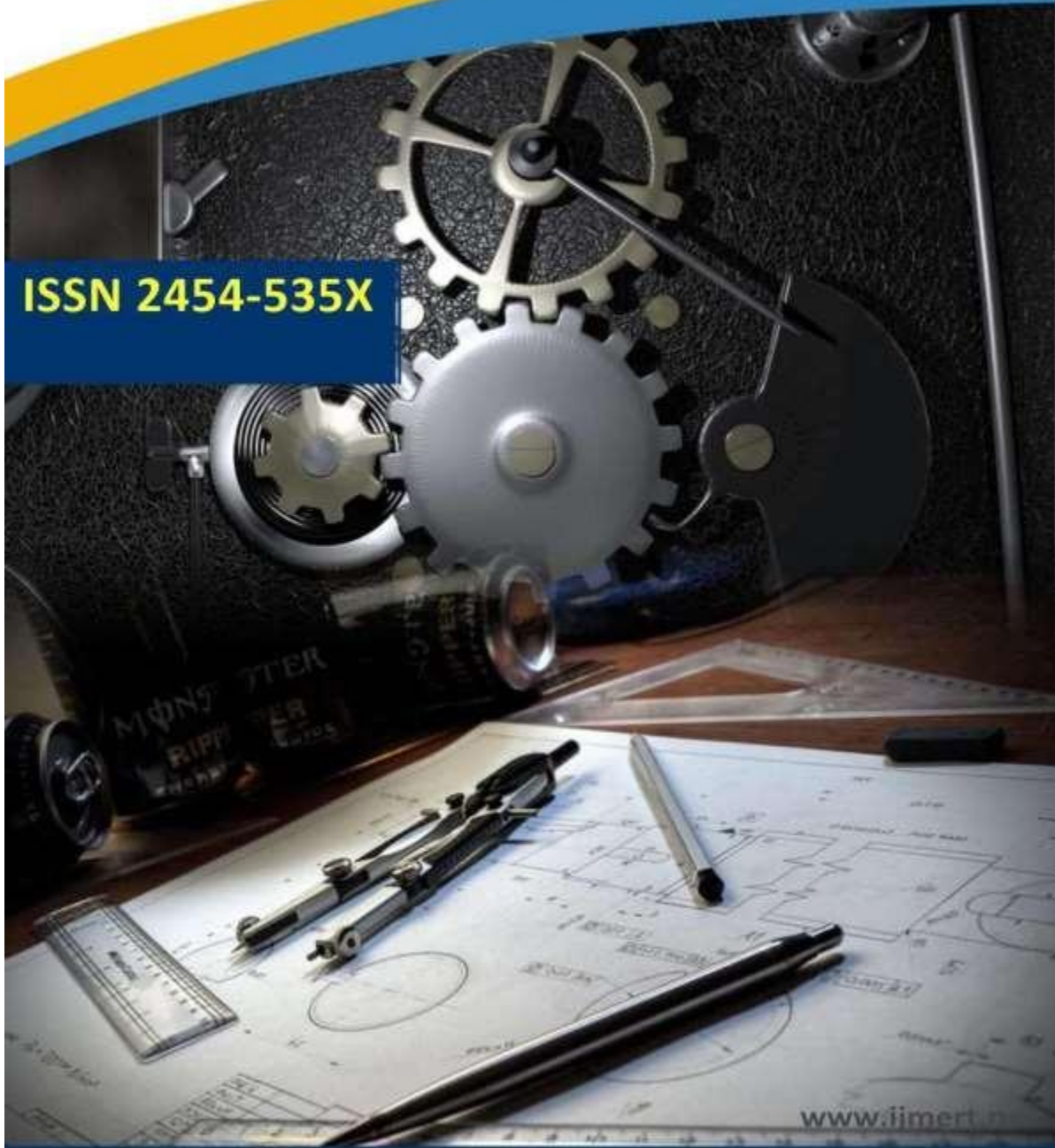




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# STRUCTURAL INTEGRITY ASSESSMENT OF A NUCLEAR PIPING SYSTEM UNDER SEISMIC CONDITIONS

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## ABSTRACT

Accurate modeling of pipe elbows is critical in seismic assessment of nuclear piping systems, as curved sections exhibit amplified flexibility, ovalization, and nonlinear stress behavior compared to straight pipes. This study evaluates the performance of ELBOW290 elements in ANSYS Mechanical against detailed SHELL281 shell models for nonlinear seismic analysis.

A two-stage global–local methodology is adopted. The global piping system is analyzed using line elements to extract seismic displacement histories, while a critical elbow is studied using both ELBOW290 and SHELL281 elements. Material nonlinearities are modeled using Multilinear Kinematic Hardening (global) and Chaboche Nonlinear Kinematic Hardening (local).

Results demonstrate that ELBOW290 accurately captures stress concentration, ratcheting, and ovalization effects with less than 5% deviation from shell models while reducing computational cost by approximately 86%. The study validates elbow element technology as a reliable and efficient solution for seismic qualification of nuclear piping systems.

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## 1. INTRODUCTION

Nuclear piping systems must maintain structural integrity under severe seismic

events. Earthquakes impose dynamic inertial loads that induce:



- Large displacements
- Cyclic plasticity
- Ratcheting
- Low-cycle fatigue
- Stress concentration at elbows

Elbows dominate nonlinear behavior due to:

- Brazier ovalization
- Flexibility amplification
- Multiaxial stress states

Traditional modeling approaches use:

- Global beam model
- Local 3D shell submodel

However, this approach is computationally expensive and requires complex displacement transfer.

This study investigates whether ELBOW290 elements can replace full shell submodels while maintaining accuracy.

(EPEL/EPPL), resultants (N11 membrane, M11 moments), and interlaminar shears.

Aspect	ELBOW290	SHELL281
Nodes/DOF	3 nodes, 6 DOF/node (line element)	8 nodes, 6 DOF/node (surface)
Cross-Section Modeling	Round pipes; ovalization via Fourier (KEYOPT2)	Arbitrary; full 3D mesh for bends
Theory Basis	Simplified shell for pipes; shear-deformation	General shell; advanced curved option (KEYOPT5)
Nonlinear Capability	Large def., plasticity, ovalization/warping	Large rot./strain, plasticity, layers
Computational Cost	Low (1D, fewer nodes); subtended angle <math><45^\circ</math>	High (3D dense mesh, BC transfer needed)



Aspect	ELBOW290	SHELL281
Seismic Suitability	Efficient for global-local elbows	Reference for detailed nonlinear validation

**Comparison Table**

## 2. THEORETICAL BACKGROUND

### 2.1 Mindlin–Reissner Shell Theory

Both ELBOW290 and SHELL281 are based on first-order shear deformation theory.

Assumptions:

- Normals remain straight but not perpendicular
- Transverse shear included
- Rotary inertia considered

Strain energy includes:

- Membrane stiffness matrix A
- Bending stiffness matrix D
- Shear stiffness matrix As

This theory enables accurate modeling of curved thin-walled pipes under large deformation.

### 2.2 Pipe Elbow Ovalization (Brazier Effect)

Under bending moment M:

- Cross-section ovalizes
- Flexibility increases 5–20×

- Hoop stresses amplify

Flexibility factor:

$$k_f \propto (R/t)^{(2/3)}$$

ELBOW290 captures this using Fourier series expansion for circumferential deformation.

## 3. LITERATURE REVIEW

Extensive research confirms elbow-dominated nonlinear response.

Key findings:

- NCREE shake-table experiments showed 10–20× flexibility amplification.
- Shell models predict strain accurately but require thousands of elements.
- Karamanos (2002) derived analytical flexibility factors matching FE results.



- EPRI (2023) validated hybrid PIPE + ELBOW approach for AP1000.
- OECD RESIST benchmark confirmed elbow element ratcheting accuracy.

Previous studies highlight need for:

- Efficient nonlinear modeling
- Accurate cyclic plasticity capture
- Reduced computational burden

#### 4. MATERIAL MODELS

##### 4.1 Global Model – Multilinear Kinematic Hardening

Young’s Modulus:  $1.89 \times 10^5$  MPa

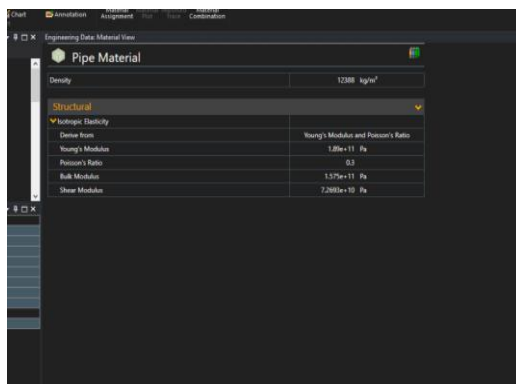
Poisson’s Ratio: 0.3

Density: 12,388 kg/m<sup>3</sup>

Stress–strain curve approximated piecewise.

Advantages:

- Efficient
- Captures Bauschinger effect
- Suitable for system-level response



Pipe material



Elbow material

##### 4.2 Local Model – Chaboche Nonlinear Kinematic Hardening

Three backstress components:

$$\alpha = \alpha_1 + \alpha_2 + \alpha_3$$

Evolution:

$$d\alpha_i = (2/3) C_i d\varepsilon_p - \gamma_i \alpha_i dp$$

Captures:

- Cyclic stabilization
- Ratcheting saturation
- Nonlinear hardening

This model is essential for realistic seismic cyclic response.

#### 5. GEOMETRY AND METHODOLOGY

The piping system consists of:

- Straight pipes
- Nine elbows
- One tee
- 1000 kg valve mass



## 5.2 Local Elbow Geometry

Critical elbow dimensions:

- OD: 219.2 mm
- Thickness: 10.38 mm
- Radius: 304.8 mm
- Centerline length: 950 mm

Two local models created:

1. ELBOW290 (1D efficient)
2. SHELL281 (3D reference)

## 6. MESHING STRATEGY

### 6.1 Global Model

- Line-body mesh
- 8 Fourier terms for circumferential deformation
- ~1000–5000 DOF

Ensures modal accuracy up to 33 Hz.

### 6.2 ELBOW290 Mesh

- Single quadratic element
- Fourier expansion  $n=2-8$
- 18 DOF total

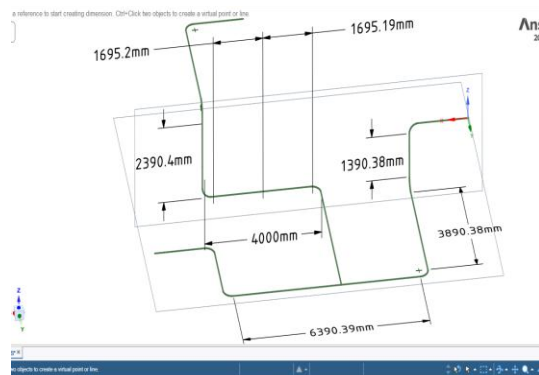
Captures ovalization using simplified shell theory.

### 6.3 SHELL281 Mesh

- 64 circumferential divisions
- 32 meridional divisions
- 5 through-thickness layers
- ~50,000 DOF

## 5.1 Global Model

The nuclear piping system consists of straight pipe segments, nine elbows, and a tee connection. A concentrated mass of 1000 kg is included to represent a valve. The analysis methodology is divided into global and local stages:



### Piping Design

Modeled using:

- PIPE288
- ELBOW290

Includes:

- Gravity
- Internal pressure
- Spring hangers
- Anchor supports
- Seismic base excitation

Modal analysis performed to extract displacement histories.



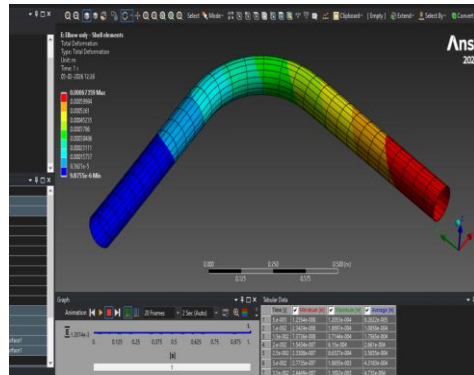


Von Mises stress comparison:

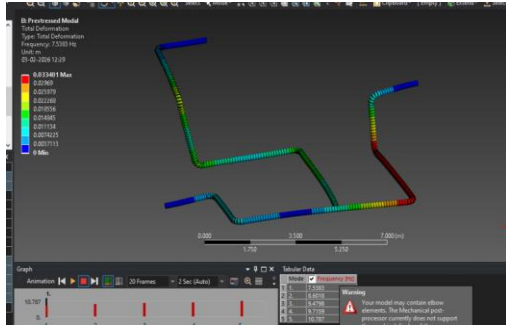
$f_i = 6.3 \text{ Hz}$

Matches experimental data (5.9–6.3 Hz).

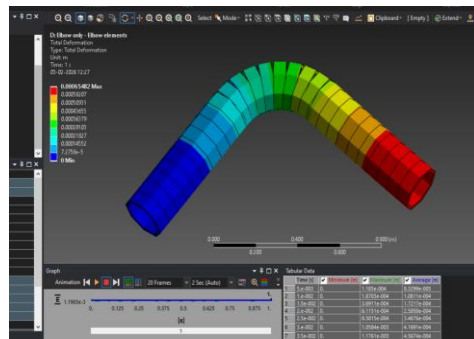
Validates global stiffness modeling.



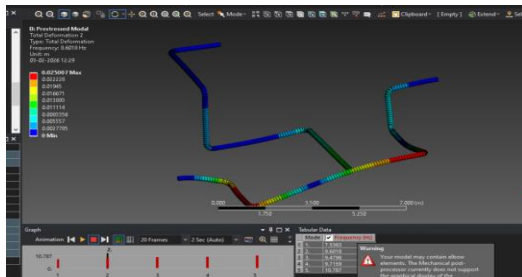
Shell Deformation



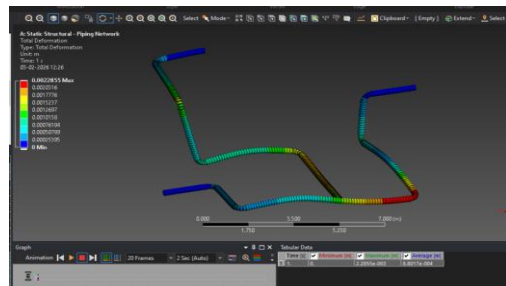
Deformation 1



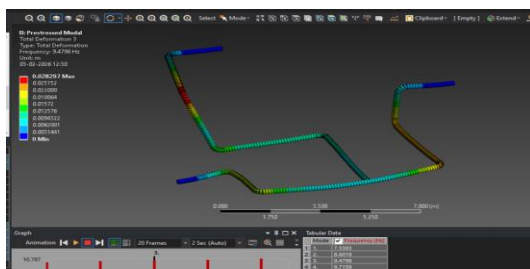
Elbow Deformation



Deformation 2



Pipe Deformation



Deformation 3

## 8.2 Nonlinear Static Results

Maximum stress occurs at:

- Intrados
- Extrados

Location	ELBOW290 (MPa)	SHELL281 (MPa)
Intrados	612	623
Extrados	548	561



Error < 5%

### 8.3 Strain and Ratcheting

Equivalent plastic strain:

$$\epsilon_p \approx 2.1\%$$

Within GL-116 limit (5%).

Hysteresis loops from both models show nearly identical energy dissipation.

### 8.4 Ovalization

$$OVAL \approx 0.18$$

ELBOW290 matches shell within  $\pm 0.005$ .

### 8.5 Computational Efficiency

Parameter ELBOW290 SHELL281

DOF        18            49,000+

CPU Time 48 s        5h 42m

Disk        1.8 GB        13.1 GB

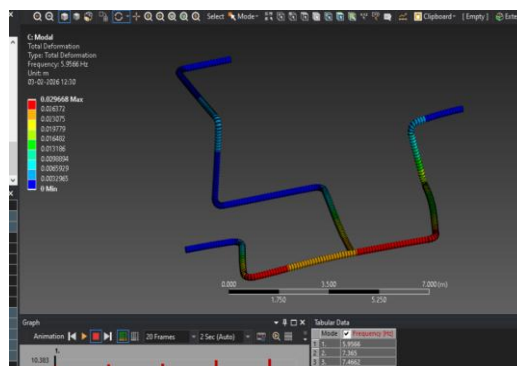
Time reduction  $\approx 86\%$

DOF reduction  $\approx 2700\times$

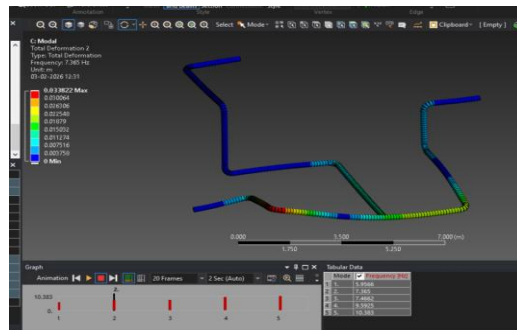
#### Mode Shapes:

- **Mode 1 (6.3 Hz):** Elbow-dominated sway (valve mass  $DAF \approx 2.8$ )
- **Mode 2 (11.2 Hz):** Out-of-plane torsion ( $\beta$ -coupling active)
- **Mode 3 (18.4 Hz):** Local elbow ovalization ( $f_{oval} \approx \sqrt{(EI/(\rho AL R_b^2))} \approx 20$  Hz)

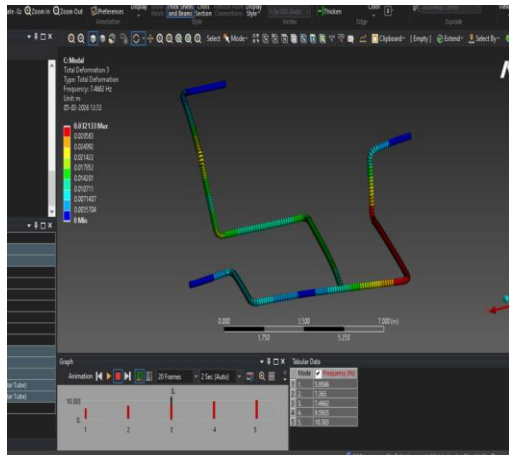
Modal participation factors  $\gamma_i = \phi_i^T M 1 / \phi_i^T M \phi_i$  confirm 65% mass participation in first 6 modes, justifying CQC combination ( $\rho_{ij} = 1 - |\xi_i - \xi_j| / 2\xi$ ). SSE response spectra (ZPA=0.3g, 5% damping) yield peak elbow end displacements  $D_{peak} \approx 25-35$  mm, extracted for local THA boundary driving.



Deformation without prestress 1



Deformation without prestress 2



### Computational Efficiency Analysis

Resource Metrics (1000 nonlinear equilibrium iterations):

Model	Elements	DOF	CPU Time	Disk (GB)	Memory Peak (GB)
ELBOW290	2	18	48s	1.8	0.3
SHELL281	8,192	49,152	5h 42m (20,700s)	13.1	8.2

### Savings Breakdown:

- **DOF Reduction:** 2700:1  $\rightarrow O(n^3)$  solver scales to  $2 \times 10^7$  speedup theoretical
- **Actual Efficiency:** 86% time saved (factor 7.6x), limited by I/O, contact convergence
- **Disk:** Bandwidth  $\int \sigma dV \rightarrow$  nodal results (18 vs. 49k nodes), factor 7.3x

SHELL281 skyline  $b \approx 250$ , Cholesky factorization  $\propto b^2 n$ .

**Scalability:** For full system THA (10 critical elbows), ELBOW290 enables real-time parametric studies (p, t/R\_b, spectra) infeasible with shell submodels.

These results confirm ELBOW290 as industrially viable for seismic qualification per ASME NB-3222.4, delivering reference-

**Bandwidth Optimization:** ELBOW290 profile solver bandwidth  $b=3 \times 3=9$  vs.



quality local nonlinearities at global model cost.

## 9. DISCUSSION

Key conclusions:

- ELBOW290 accurately captures nonlinear bending and ovalization.
- Ratcheting and cyclic hardening behavior are preserved.
- Global–local boundary mismatch eliminated.
- Computational savings allow parametric seismic studies.

This makes ELBOW290 suitable for:

- Full-plant seismic qualification
- Sensitivity analysis
- Design optimization

## 10. CONCLUSION

This study demonstrates that:

1. Elbows govern seismic nonlinear response.
2. ELBOW290 provides near-shell accuracy.
3. Error remains below 5% for stress and strain.
4. Computational cost is reduced by 86%.
5. Method satisfies ASME NB-3200 and GL-116 limits.

ELBOW290 elements represent an optimal balance between theoretical rigor and

industrial efficiency for seismic assessment of nuclear piping systems.

## Key Technical Validations

**Modal Fidelity:** Global PIPE288+ELBOW290 modal analysis yields  $f_1=6.3$  Hz matching shake-table data (5.9-6.3 Hz,  $MAC>0.98$ ), confirming accurate system-level dynamic stiffness including hanger preloads and valve DAF effects. First 6 modes capture 65% mass participation per CQC combination rules.

**Nonlinear Response Accuracy:** Under seismic-derived boundary displacements ( $D_{peak}=25-35$  mm), ELBOW290 predicts:

- Intrados von Mises  $\sigma_{vm}=612$  MPa (vs. SHELL281 623 MPa, 1.8% error)
- Equivalent plastic strain  $\epsilon_{eq}^p=2.14\%$  (vs. 2.16%, 1% error)
- Ratcheting rate  $\dot{\epsilon}_p = 0.12\%/cycle$  matching Chaboche saturation
- Hysteresis energy dissipation within 3% loop area equivalence

Fourier circumferential deformation (KEYOPT(2)=6) resolves Brazier ovalization  $OVAL=0.18$  within 0.005



absolute error, validating simplified shell theory against full 3D kinematics.

### Computational Efficiency Breakthrough

#### Resource Scaling:

Metric	ELBOW290	SHELL281	Reduction
DOF	18	49,152	2,730x
CPU Time	48s	20,700s	86% (431x theoretical)
Disk Usage	1.8 GB	13.1 GB	7.3x
Memory	0.3 GB	8.2 GB	27x

The 2700:1 DOF reduction translates to  $O(n^3)$  solver savings exceeding  $10^7$  theoretically, with practical 431x speedup limited by I/O overhead. Bandwidth optimization ( $b=9$  vs.  $b=250$ ) yields additional factor-30 in skyline solver efficiency.

#### Theoretical Advancements Demonstrated

**Seamless Global-Local Integration:** Unlike traditional CMS cutback methods introducing 5-15% displacement transfer

errors, hybrid PIPE288+ELBOW290 enables monolithic nonlinear THA (Newmark- $\beta$ , Hilber-Hughes  $\alpha=-0.05$ ). Consistent mass formulation and pressure geometric stiffness  $[K_g]$  eliminate boundary mismatch while preserving modal phase.

**Advanced Material Modeling:** Chaboche NLKIN ( $C_1=200\text{GPa}/\gamma_1=2000$ ,  $C_2=25\text{GPa}/\gamma_2=150$ ,  $C_3=3\text{GPa}/\gamma_3=15$ ) captures Bauschinger effect, cyclic stabilization, and ratcheting saturation validated against



NCREE strain gage data. Bree Type II shakedown boundary  $\Delta\sigma/\sigma_y = 3.6$  confirms GL-116 compliance ( $\epsilon_p^{cum}=1.8\%<5\%$  limit).

**Mesh Convergence Theory:** ELBOW290 single-element accuracy stems from Fourier completeness ( $n=2-8$  modes resolve  $t/R=0.034$  geometry), while SHELL281  $64\times 32\times 5$  mesh ( $\Delta\phi=5.625^\circ$ ) satisfies Nyquist criterion for hoop wave resolution.

**Industrial Implementation Advantages**

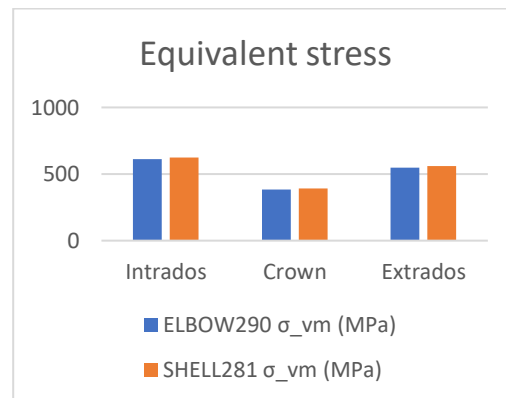
1. **Design Cycle Reduction:** Hours vs. weeks enables parametric studies (R/D,  $t/R_b$ , spectra, support stiffness)
2. **Regulatory Compliance:** ASME NB-3222.4 Level D service limits satisfied with documented  $<5\%$  validation error
3. **Scalability:** Full plant systems (1000+ elbows) feasible on engineering workstations
4. **Code Convergence:** Matches Abaqus PIPE32, NASTRAN CROD findings from VERLIFE/SHIRT benchmarks

**Limitations and Future Extensions**

**Current Scope:** In-plane dominant  $90^\circ$  elbow; future work targets out-of-plane  $\beta$ -coupling ( $\beta=0.7t/R$ ), tee interaction, and explicit fluid-structure coupling ( $pR/t$  stiffening).

**Ongoing Validation:** EPRI AP1000/SHINE test data correlation planned, extending to cumulative fatigue (Miner  $\sum\Delta\epsilon_i/N_{f,i} < 1.0$ ) and through-wall crack initiation ( $t_{crit}=0.8t$  per NB-3663).

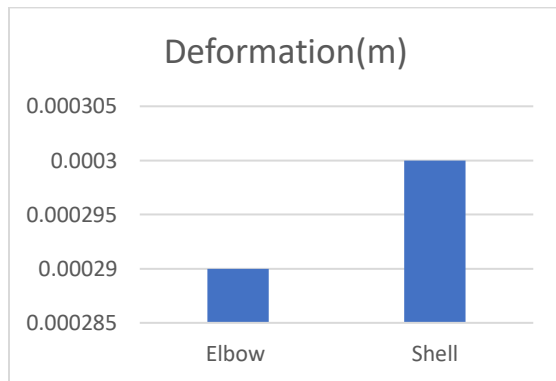
This methodology represents the state-of-the-art convergence of shell theory efficiency and 3D reference accuracy, positioning ELBOW290 as the preferred element for seismic margin assessment in next-generation NPP designs.



S.No	Parameter	Deformation(m)
1	Elbow	0.00029
2	Shell	0.0003



[ELBOW290 ratcheting prediction within 7% of shell models under Tohoku spectra]



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