180 Series elements: Why should one use them in Linear Analysis

Mechanics & Simulation Support Group

Introduction

- 180 series elements were designed & developed for large deformation analysis with plenty of advanced element technologies and a very rich nonlinear constitutive support.
- During the development, consistency and generality were the main theme.
  - Fewer assumptions were made.

Introduction (cont.)

- They are natural candidates for nonlinear analysis in general for:
  - Finite strain and large rotation analysis
  - History dependent and independent materials
- We will not focus on nonlinear functionalities in general here.
- But … they are excellent choices even in linear analysis. The reasons are discussed here.

Solid Elements; Formulations

Formulations	Core Legacy	180 Series	Comment on 18x Series
Displacement			•Both Shear and Volumetric locking are addressed in 180 series • Independent of Poisson's Ratio (nearly or equal to 0.5) and useful for small strain plasticity
Conventional	✓[4]	☑[3]	
Selective Reduced Integration(B-bar)	×	✓	
Uniform Reduced Integration	☑[1]	✓	
Enhanced Strain	☑[2]	✓	
Mixed u-P			•ANSYS automatically switches among the mixed u/P formulations according to the materials.
Elasto-plastic materials	×	✓	
Fully incompressible hyperelastic	×	✓	
Nearly incompressible hyperelastic	✓	✓	

[1] PLANE82, SOLID45 and SOLID95 only

[2] Extra shapes meant for bending application only

[3] Degenerate forms, Plane stress state of PLANE182

[4] Not desirable most frequently!

Enhanced Strain vs Extra Shapes

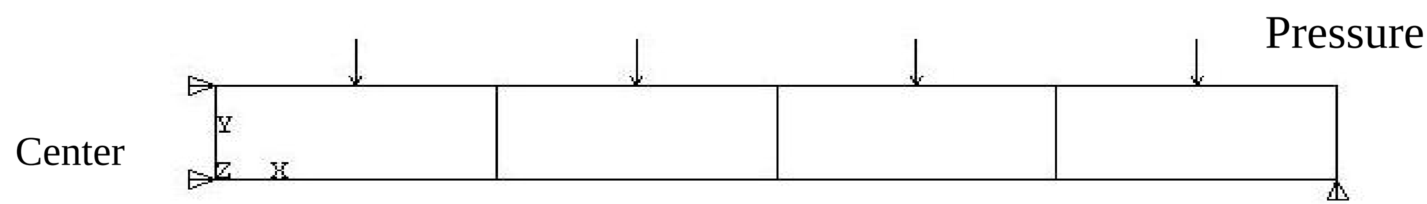
– Bending of a thin plate (R=10, h=1)

– Element 182 with enhanced strain formulation and 42 with extra shape function

– Axisymemtric stress state

– Pure elastic material, different Poisson's ratios (E=1875, nu=0.0, 0.25, 0.3, 0.49, 0.499, 0.4999)

– Linear analysis, under pressure (p=1)



Enhanced Strain vs Extra Shapes

- Vertical displacements of central point
  - No locking in element 182 for high Poisson's ration

Results from Element 42

NU	Node	Theory	ANSYS	Error(%)
0	1	5.03200	4.95185	1.59273
	7	5.03200	4.95220	1.58579
0.25	1	3.97070	3.91587	1.38088
	7	3.97070	3.91623	1.37170
0.3	1	3.74360	3.69292	1.35370
	7	3.74360	3.69329	1.34380
0.49	1	2.82480	2.72489	3.53689
	7	2.82480	2.72529	3.52272
0.499	1	2.79000	2.36694	15.16353
	7	2.79000	2.36734	15.14912
0.4999	1	2.78550	2.06928	25.71246
	7	2.78550	2.06968	25.69802

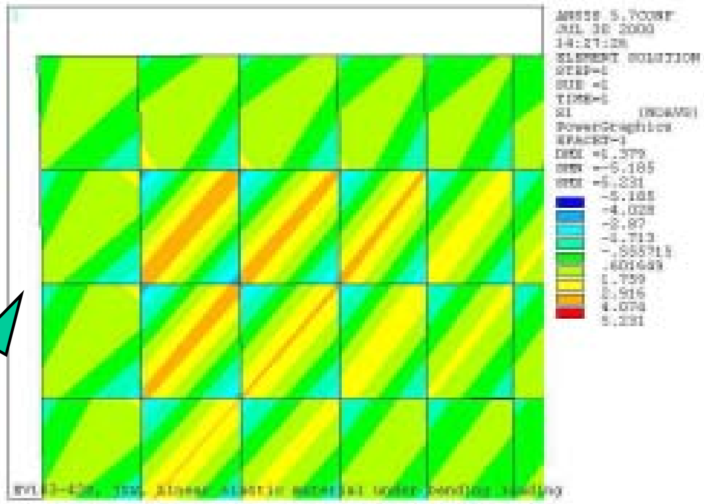
Results from Element 182

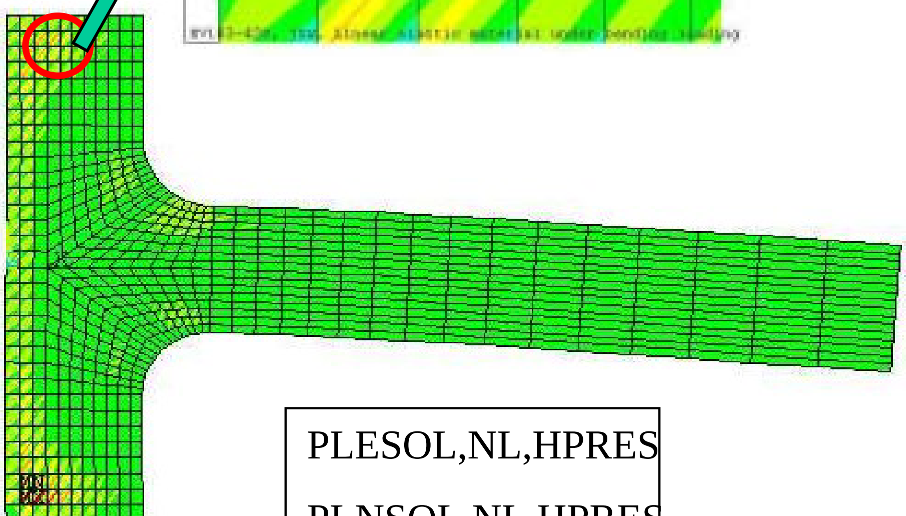
NU	Node	Theory	ANSYS	Error(%)
0	1	5.03200	5.15370	2.41859
	7	5.03200	5.15406	2.42564
0.25	1	3.97070	4.04281	1.81599
	7	3.97070	4.04317	1.82514
0.3	1	3.74360	3.79787	1.44975
	7	3.74360	3.79824	1.45955
0.49	1	2.82480	2.79481	1.06156
	7	2.82480	2.79520	1.04796
0.499	1	2.79000	2.74437	1.63538
	7	2.79000	2.74476	1.62158
0.4999	1	2.78550	2.73931	1.65809
	7	2.78550	2.73970	1.64426

Mixed u-P in Linear Analysis

18x only!

When Poisson’s ratio is too high and other technologies can not eliminate volumetric locking, mixed u-P formulation should be employed.

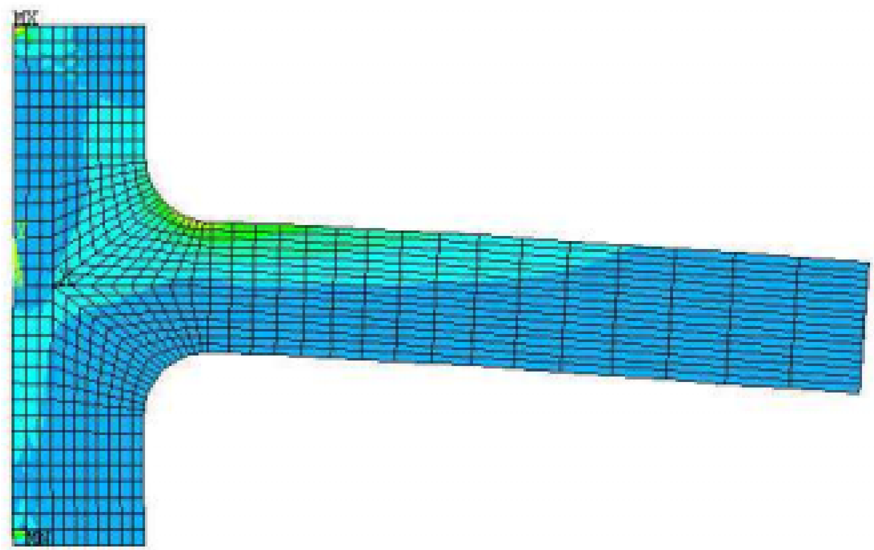




PLESOL,NL,HPRES

PLNSOL,NL,HPRES

Checkerboard patterns of pure displacement formulations



Mixed u-P results, no checkerboard patterns

Solid Elements; Stress States

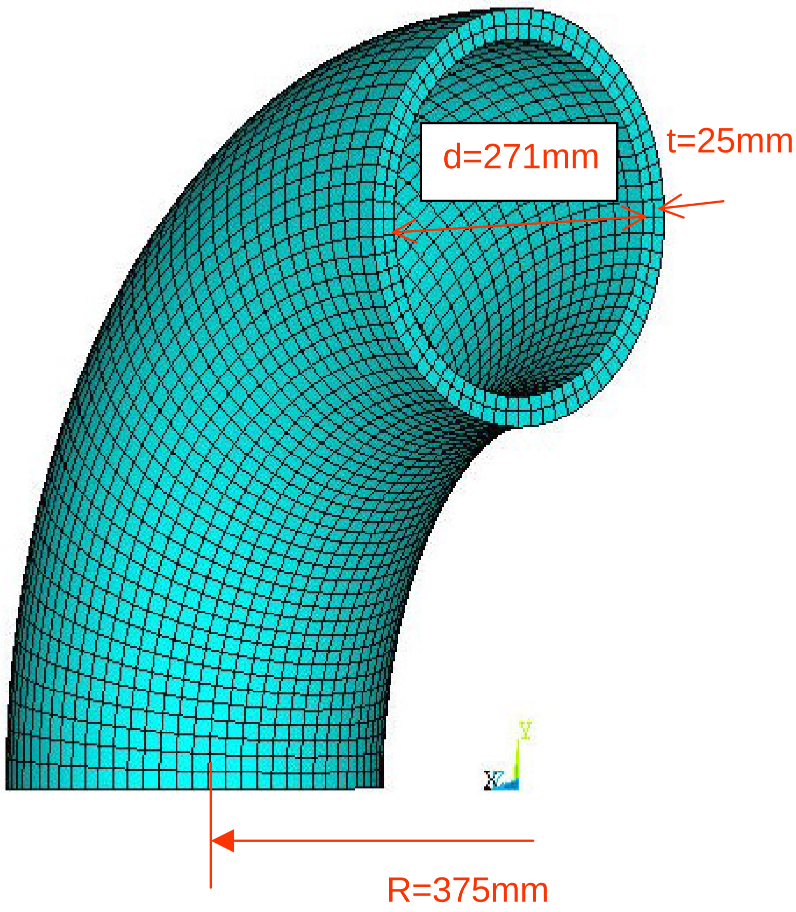
Stress States	**Core Legacy**	**180 Series**[1]
Plane Stress	✓	✓
Plane Strain	✓	✓
Generalized Plane Strain	✗	✓
3D Continuum	✓	✓
Axisymmetric	✓	✓

[1] All formulations pass patch test for all stress states

Generalized Plane Strain

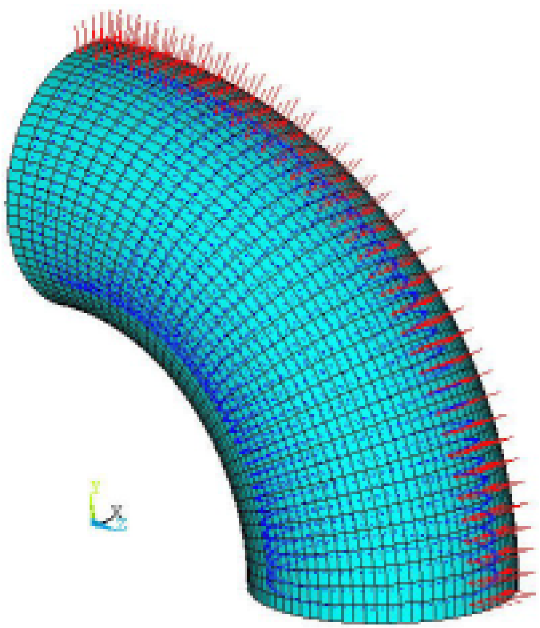
182/183 only!

- To simulate elbow pipe under pressures
  - Geometry
    - As shown in the figure
    - The two end planes have an angle of 90 degrees
  - Material
    - E=200 Gpa
    - Nu=0.28
  - Load
    - Inner pressure: 150 Mpa
    - External pressure: 1200 Mpa
  - FE model
    - 2D 183 generalized [lane strain
    - 3D 186

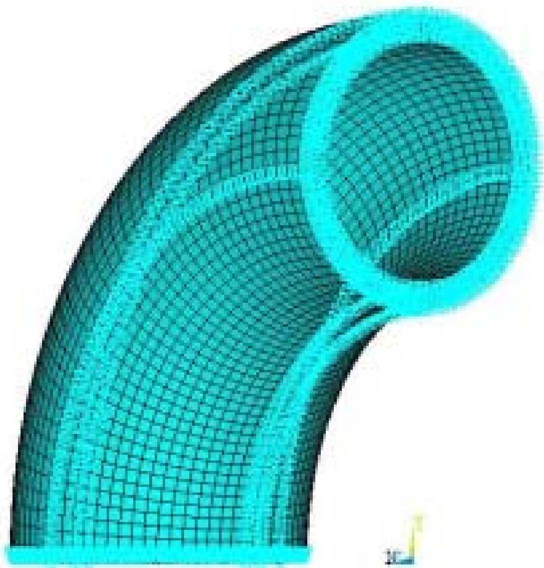


3D Simulation of The Elbow Pipe

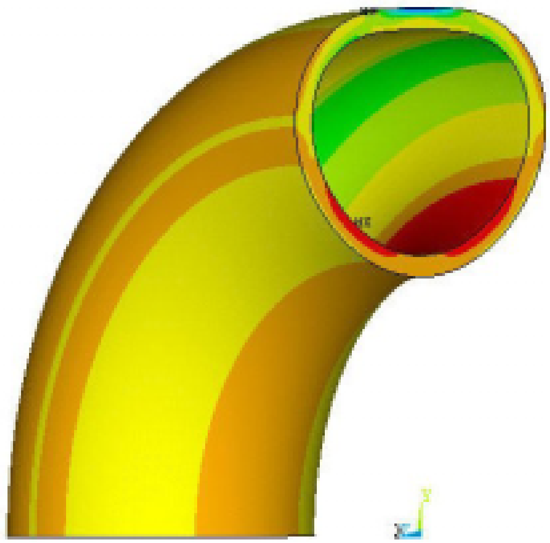
– Model creation and solution need more time



Loads



Boundary conditions



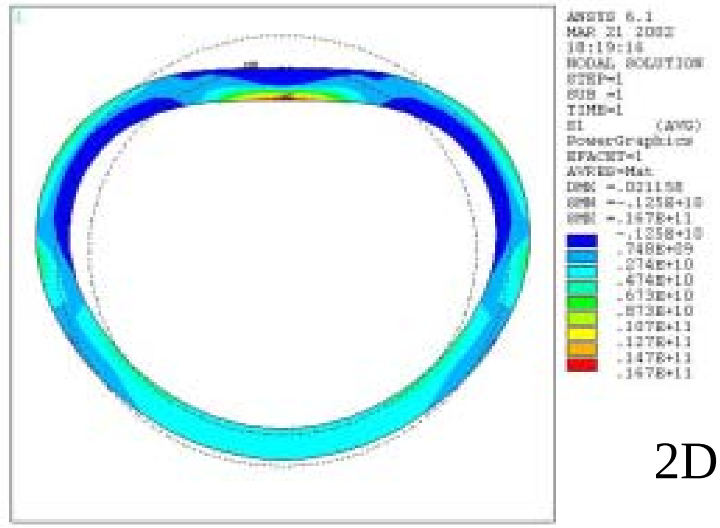
Solutions

3D Model

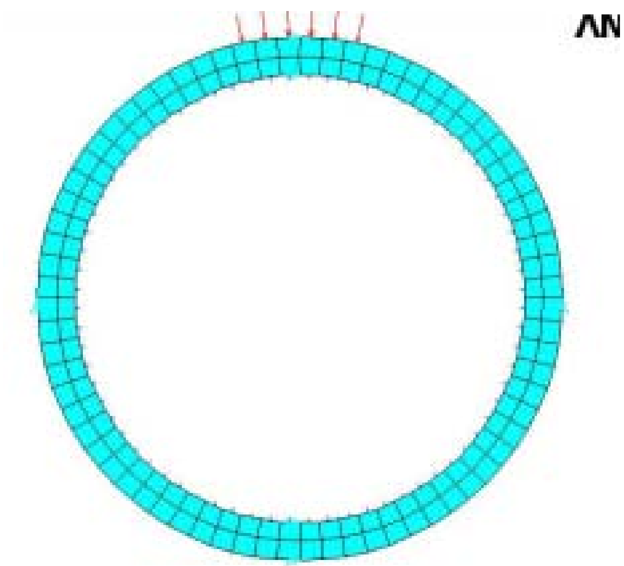
182/183 only!

2D Simulation of The Elbow Pipe

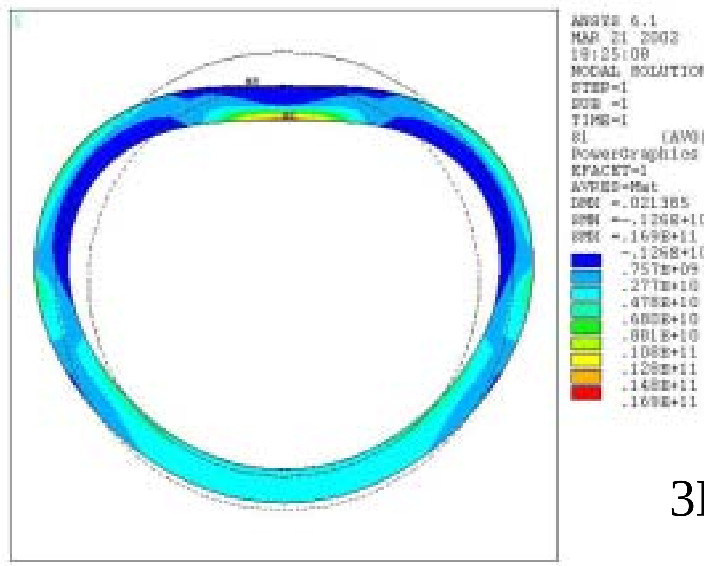
- Modeling so simple
- Simulation is about 100 times faster than 3D
- Results are almost identical



2D Solution



2D Model



3D Solution

Solid Elements; Materials

- 180 series of continuum elements are applicable for all different type of materials
    - Anisotropic materials
    - Hyperelastic
    - Viscoelastic
    - Viscoplastic
    - Elastoplastic
    - Foam
    - Cast-Iron
    - Many more

Solid Elements: Other advantages

- Variational analysis using CADOE is supported with 180 series
- Mass matrix evaluated with numerically exact order of integration in 180 series
  - Consistent performance in modal/frequency analysis
- Pressure load stiffness terms are included by default
  - More accurate eigenvalue buckling prediction
  - Consistent stiffness matrix for nonlinear analysis

Other advantages (cont.)

- Mixed u/P formulations can be combined with different element technologies and applied to all stress states
- Automatic selection of element technologies is under development

Beam Elements

- What is available?

Core Legacy	180 series
BEAM4 BEAM44 BEAM3 BEAM24 BEAM23 BEAM54	BEAM188 BEAM189

Beam188/189 – Section Support

Function	Core Legacy	180 series
Standard Cross sections	☑ BEAM44 only	✓
Arbitrary User Mesh	✗	✓
Multi-Material Cross section	✗	✓
Geometrically Exact Tapered Section	✗	✓[1]
User Control over cross section mesh	✗	✓

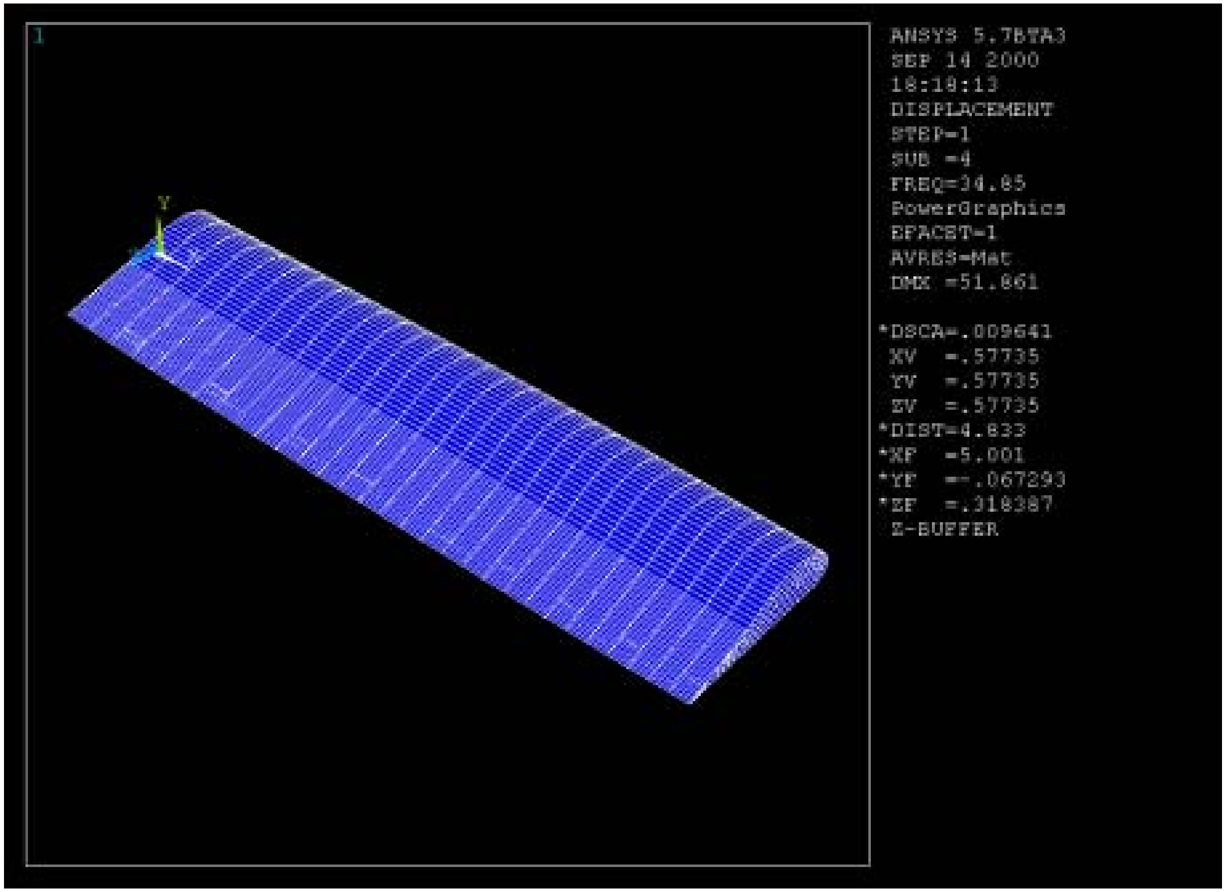
[1]Beta at 7.0

188/189 only!

BEAM188/189 – Modal analysis

- 180 Series provides Consistent Mass Matrix inclusive of rotary inertia terms

Mode	*SOLID45*	*BEAM189*
1	3.56799	3.5306
2	17.2689	17.174
3	22.0382	21.830
4	35.6358	34.850
5	60.4129	60.019



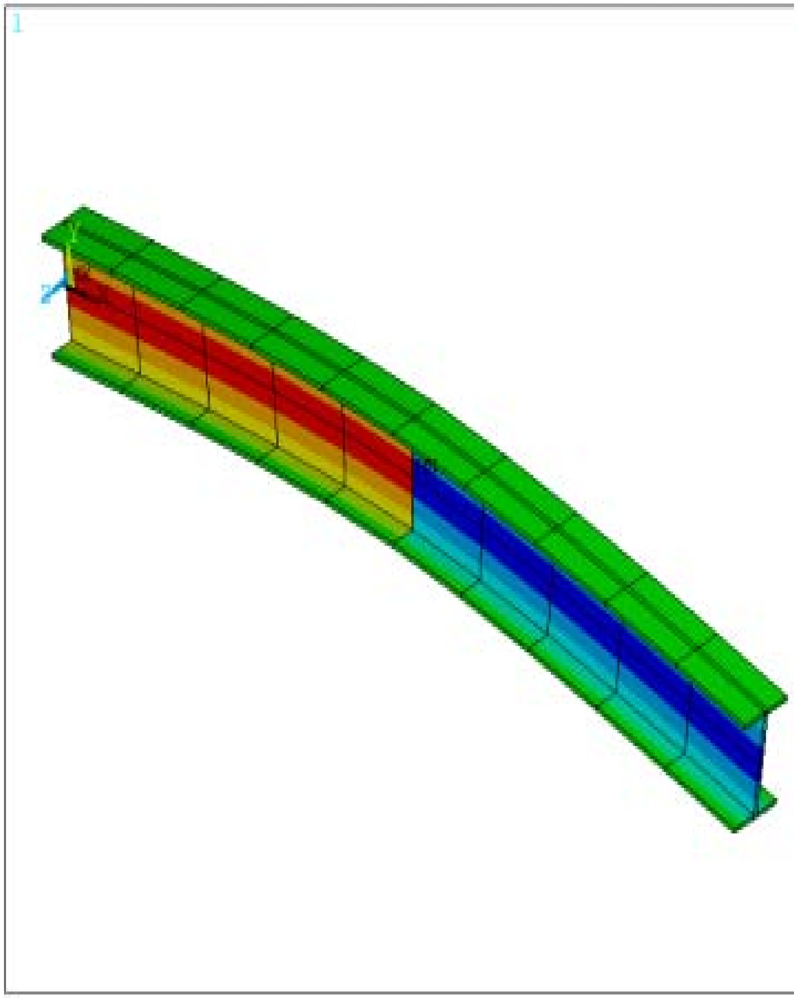
188/189 only!

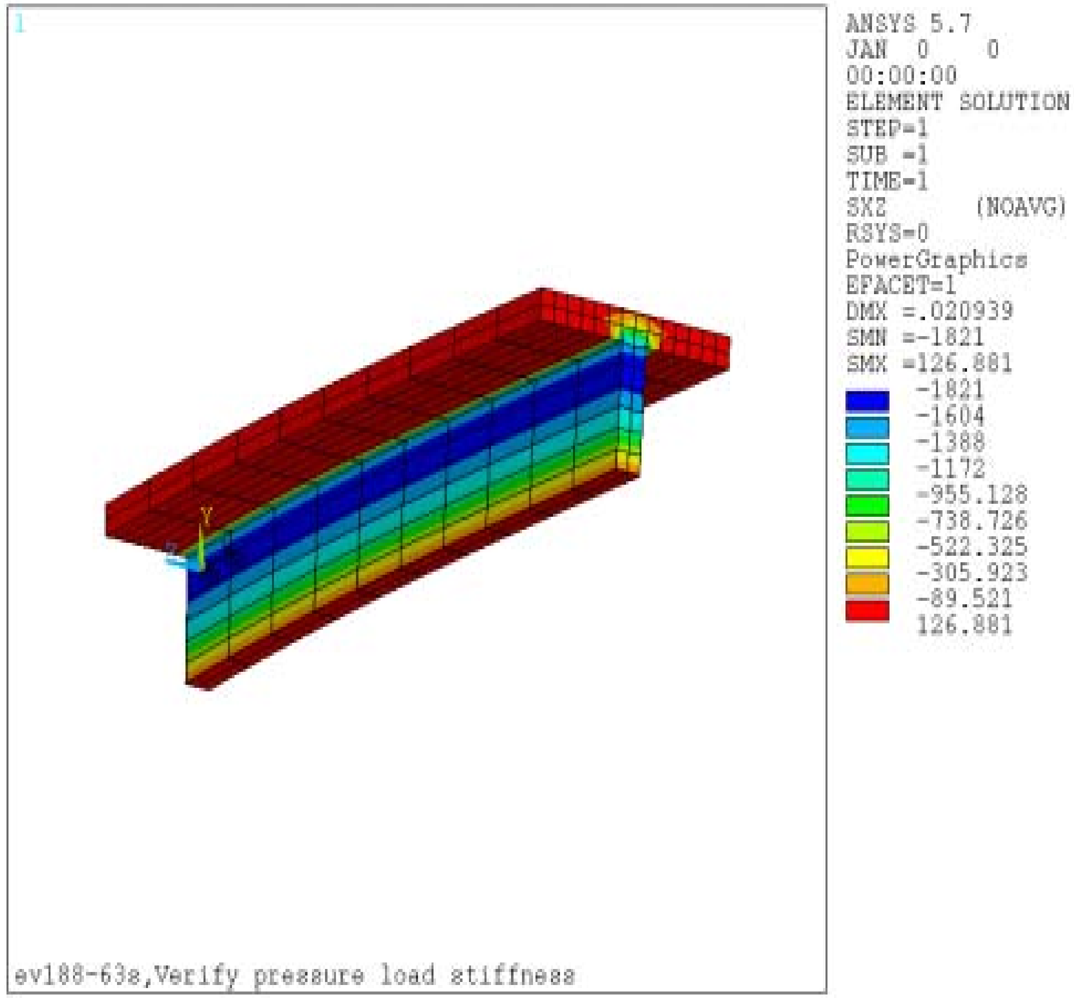
BEAM188/189-Shear Stresses

- Torsional
  - 188/189 provide highly accurate torsional shear stresses varying in a quite complex manner over the cross section (irrespecive of particular shapes or topological complexities)
- Transverse shear
  - 188/189 provide highly accurate transverse shear stress output (either in numbers or graphically). Traditionally these are referred to as Vq/I terms, and is deemed important in civil engineering. Again, the complexity of cross section is immaterial.

188/189 only!

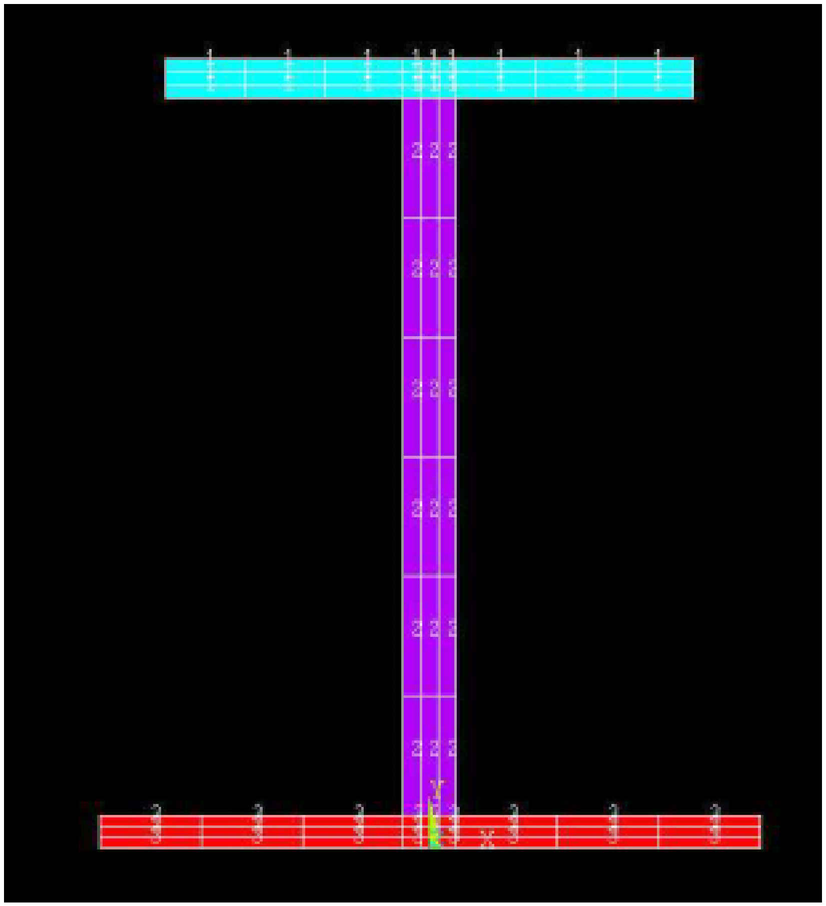
BEAM188/189
Shear Stresses Visualization



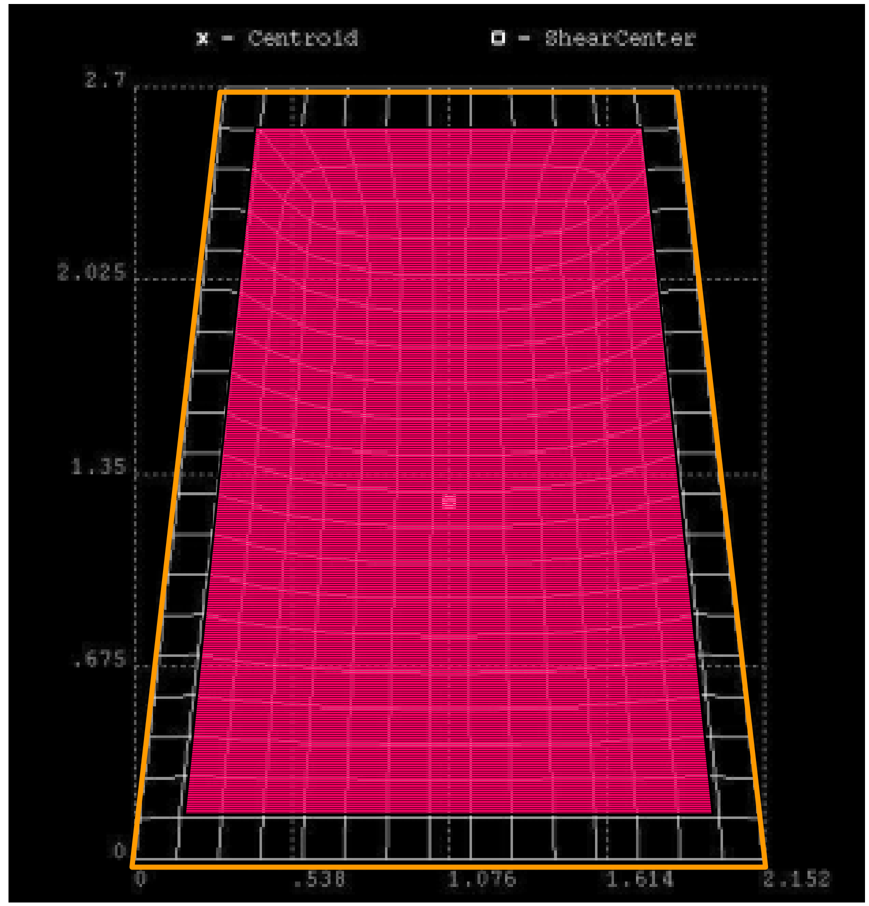


188/189 only!

Built-up Multi-material Sections



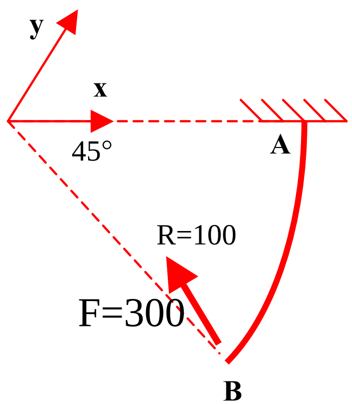
Define Materials for
a Standard Section

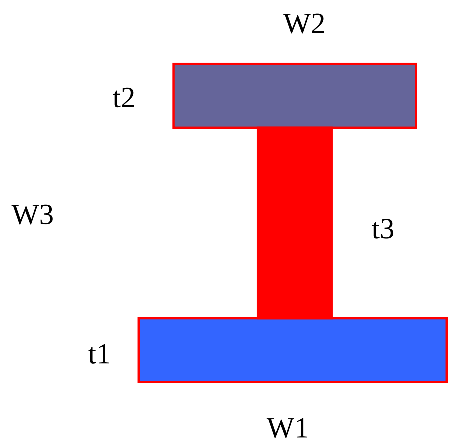


Define Materials for a Custom Section

188/189 only!

Curved composite cantilever beam





Cross section
has 3 materials

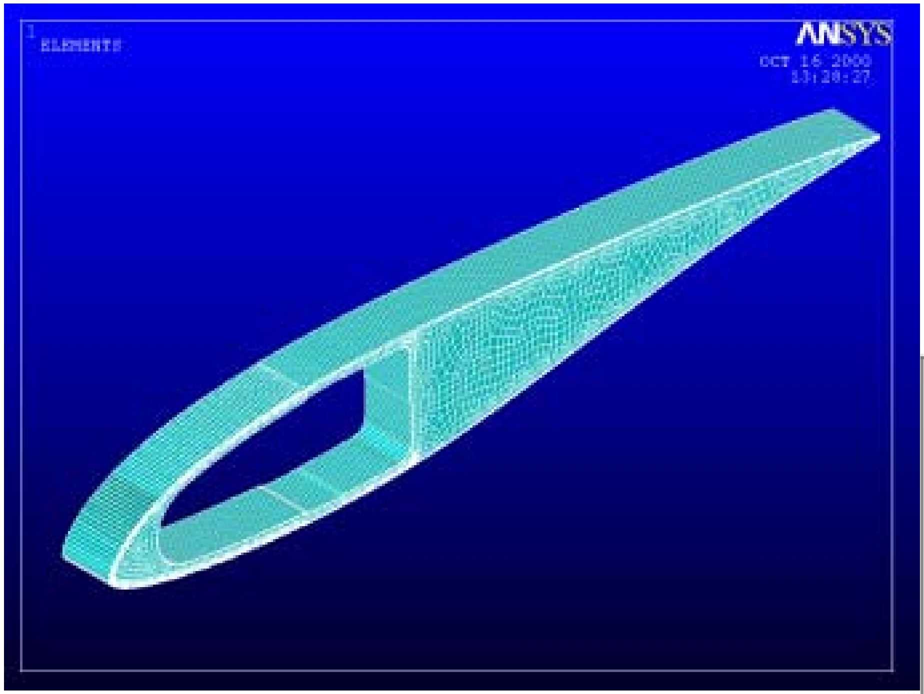
Material	EX
1	0.5E7
2	1.0E7
3	3.0E7

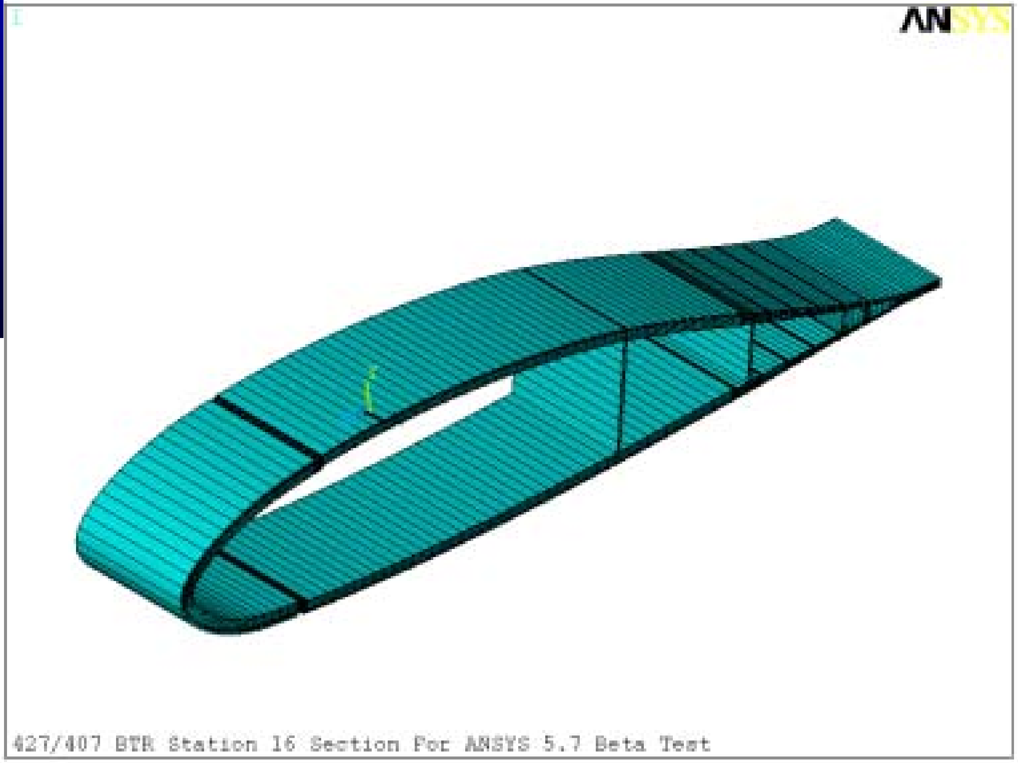
	BEAM189 (NDOF=96)		BEAM189 (NDOF=192)		SOLID186 (NDOF=18900)
Max. displacement	Value	% diff.	Value	% diff.	Reference value
Ux	19.664	0.2	19.666	0.2	19.625
Uy	24.819	1.9	24.822	1.9	25.310
Uz	54.486	0.5	54.490	0.5	54.769
CPU Time	82.610		115.460		4587.850

w1=1,w2=0.75,w3=1,t1=0.2, t2=0.15,t3=0.15

188/189 only!

Composite Rotor Section





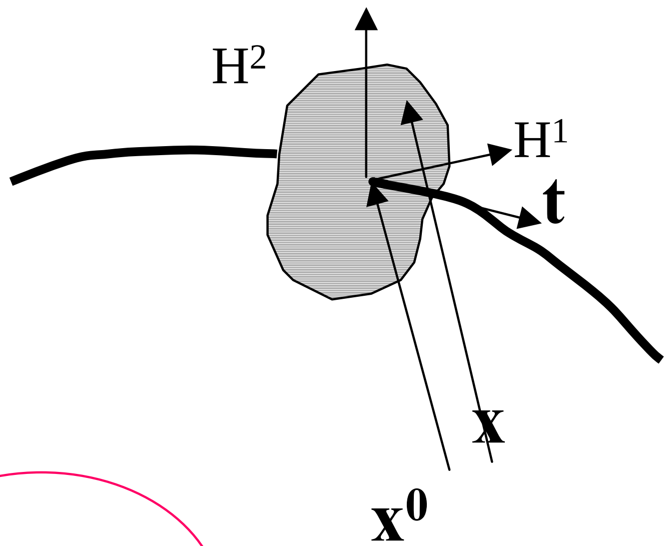
Parametric Study
(Sandwich Beam)

188/189 only!

Normalized Results (BEAM189/SOLID45)									
E-Face/E-Core	Length/Thickness	UZ	UY	UX	ROTX	Frequencies			
1	40	1.0025	1.0025	1.0000	1.0162	0.9987	0.9989	0.9757	0.9768
2	40	1.0025	1.0025	1.0000	1.0148	0.9987	0.9989	0.9758	0.9770
20	40	1.0025	1.0025	1.0030	1.0281	0.9988	0.9989	0.9758	0.9323
200	40	1.0026	1.0025	1.0050	1.0704	0.9988	0.9987	0.9759	1.0402
2000	40	1.0062	1.0025	1.0050	1.0659	0.9988	0.9930	0.9759	0.9625
20000	40	1.0510	1.0025	1.0040	0.9252	0.9987	0.9436	0.8883	0.9761
1	20	1.0025	1.0023	0.9930	1.0186	0.9987	0.9993	0.9757	0.9799
2	20	1.0025	1.0025	0.9940	1.0187	0.9988	0.9994	0.9760	0.9807
20	20	1.0025	1.0025	1.0030	1.0425	0.9988	0.9995	0.9762	1.1674
200	20	1.0035	1.0025	1.0190	1.0654	0.9988	0.9987	0.9762	0.9757
2000	20	1.0232	1.0025	1.0080	1.0537	0.9988	0.9930	0.9726	0.9763
20000	20	1.1332	1.0070	1.0090	0.7943	0.8676	0.9988	0.7716	0.6789

188/189 only!

Inclusion of warping



$$\{\mathbf{u}, \boldsymbol{\varphi}, \omega\}$$

$$\mathbf{x} = \mathbf{x}^0 + H^\alpha \mathbf{n}^\alpha + \omega\psi\mathbf{t}$$

$$\varepsilon = \ln(\lambda) + H^\alpha \varepsilon_\alpha^\beta \kappa^\beta + \frac{d\omega}{dS}\psi\mathbf{t} + O(h^2)$$

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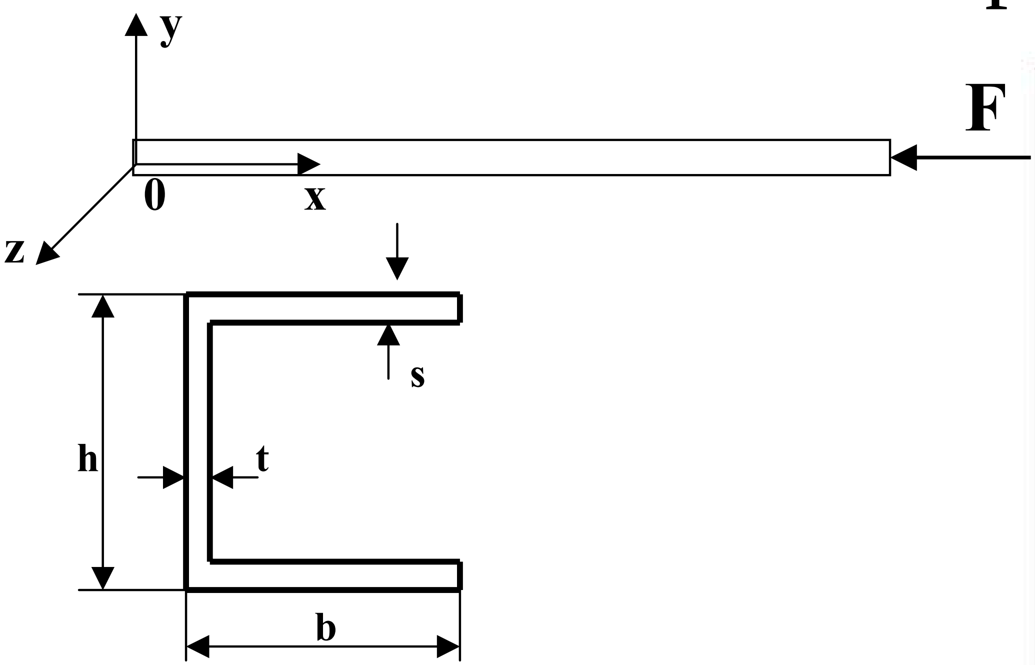
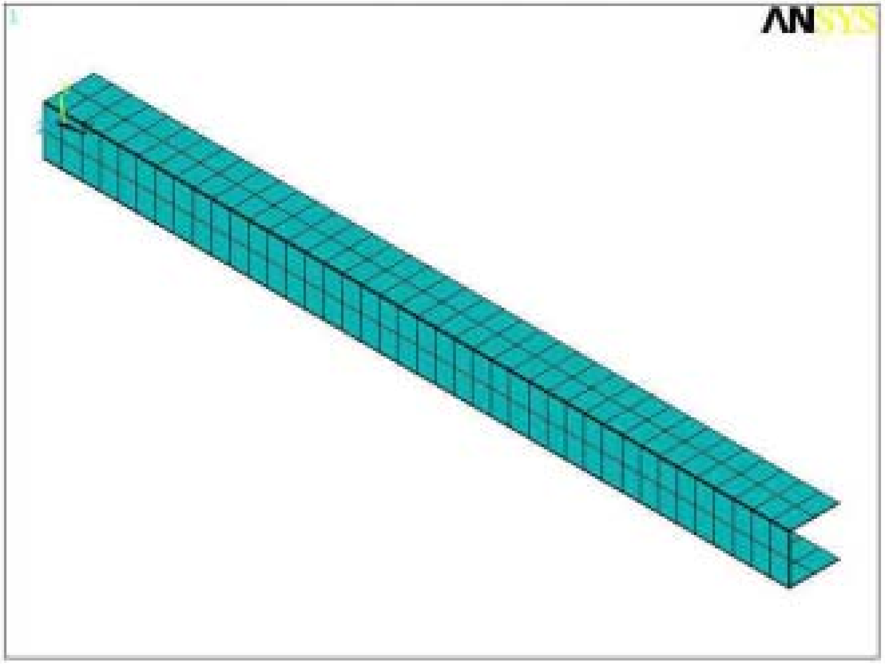
Restrained Warping Analysis





Geometry

h = 10 cm, b = 10 cm, s = t = 0.2 cm,

L =150 cm (length)

Material Properties

E = 21000 kN/cm², G = 8077 kN/cm²

Boundary Conditions

x = 0: $u_x = u_y = u_z = 0$

$\theta_x = 0$

x = L: $u_y = u_z = 0$

$\theta_x = 0$

188/189 only!

Warping restraint is important!

Critical buckling loads (Theory and numerics of three-dimensional beams with elastoplastic material behavior by F. Gruttmann et al.):

$$F_1 = n^2 \frac{\pi^2 EI_{22}}{L^2} \qquad F_2 = n^2 \frac{\pi^2 EI_{33}}{L^2} \qquad F_3 = \frac{1}{(i_M)^2}\left(GI_T + n^2 \frac{\pi^2 EI_w}{L^2}\right)$$

The theoretical critical buckling load:

$$F_{cr} = 2\left[\left(\frac{1}{F_2}+\frac{1}{F_3}\right)+\sqrt{\left(\frac{1}{F_2}-\frac{1}{F_3}\right)^2+\frac{4}{F_2 F_3}\left(\frac{m_2}{i_M}\right)^2}\right]^{-1}$$

where $(i_M)^2 = (i_p)^2 + (m_2)^2$

Mode Number	Value of the Buckling Load (kN)		
	FEM (w/o warping)	FEM (w/ warping)	Reference
1	~~7.371~~	113.9	115.5
2	~~7.398~~	419.6	443.3

Pure torsional reference critical buckling load w/o warping = 7.386 (kN)

188/189 only!

Lateral Buckling

NAFEMS BENCHMARK TEST

FOR BEAMS AND SHELLS, January 1993

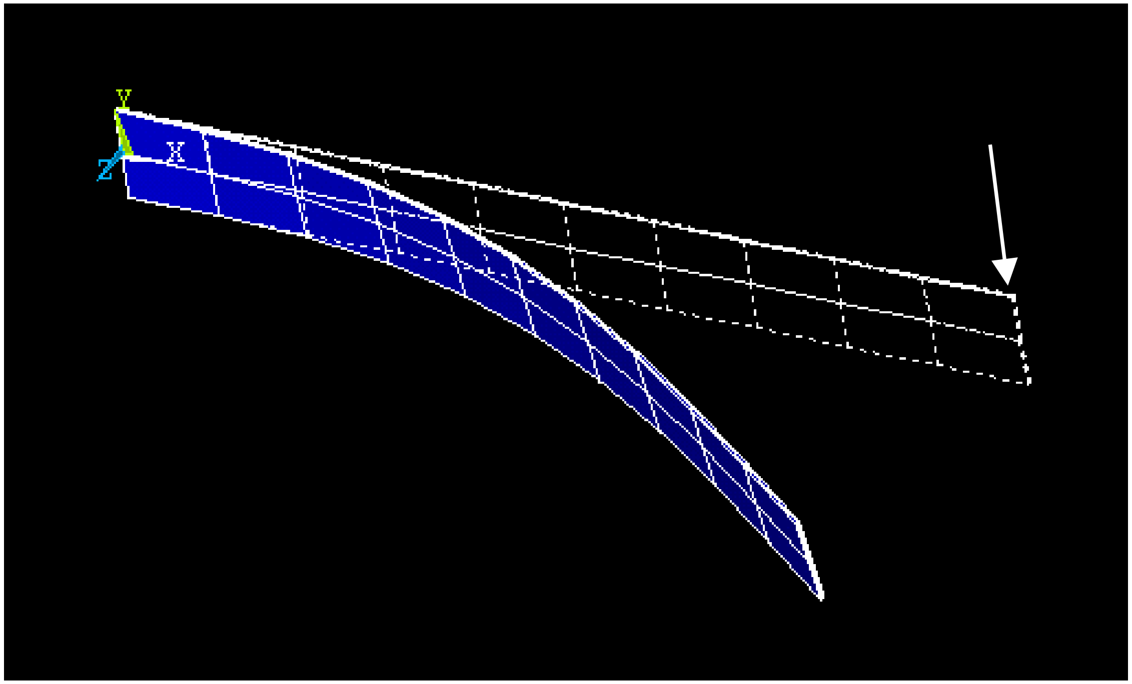
Problem ID 3DNLG-4

Critical Buckling Load

Target Solution= 0.01892

BEAM188 = 0.01902

BEAM44 produces a error message:



*** ERROR *** CP= 1.090 TIME= 10:04:53

Stress stiffness matrix is all zero. No load factor solution is possible.

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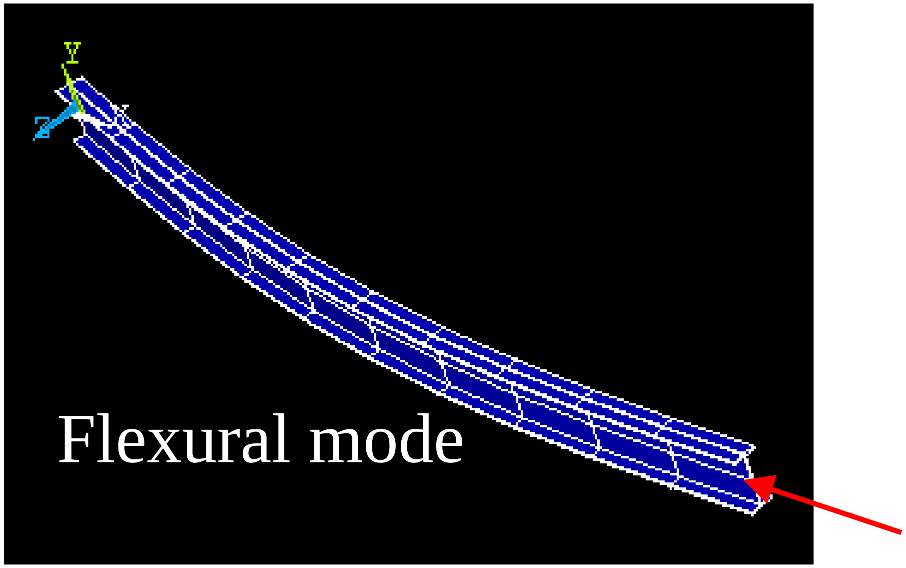
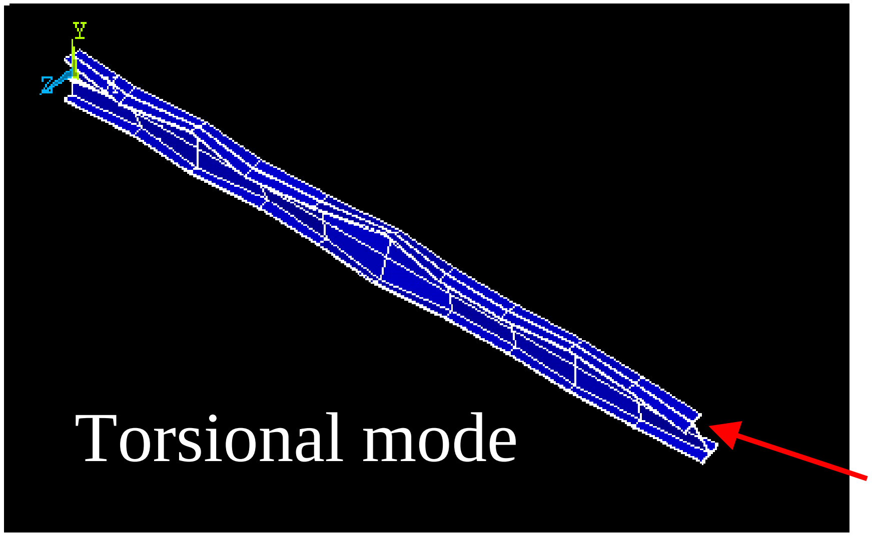
Lateral/Torsional Buckling

BEAM44	0.17484E+07 ✓
BEAM188	0.17732E+07
Target	0.17510E+07



BEAM44	missed mode ✗
BEAM188	0.42867E+07
Target	0.40632E+07



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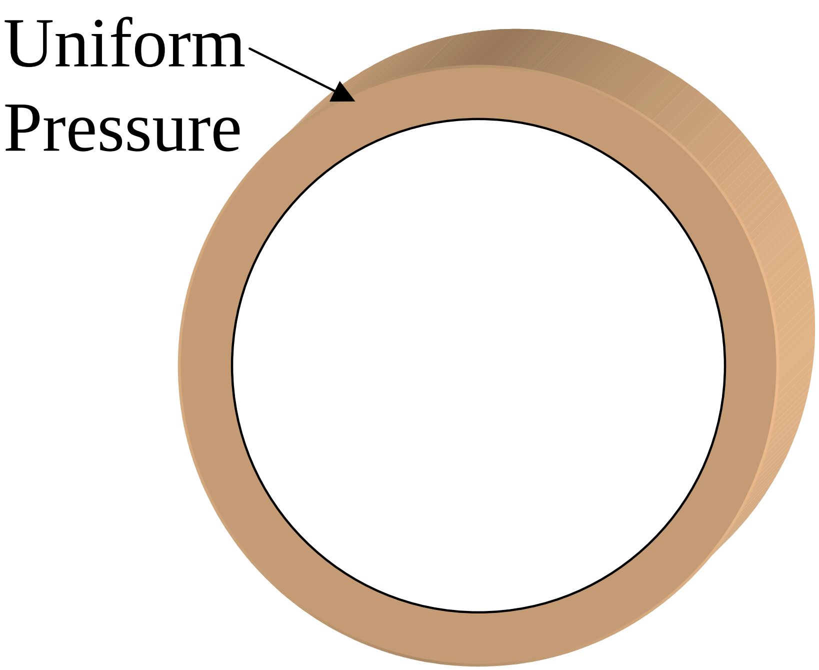
Buckling & Load Stiffness of A Ring



BEAM188

Buckling load

	BEAM188	BEAM44
1	7.5061	10.002
2	37.607	39.998
3	88.045	89.959
4	159.23	159.84

Critical Load
Target = 7.500

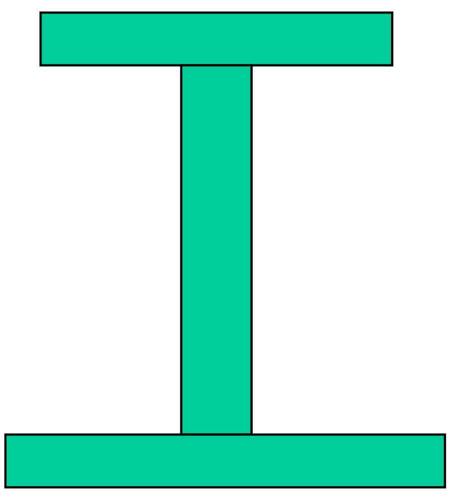
* SURF153 can be overlaid on BEAM44 to get correct results

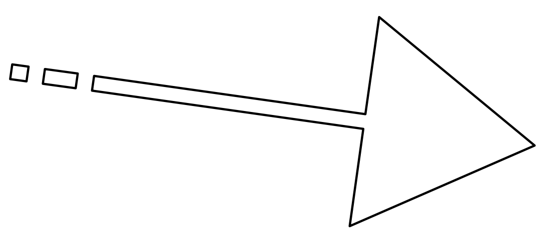
188/189 only!

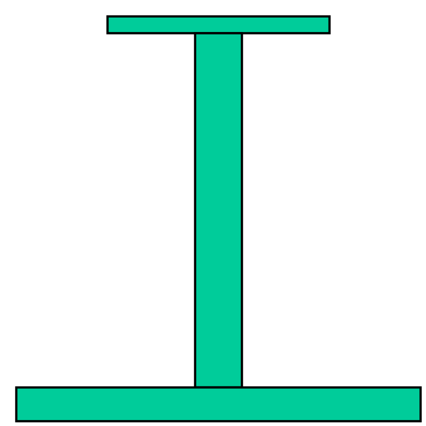
Tapered sections*

Geometrically Exact Tapering:
Cross section properties are evaluated at points of integration using linear interpolation of section dimensions spatially.

- More accurate
- Allows for optimizing web & flanges
- Is applicable to all Standard/User Mesh sections!







* Scheduled for release in 8.0 (beta in 7.0)

188/189 only!

BEAM188/189 - Others

- Curved beams may be modeled with BEAM189 without facet approximation
- CADOE variational (what-if) analysis is supported with 180 series beam elements
- Visualization in 3D of stresses, strains, mode shapes etc.

188/189 only!

Material nonlinearities in beams

Type of Element	Interpolation	Formulation				Elasticity		Plasticity								Viscoplasticity		Viscoelasticity			Other Fea	
		B-Bar	URI/Standard	Enhanced	Mixed U-P	Isotropic, Orthotropic (MP)	ANEL	BISO	MISO	NLISO	BKIN	KINH/MKIN	CHAB	CAST/UNIAXIAL	HILL	RATE (PEIRCE, PERZYNA)	CREEP (Implicit)	Viscoelasticity (hypoelasticity)	Viscoelasticity (hyperelasticity)	User-Defined	Element Birth and Death	Initial Stress
188	Linear		•			•		•	•	•	•	•	•	•		•	•	•		•	•	•
189	Quadratic		•			•		•	•	•	•	•	•	•		•	•	•		•	•	•

BEAM23 & BEAM24 provide plasticity support

Beams: Linear, Small & Large Strain!

- Core legacy elements use “linear” strain measure (even in nonlinear analysis)
- BEAM 188/189 use natural strain (logarithmic)
- Usually– small strain implies an approximation to “logarithmic” (such as Green-Lagrange)

Strain reported in a single element stretched by 20%:

Target = 0.18232, BEAM189 = 0.18232, BEAM44=0.20

SHELL181

ANSYS Element Library	Type of Element	Interpolation	Formulation				Elasticity		Plasticity								Viscoplasticity		Hyperelasticity				Viscoelasticity	
			B-Bar	URI/Standard	Enhanced Strain	Mixed U-P	Isotropic, Orthotropic (MP)	ANEL	BISO	MISO	NLISO	BKIN	KINH/MKIN	CHAB	CAST/UNIAXIAL	HILL	RATE (PEIRCE, PERZYNA)	CREEP (Implicit)	Mooney-Rivlin	Polynomial Form	Ogden	Arruda-Boyce	Viscoelasticity (hypoelasticity)	Viscoelasticity (hyperelasticity)
SHELL181	Shell	Bilinear		•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

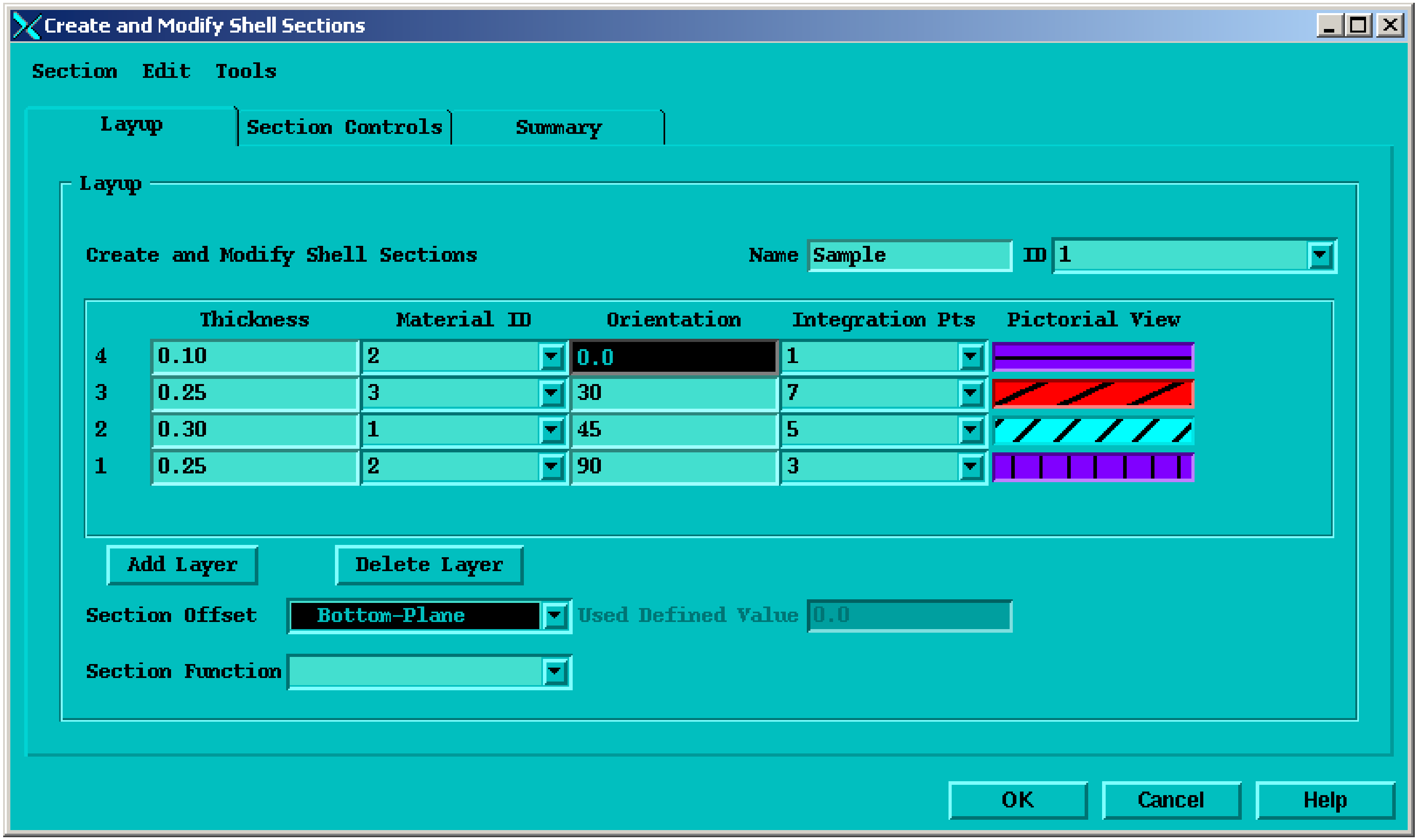
- HILL (anisotropic Hill potential) can be used with any plasticity model (including CREEP, RATE).
- CHAB (Chaboche nonlinear kinematic hardening) can be combined with any isotropic hardening.
- RATE is combined with any isotropic hardening law
- All 18x elements support USERMAT user-defined material as well as USERCREEP user-defined implicit creep law.
- SHELL181 supports composite definition.

SHELL181 features

	Core Legacy 4-node Shell elements	SHELL 181
Layered Composites	×	✓
Offset (reference surface)	×	✓
Function builder support for thickness	×	✓
Choice of Incompatible mode vs. Uniform Reduced Integration	×	✓

181 only!

Friendly interface for sections



181only!

Section Offset

- SECOFFSET, Location, OFFSET1..
  - Location is one of TOP, BOT, MID, USER
  - OFFSET is valid only when POSITION=USER
- SHELL181 will include rotary inertia effects
  - Other shell elements in ANSYS ignore rotary inertia effects in all circumstances.

181 only!

Transverse Shear Stiffness

- In the beginning of each load step, ANSYS will evaluate
  - Interlaminar shear stress distribution coefficients
  - Consistent energy equivalent transverse shear correction factors (not available in any other ANSYS shell element)
- Abundant choice of material models (including hyperelasticity)

Error* in Frequencies of a sandwich beam

Element	SHELL 91 (Regular)	SHELL 91 (Sandwich)	SHELL 181
1	2.87%	-4.39%	0.97%
2	-0.78%	-0.42%	0.60%
3	19.22%	-20.28%	4.31%
4	60.41%	-42.82%	7.40%
5	39.66%	-34.30%	7.74%
6	57.92%	-42.51%	8.12%
7	36.30%	-34.50%	10.40%
8	23.88%	-27.28%	9.49%
9	44.18%	-35.45%	5.74%
10	64.43%	-44.48%	7.63%

*Comparison with SOLID45 results

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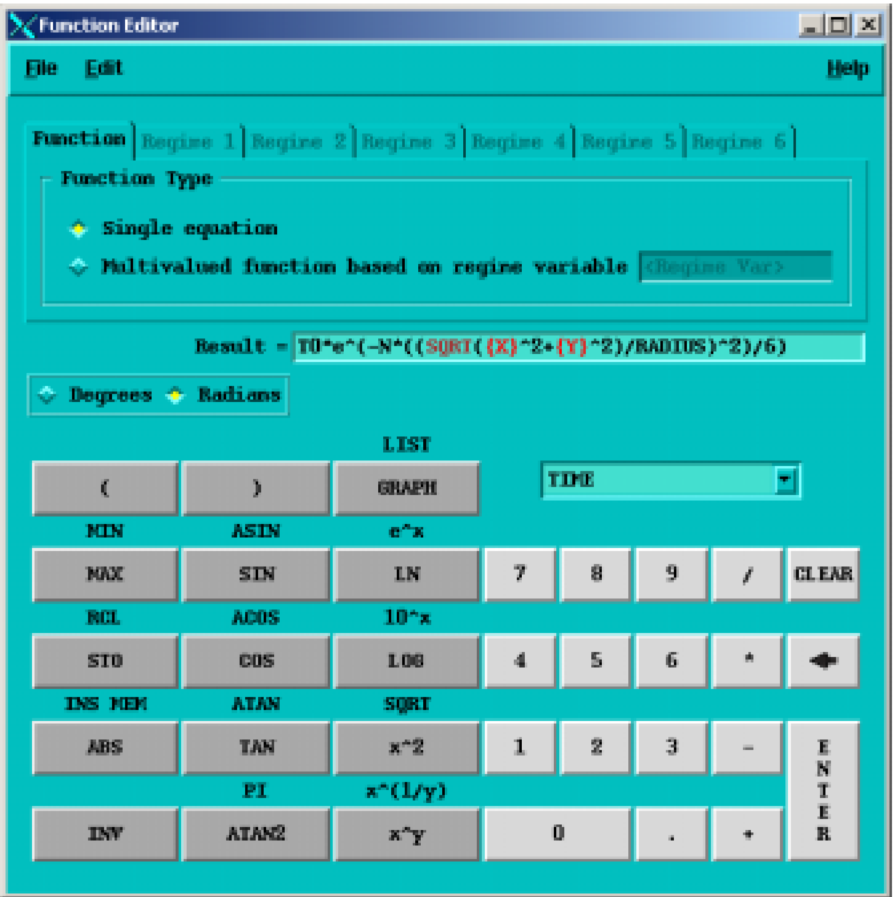
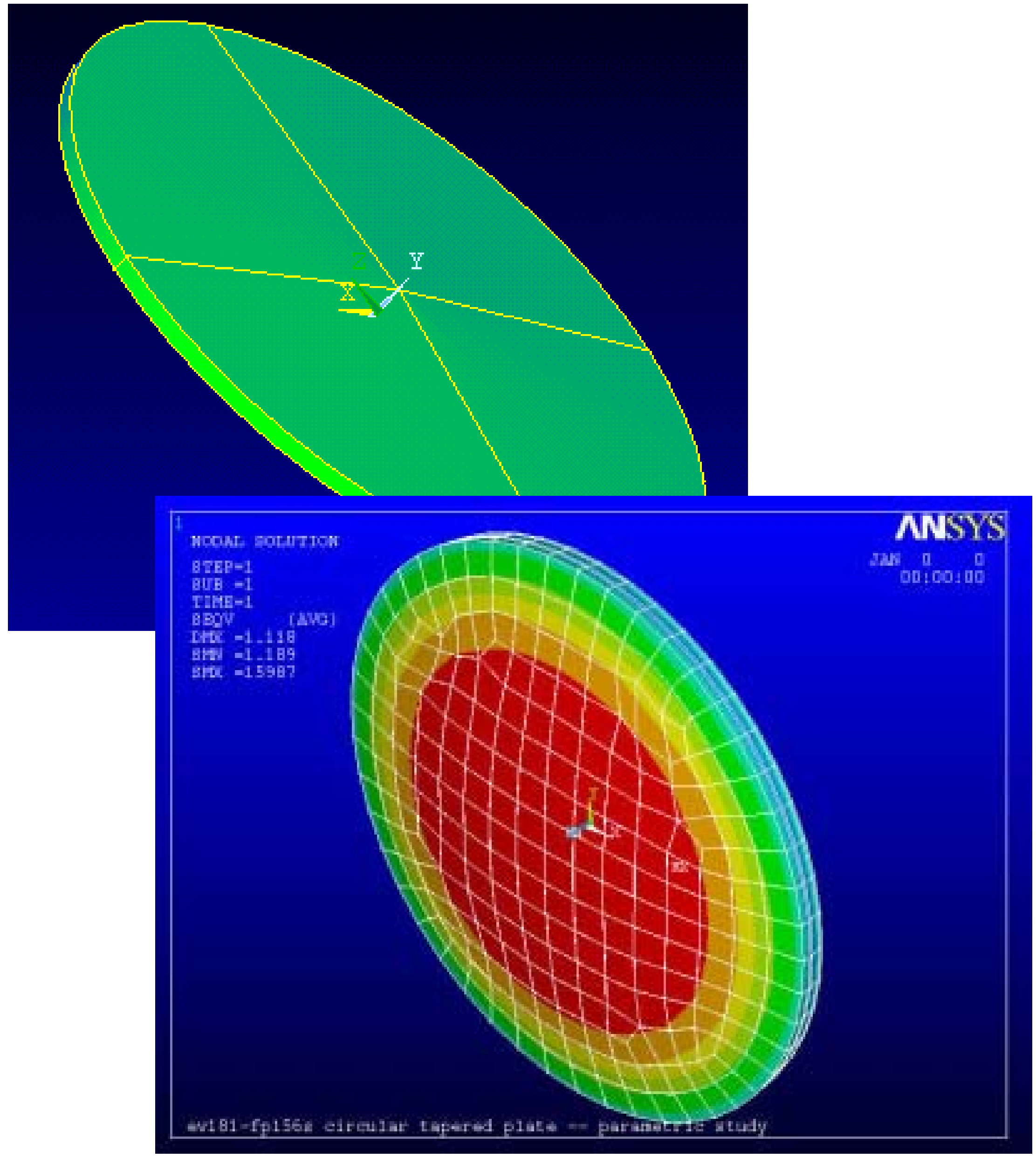
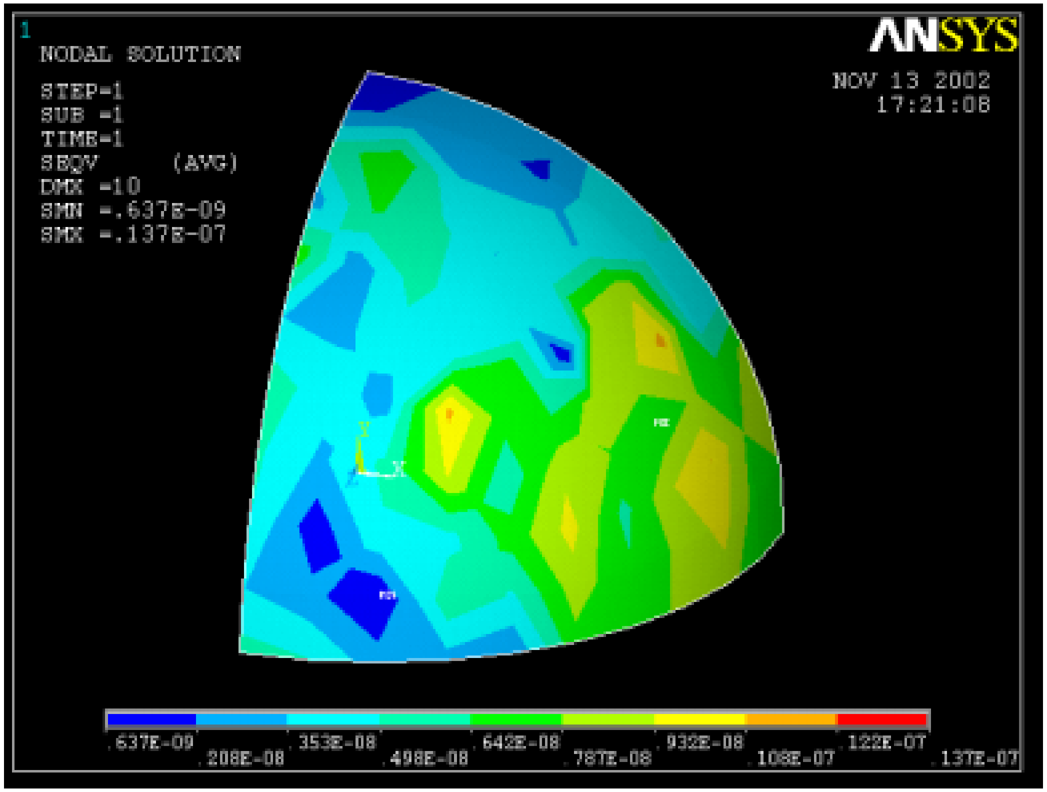
Tapered circular plate using Function Builder





Free thermal expansion



Element	Order of stress
Target	0.0
SHELL 63	10e-6
SHELL 143	1417
SHELL 181	10E-7
SHELL 43	2.742

SHELL181 - advantages

- Wide variety of elasto-plastic, viscoelastic, viscoplastic, and hyperelastic material models
- Formulation is equivalent to a “Field consistent” algorithm*
- Robust nonlinear convergence behavior
- CADOE Variational analysis support
- UserMat is supported

*

Conclusions

- Be it a linear or nonlinear analysis, 180 series is a good choice
- They provide
  - More functionality
  - Better accuracy (by strong emphasis on consistency)
  - State of the art formulations
  - More friendly interfaces and internal architecture
  - Higher customizability (e.g. UserMat and cross section building for beams)
  - Higher robustness