

2009 ESSS South American ANSYS Users Conference

Costão do Santinho Resort - Florianópolis, SC - Brasil
10 a 13 de Novembro de 2009

THE STRUCTURAL DESIGN OF NUCLEAR COMPONENTS IPEN DESIGN BY ANALYSIS EXPERIENCE



Miguel Mattar Neto (mmattar@ipen.br)

IPEN-CNEN/SP

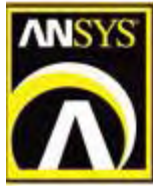
Nuclear Engineering Center

Structural Mechanics Division



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Presentation Topics

IPEN Overview

Structural Mechanics Division Main Activities

Design by Analysis

Stress Categorization and Stress Linearization

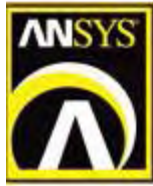
Examples

Conclusions



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IPEN Overview

IPEN – CNEN/SP is the Nuclear and Energy Research Institute (Instituto de Pesquisas Energéticas e Nucleares)

IPEN is an autarchy of the estate of São Paulo, managed by the Brazilian Federal Government through CNEN, the Brazilian Nuclear Energy Commission, and associated to the University of São Paulo.

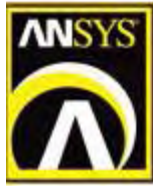
IPEN is organized in 12 centers and CEN, the Nuclear Engineering Center, is one of them.

The CEN Structural Mechanics Division has worked since 1980 in the nuclear reactors components design.



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Structural Mechanics Division Main Activities

1980 – 1995 – Structural design of nuclear components for the Brazilian Navy Submarine Nuclear Propulsion Program

1995 – present – Structural design of nuclear components for Angra 1 and Angra 2 Nuclear Power Plants

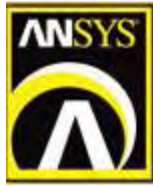
1995 – present – Structural design of nuclear components for the nuclear research reactor IEA-R1

1995 – present – Structural design of mechanical components for the industrial sector



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Design by Analysis

Until the early 1960s structural design rules were mainly based on accumulated experience and relatively simple mechanics.

Two stimuli led to the change on this approach:

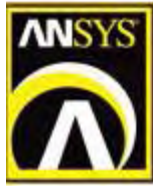
- The development of nuclear power in which safety requirements – in particular protection against radiation hazards - required more stringent structural analysis and evaluation methods than had been practised before.
- The desire to take advantage of contemporary advance in the understanding of structural behavior so as to eliminate potential weaknesses in the existing methods whilst at the same time reduce over-conservatism in conventional design.

Changes in design philosophy might permit use of higher allowable stresses without reduction in safety.



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Design by Analysis

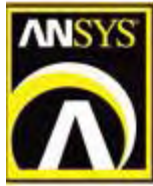
The change in design philosophy was to base the structural design on a more detailed evaluation of the actual stresses making use of the plasticity theory, fracture mechanics and fatigue design techniques to establish appropriate allowable stresses.

This approach reduces the level of uncertainty in the design thus allowing safety margins - essentially an amalgam of true conservatism and lack of knowledge – to be estimated with greater confidence and adjusted accordingly.



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Background to Design by Analysis

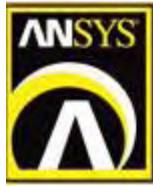
The design by analysis procedure is intended to guard against possible failure modes by performing a detailed stress analysis of the structure. The failure modes usually considered for mechanical components are:

- Excessive elastic deformation including elastic instability.
- Excessive plastic deformation.
- Brittle fracture.
- Stress rupture/creep deformation (inelastic).
- Plastic instability - incremental collapse.
- High strain - low cycle fatigue.
- Stress corrosion.
- Corrosion fatigue.



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Background to Design by Analysis

Three failure modes to be considered:

- Excessive plastic deformation.
- Plastic instability - incremental collapse.
- High strain - low cycle fatigue.

These failure modes are precluded by failure criteria based on **limit load theory**, **shakedown theory** and **fatigue theory**, respectively.

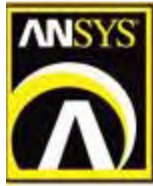
The elastic stresses calculated in the analysis are related to these specific failure criteria by decomposing the elastic stress field into three classes of stress with different degrees of significance and different allowable values:

- **Primary stress** is an equilibrium stress field associated with gross plastic deformation under static loading.
- **Secondary stress** arises from compatibility requirements and (when taken with primary stress) is associated with ratcheting under cyclic loading.
- **Peak stress** highly localized (occurring at local structural discontinuities) and is associated with fatigue failure under cyclic load.



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Design by Analysis Stress Categorization

There are definitions of stress categories and example classifications for mechanical components configurations under a variety of loading conditions.

The designer is required to categorize the calculated stress into primary, secondary and peak constituents and apply specified allowable stress limits.

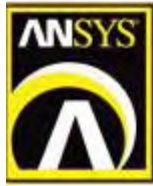
The magnitude of the allowable values assigned to the various stress categories reflects the nature of their associated failure mechanisms, therefore it is essential that the categorization procedure is performed correctly.

Stress categorization is probably the most difficult aspect of the design by analysis procedure and paradoxically the problem has become more difficult as stress analysis techniques have improved.



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Design by Analysis Stress Categorization

When the design by analysis procedure was introduced, the dominant analysis technique in pressure vessel design was thin shell discontinuity analysis.

This is reflected in the definitions of stress categories, which are based on the assumption of shell theory stress distributions: **membrane and bending stresses**. It is therefore difficult to reconcile the calculated stresses and the categories unless the design is based on shell analysis.

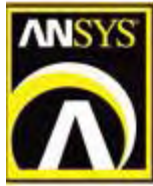
In current practice, the design by analysis is performed using the Finite Element Method (FEM). Various types of finite element models can be created using a variety of element types.

Many pressure vessels can be modeled using shell elements which are relatively easy to generate, are computationally efficient and give results in the form of membrane: and bending stresses.



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Design by Analysis Stress Categorization

However, shell models cannot easily incorporate construction details such as reinforcement, fillets, etc., nor can through-thickness effects be considered in detail.

To include these effects, solid elements - based on 2-D or 3-D solid mechanics - must be used. Solid finite element models may be create directly from solid models but have the real problem with categorizing the calculated stress, which is not in the membrane plus bending format.

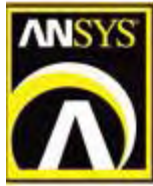
A great deal of effort has been expended trying to formulate procedures to aid the designer perform rigorous stress categorization for solid finite element models.

The most common method is to apply stress linearization procedures to specific regions of the model to calculate constant (membrane) and linear (bending) stress distributions giving the same net section forces and moments as the solid finite element stress distributions.



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Design by Analysis Stress Categorization

Another approach to avoid the idea of capturing an inelastic behavior through an elastic analysis by performing the stress categorization is to do inelastic analyses, directly.

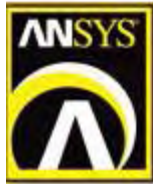
In the past, the inelastic approach was simply impracticable for most analysts but advance computer technology and non-linear finite element methods make inelastic analysis viable alternative to the elastic analysis approach for many designers.

It is therefore likely that inelastic analysis will become much more widely used in pressure vessel design by analysis.



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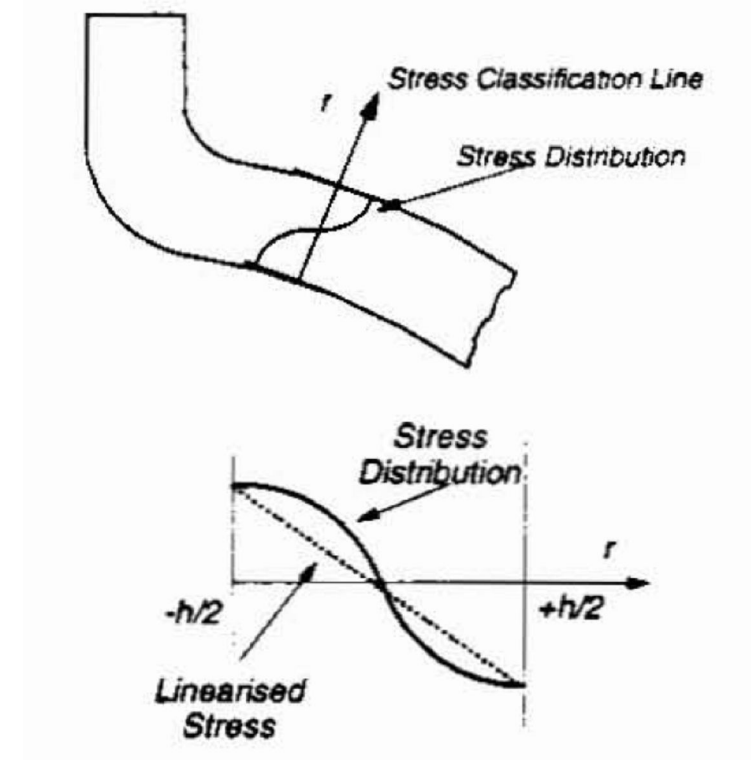
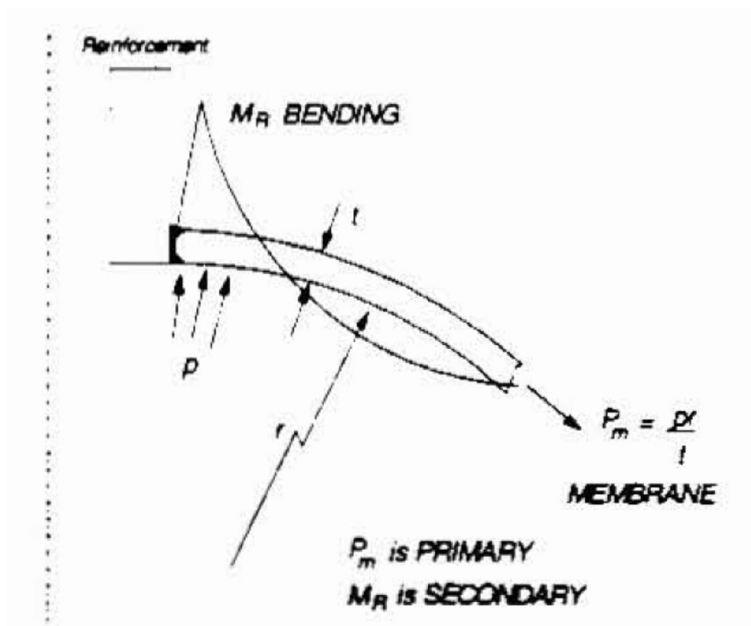




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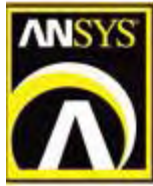
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Stress Linearization



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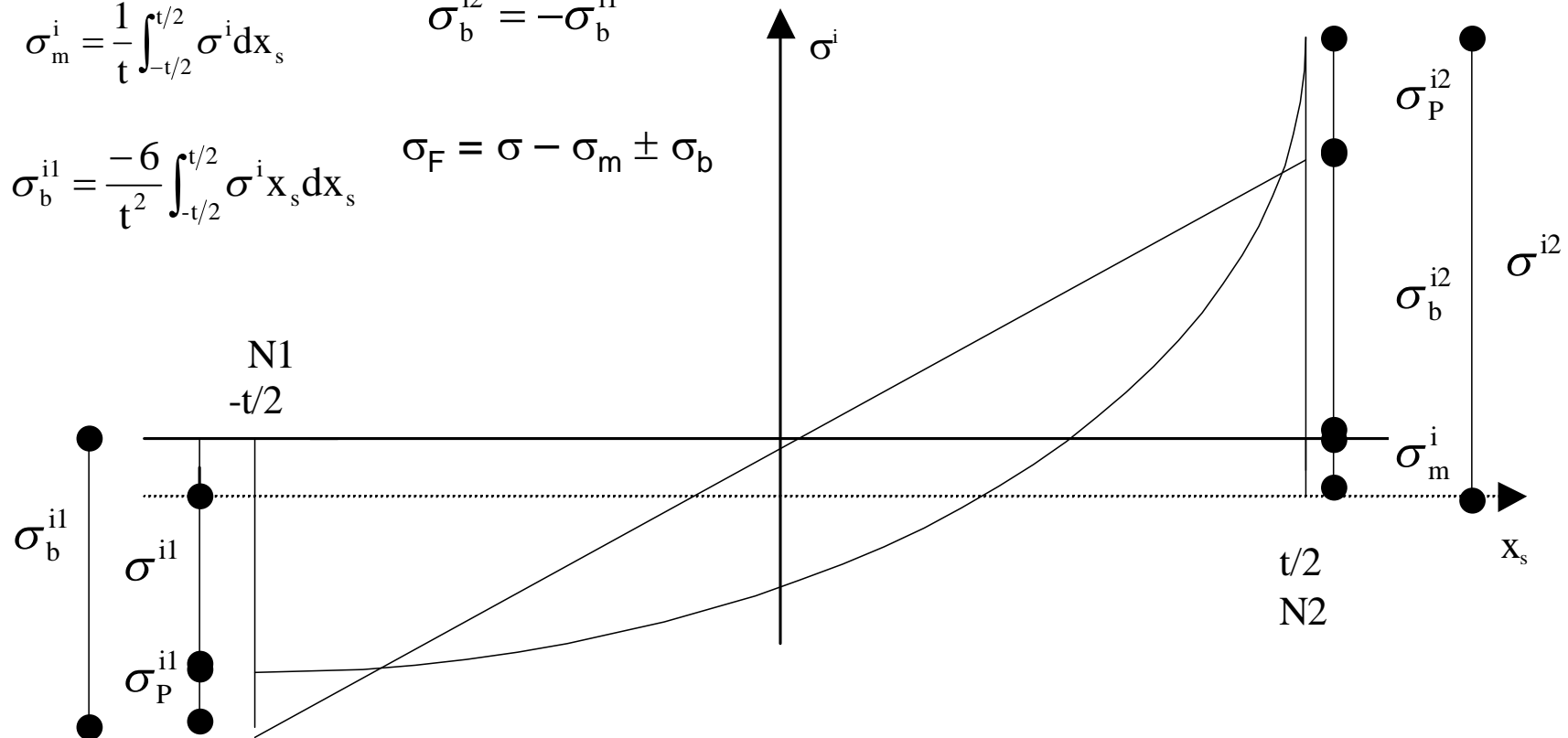
Stress Linearization

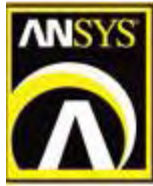
$$\sigma_m^i = \frac{1}{t} \int_{-t/2}^{t/2} \sigma^i dx_s$$

$$\sigma_b^{i2} = -\sigma_b^{i1}$$

$$\sigma_b^{i1} = \frac{-6}{t^2} \int_{-t/2}^{t/2} \sigma^i x_s dx_s$$

$$\sigma_F = \sigma - \sigma_m \pm \sigma_b$$

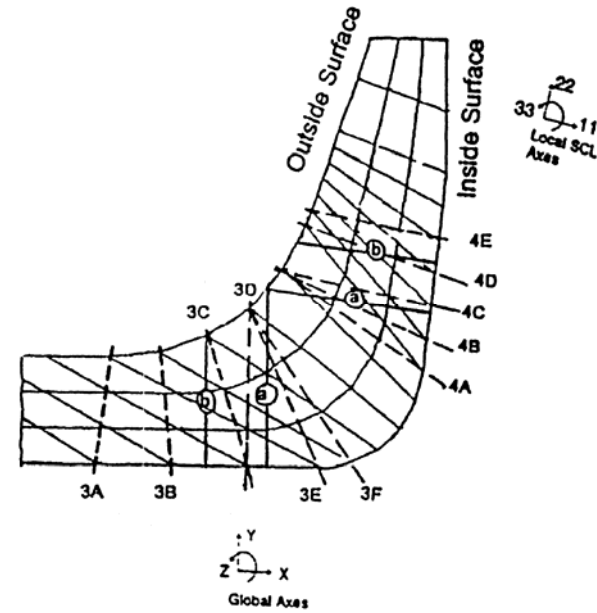
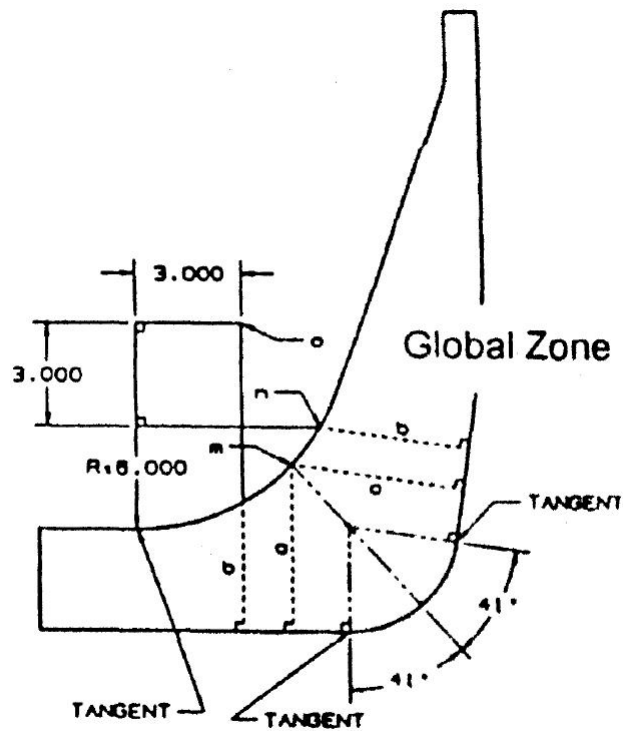




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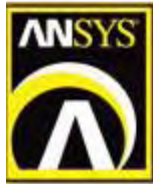
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Stress Linearization



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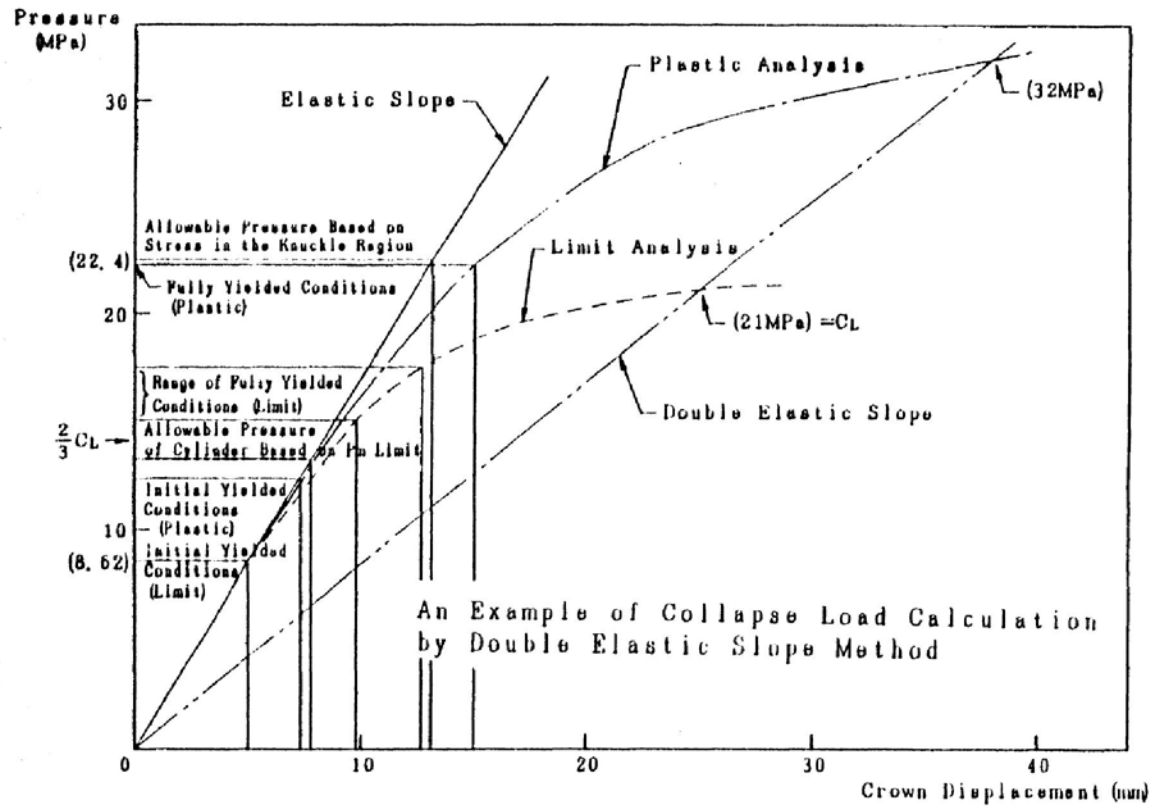


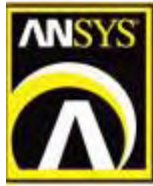


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Inelastic Analysis

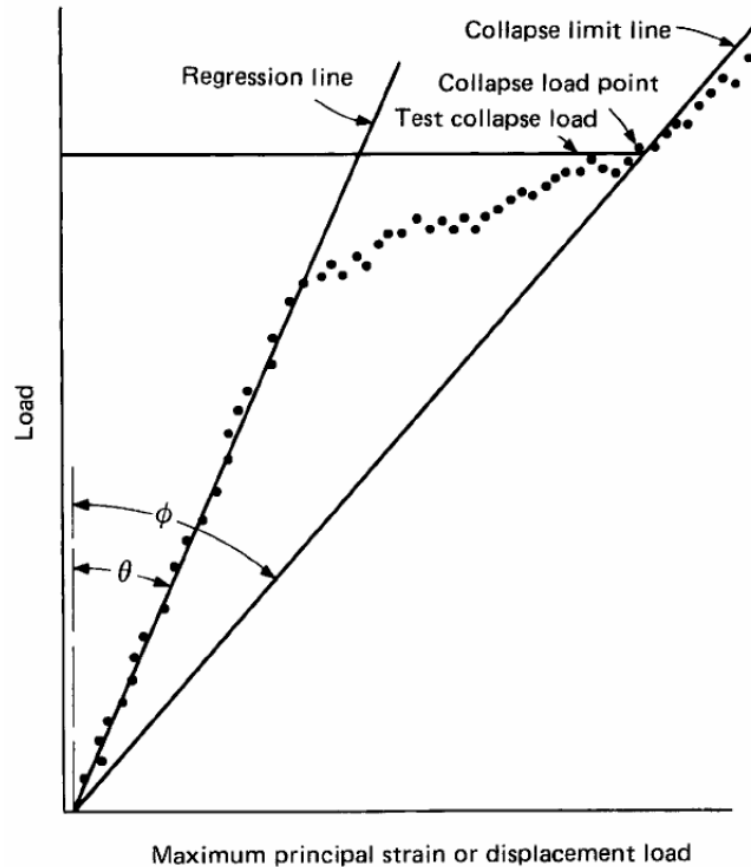




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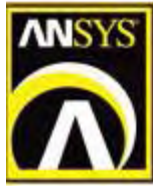
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Inelastic Analysis



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Design by Analysis Using ANSYS

1983 – Processing ANSYS with input card decks and remote card reader

1986 – Processing ANSYS in terminals connected to mainframe

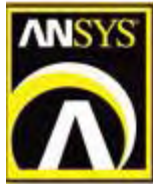
1990 – Processing ANSYS in terminals connected to workstation

1995 – present – Processing ANSYS in PCs



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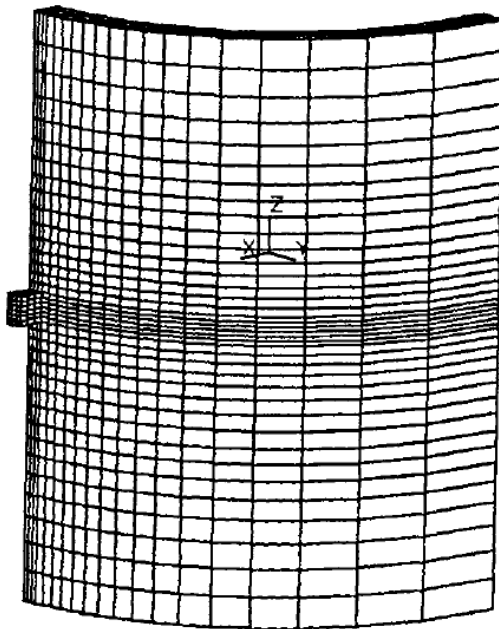
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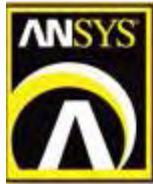
Design by Analysis Using ANSYS - Examples

Brazilian Navy Submarine Nuclear Propulsion Program

Lug-cylinder attachment



cylinder inner radius = 1000 mm
cylinder thickness = 100 mm
dimensions of the lugs = 100x100x100 mm



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Design by Analysis Using ANSYS - Examples

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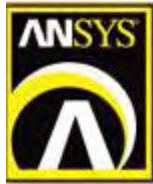
Lug-cylinder attachment

Collapse forces in the lugs (MN) from elastic-plastic FEA

Radial forces in the lugs	with internal pressure	2.72
	without internal pressure	2.65
Axial forces in the lugs	with internal pressure	1.58
	without internal pressure	1.53

Allowable load conditions from elastic-plastic FEA

Radial forces in the lugs	with internal pressure	$p = 10 \text{ MPa} +$ $F = 1.82 \text{ MN}$
	without internal pressure	$F = 1.77 \text{ MN}$
Axial forces in the lugs	with internal pressure	$p = 10 \text{ MPa} +$ $F = 1.05 \text{ MN}$
	without internal pressure	$F = 1.02 \text{ MN}$



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Brazilian Navy Submarine Nuclear Propulsion Program

Lug-cylinder attachment

Allowable load conditions from elastic FEA (P+Q)

		L1 - $0.1\sqrt{Rt}$	L2 - $0.5\sqrt{Rt}$	L3 - $1.0\sqrt{Rt}$
radial forces in the lugs	with pressure (10 MPa)	0.72	1.08	1.26
	without pressure	0.63	1.01	1.39

Allowable load conditions from elastic FEA ($P_L + P_b$)

		L1 - $0.1\sqrt{Rt}$	L2 - $0.5\sqrt{Rt}$	L3 - $1.0\sqrt{Rt}$
radial forces in the lugs	with pressure (10 MPa)	0.36	0.54	0.63
	without pressure	0.32	0.50	0.69



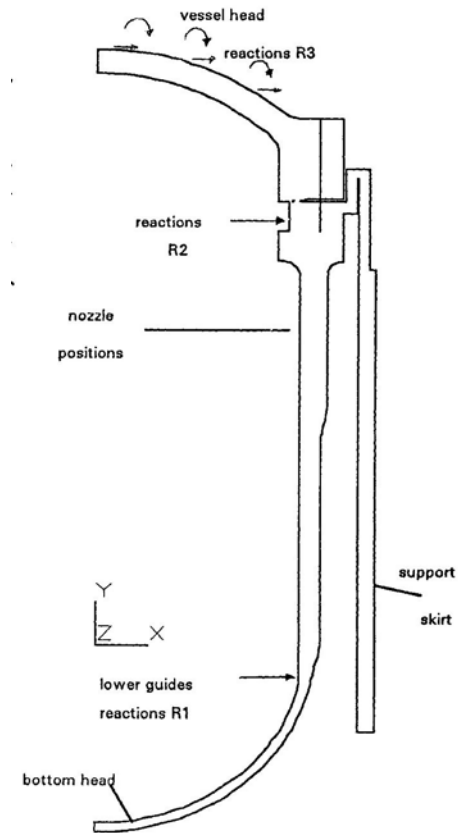
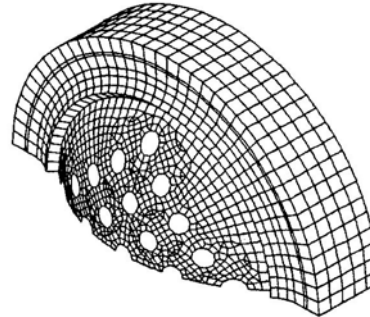
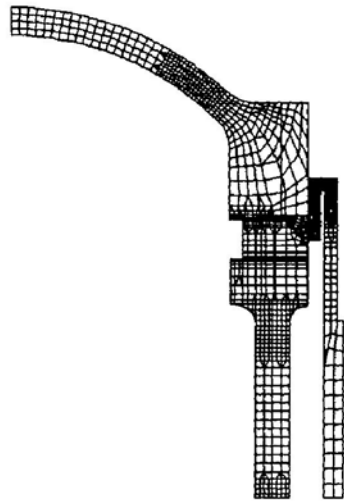
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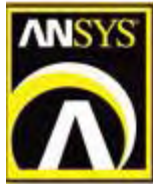
Brazilian Navy Submarine Nuclear Propulsion Program

Reactor Pressure Vessel



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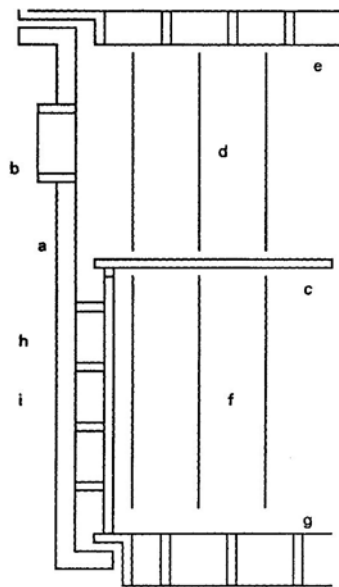
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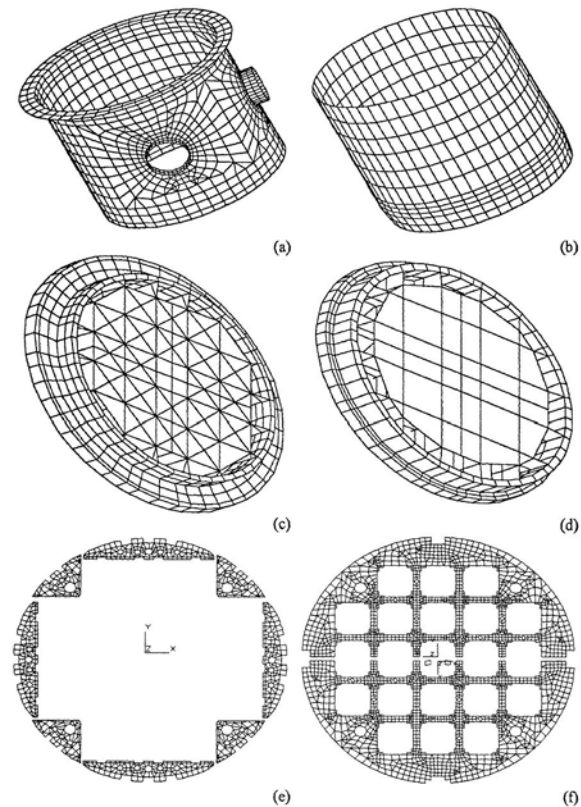
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Reactor Pressure Vessel Internals

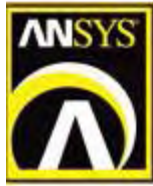


- a. Core Barrel
- b. Nozzle
- c. Intermediate Plate
- d. Control Rod Guide
- e. Upper Grid
- f. Fuel Element
- g. Lower grid
- h. Shrouds
- i. Support Plate of the Shrouds
- j. Gaps



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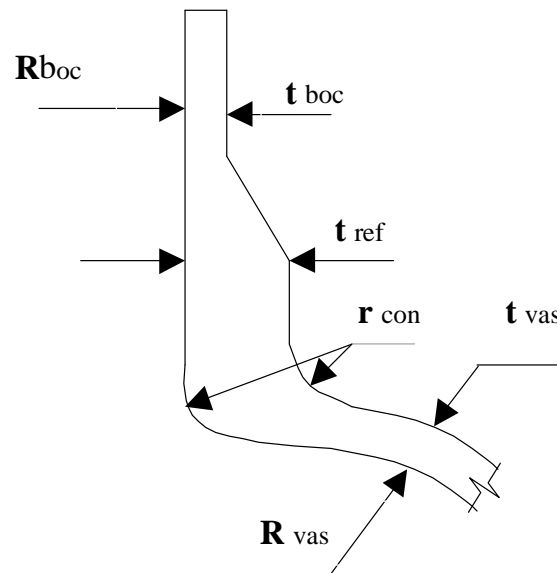
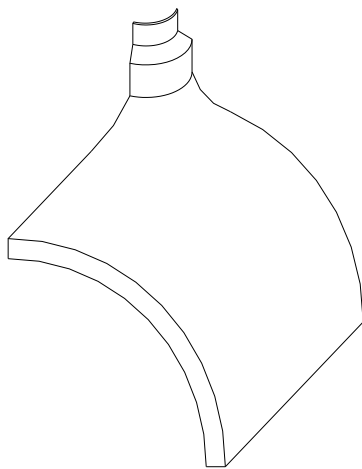
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Design by Analysis Using ANSYS - Examples

Brazilian Navy Submarine Nuclear Propulsion Program

Radial Cylindrical Nozzle in a Pressure Vessel



$$R_{boc} = 130 \text{ mm}$$

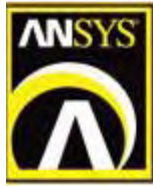
$$t_{boc} = 16 \text{ mm}$$

$$t_{ref} = 55 \text{ mm}$$

$$r_{con} = 50 \text{ mm}$$

$$R_{vas} = 1016 \text{ mm}$$

$$t_{vas} = 98 \text{ mm}$$



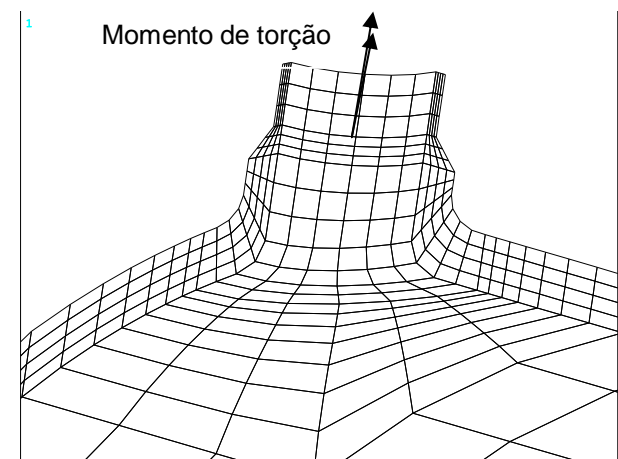
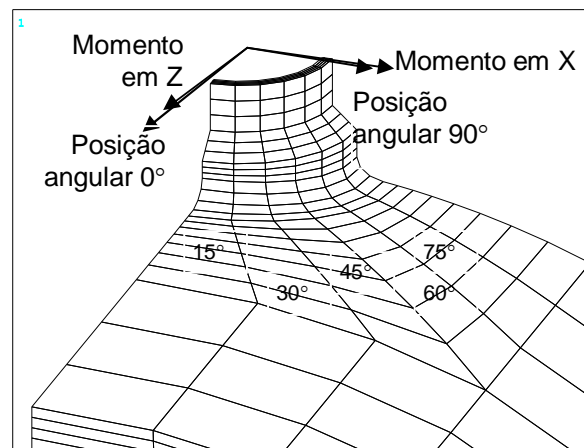
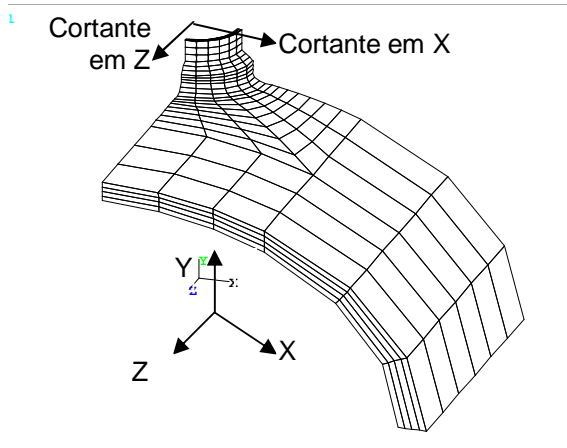
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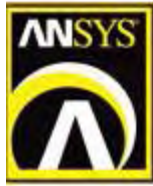
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Design by Analysis Using ANSYS - Examples

Brazilian Navy Submarine Nuclear Propulsion Program

Radial Cylindrical Nozzle in a Pressure Vessel





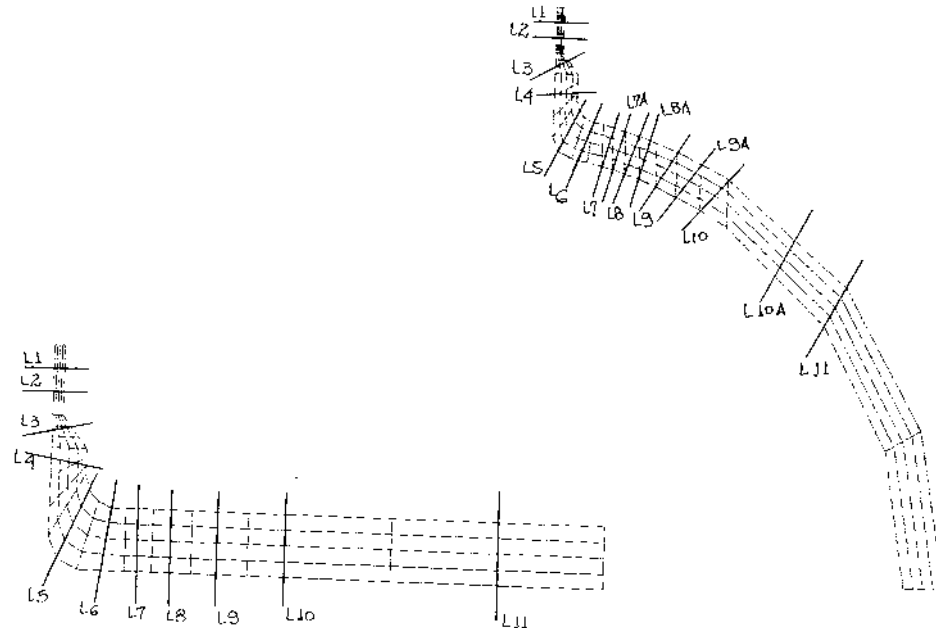
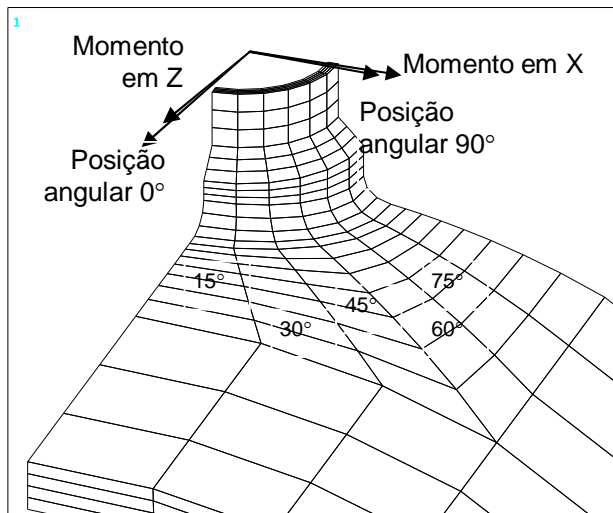
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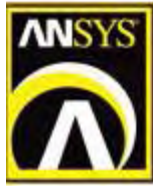
Brazilian Navy Submarine Nuclear Propulsion Program

Radial Cylindrical Nozzle in a Pressure Vessel



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Radial Cylindrical Nozzle in a Pressure Vessel

Internal pressure, only

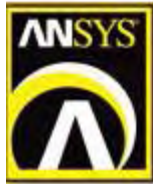
Elastic FEA – $p_{adm} = 15,53$ MPa

Limit load FEA – $p_{adm} = 15,83$ MPa



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Brazilian Navy Submarine Nuclear Propulsion Program

Radial Cylindrical Nozzle in a Pressure Vessel

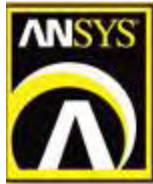
Nozzle loads, only

Load	Elastic – FEA	Limit Load - FEA
Shear force X (N)	5,39E5	6,09E5
Shear force Z (N)	5,39E5	6,22E5
Bending moment X (N mm)	1,43E8	1,64E8
Bending moment Z (N mm)	1,43E8	1,64E8
Torsion moment Y (N mm)	1,64E8	1,90E8



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Brazilian Navy Submarine Nuclear Propulsion Program

Radial Cylindrical Nozzle in a Pressure Vessel

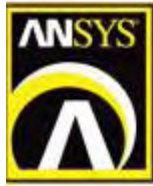
Nozzle loads + internal pressure (12,3 MPa)

Load	Elastic – FEA	Limit Load - FEA
Shear force X (N)	4,79E5	4,83E5
Shear force Z (N)	4,66E5	4,83E5
Bending moment X (N mm)	1,27E8	1,52E8
Bending moment Z (N mm)	1,23E8	1,55E8
Torsion moment Y (N mm)	1,42E8	(*)



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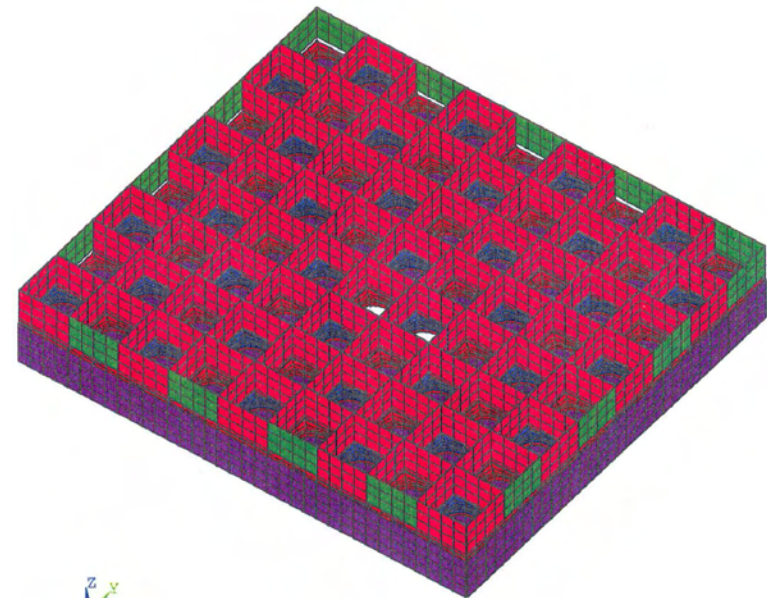
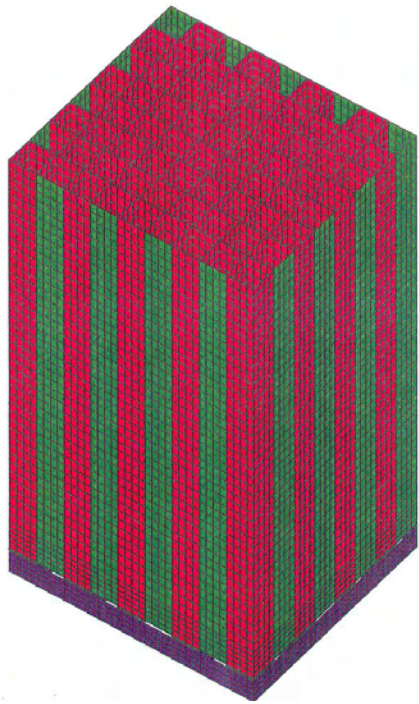
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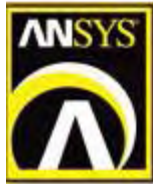
Angra 2 Nuclear Power Plant

Spent Fuel Compact Storage Racks



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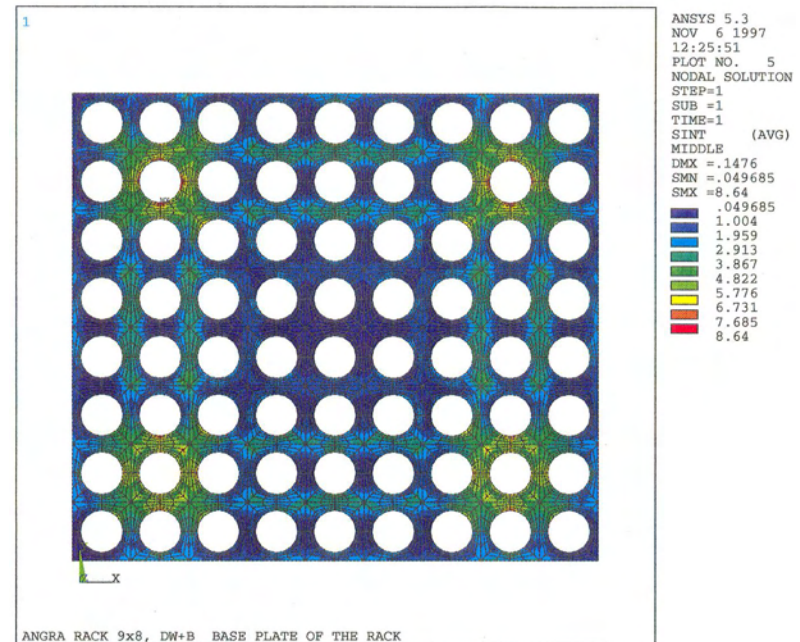
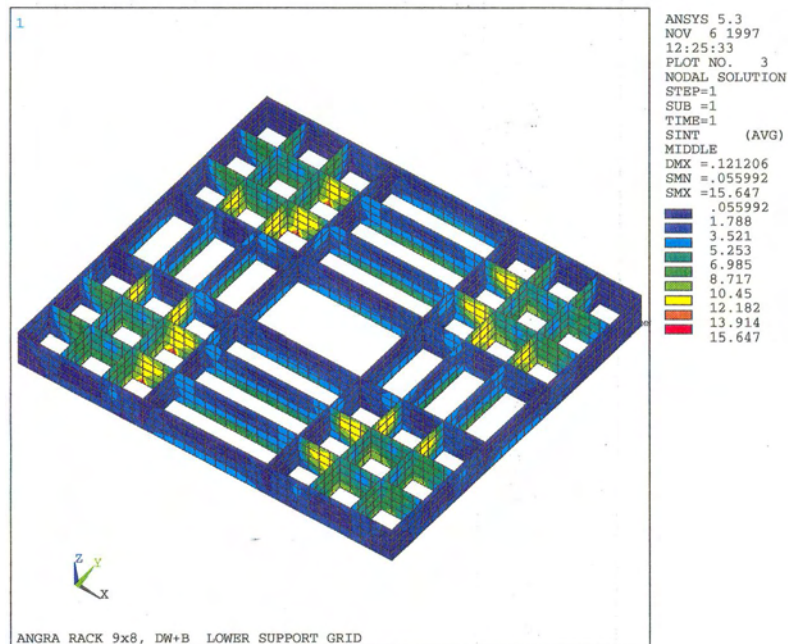
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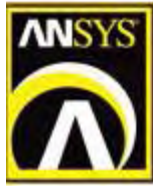
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Design by Analysis Using ANSYS - Examples

Angra 2 Nuclear Power Plant

Spent Fuel Compact Storage Racks





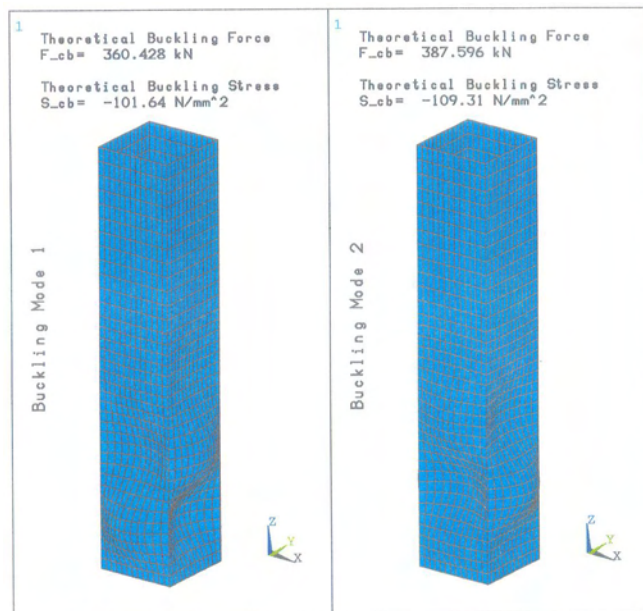
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Angra 2 Nuclear Power Plant

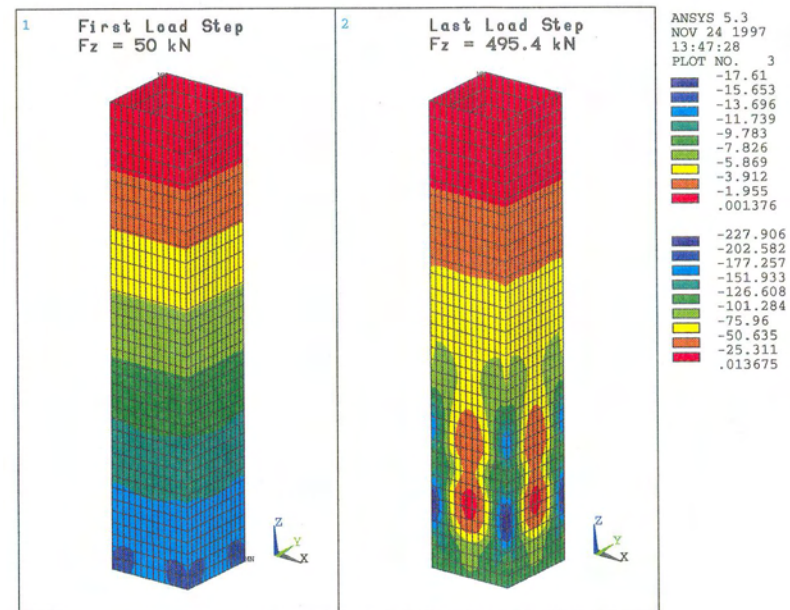
Spent Fuel Compact Storage Racks



Critical Buckling Loads $t=3 \text{ mm}$ ($P_u/P_o = 2.5$)

ANSYS 5.3
NOV 13 1997
14:49:45
PLOT NO. 8
DISPLACEMENT
STEP=1
SUB =1
FACT=3.604
RSYS=0
DMX =1
SEPC=21.58

DISPLACEMENT
STEP=1
SUB =2
FACT=3.876
RSYS=0
DMX =1
SEPC=21.65

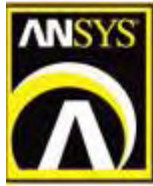


Channel $t = 3.0 \text{ mm}$ (Nonlinear Buckling Analysis, $S_y = 240$)



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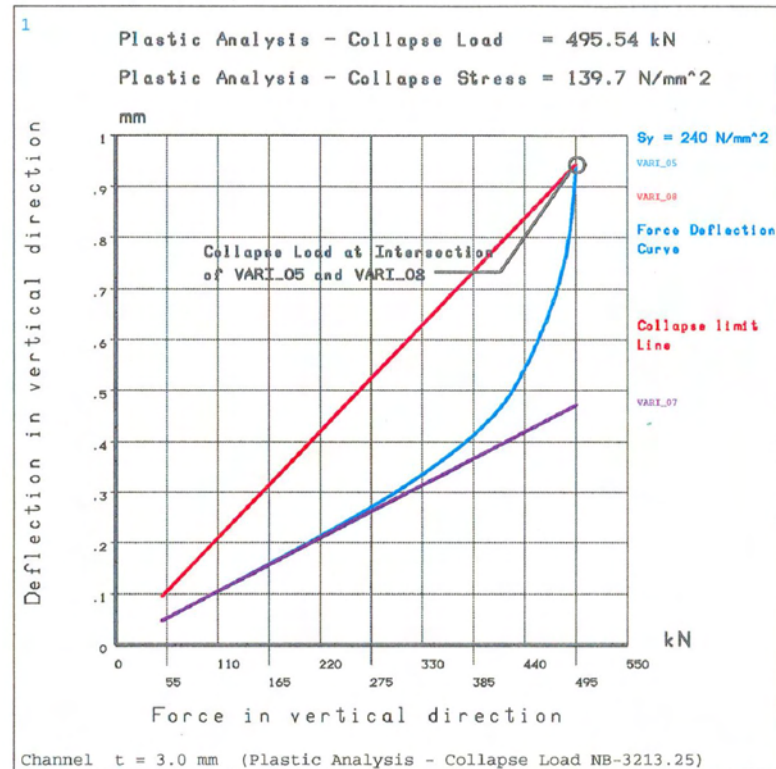
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Design by Analysis Using ANSYS - Examples

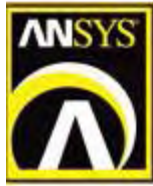
Angra 1 and Angra 2 Nuclear Power Plants

Spent Fuel Compact Storage Racks



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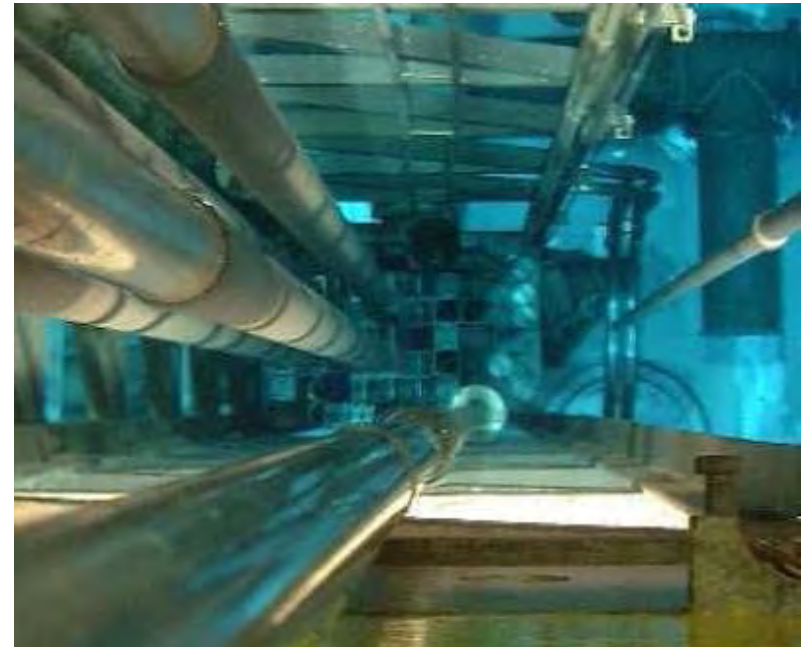
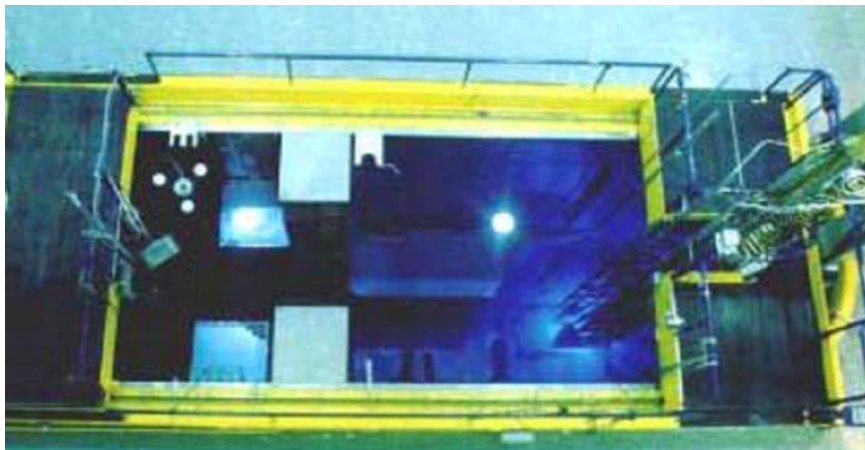
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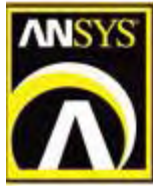
Nuclear Research Reactor IEA-R1

Core Support Plate



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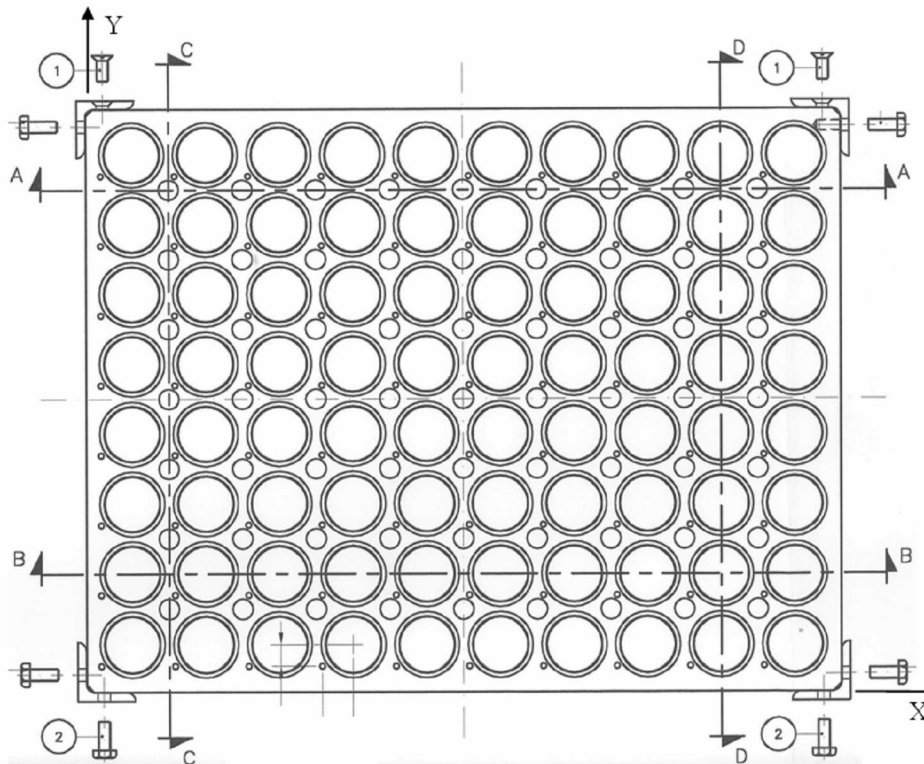


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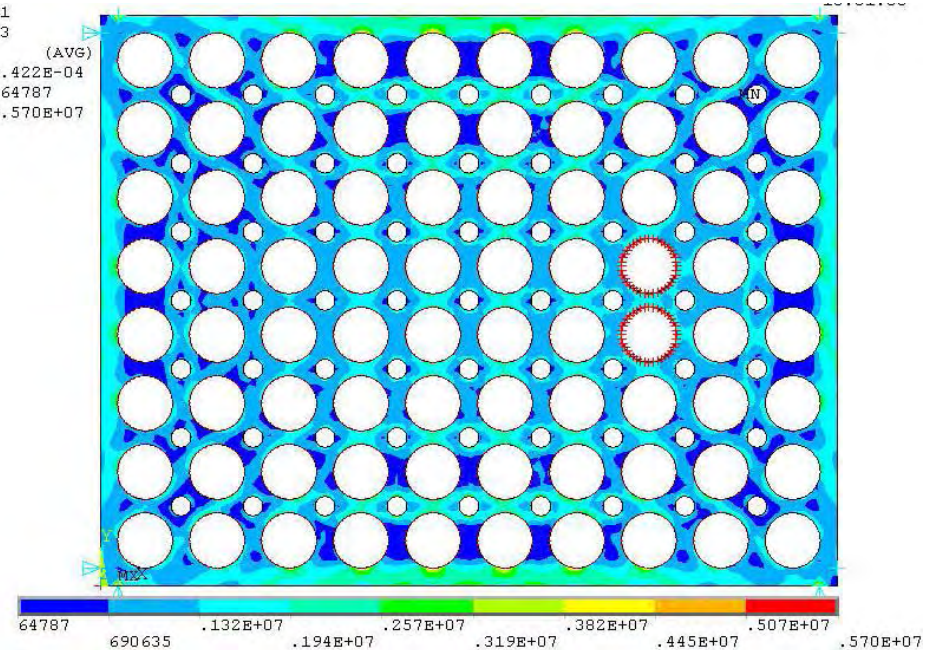
Design by Analysis Using ANSYS - Examples

Nuclear Research Reactor IEA-R1



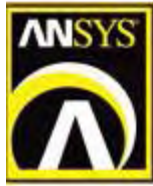
SUB = 1
TIME = 3
SINT (AVG)
DMX = .422E-04
SMN = 64787
SMX = .570E+07

D
F
ACEL



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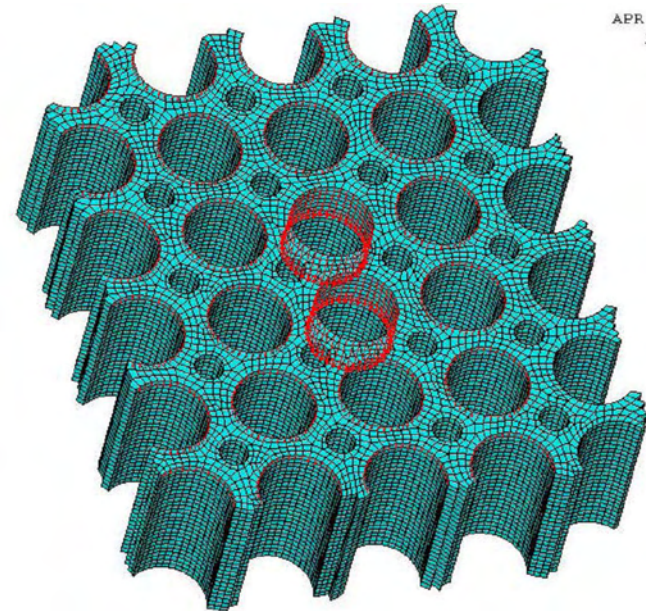
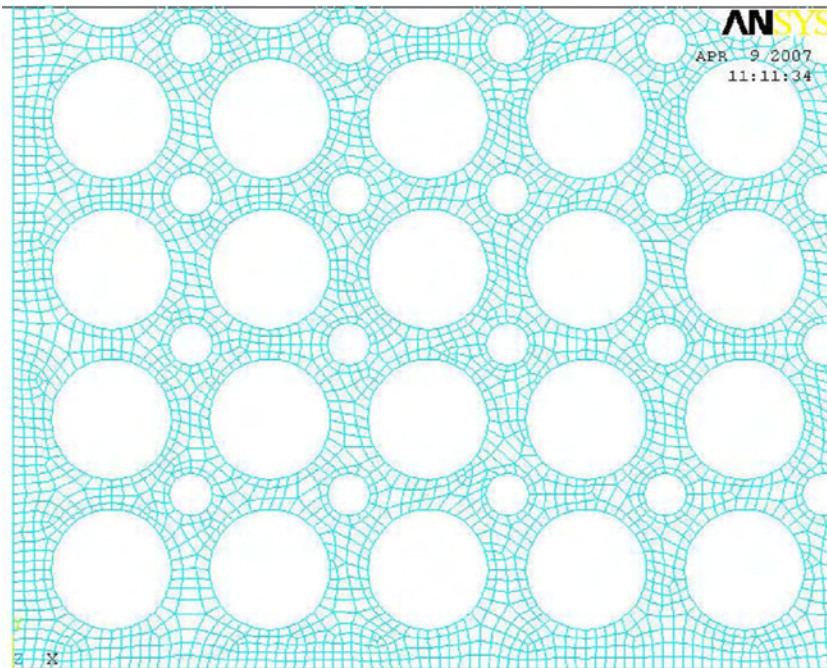
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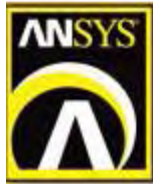
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Design by Analysis Using ANSYS - Examples

Nuclear Research Reactor IEA-R1

Core Support Plate





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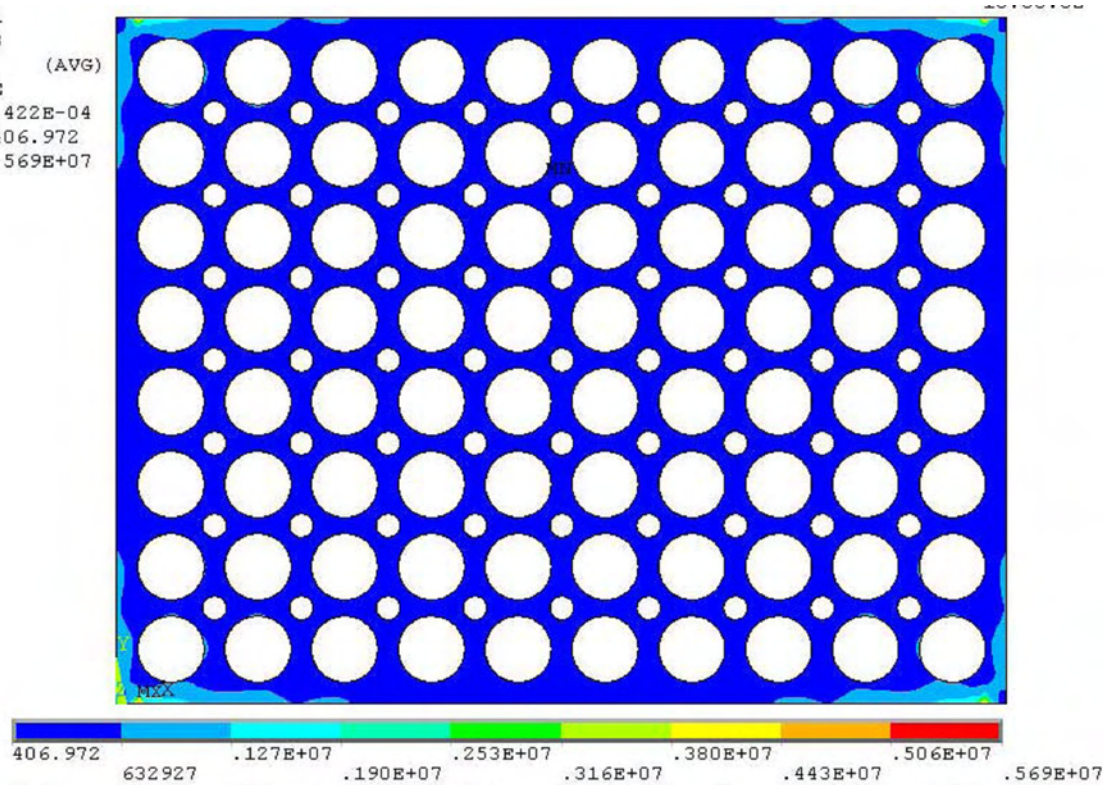
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Design by Analysis Using ANSYS - Examples

Nuclear Research Reactor IEA-R1

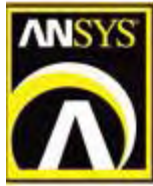
Core Support Plate

SUB =1
TIME=3
SINT (AVG)
MIDDLE
DMX =.422E-04
SMN =406.972
SMX =.569E+07



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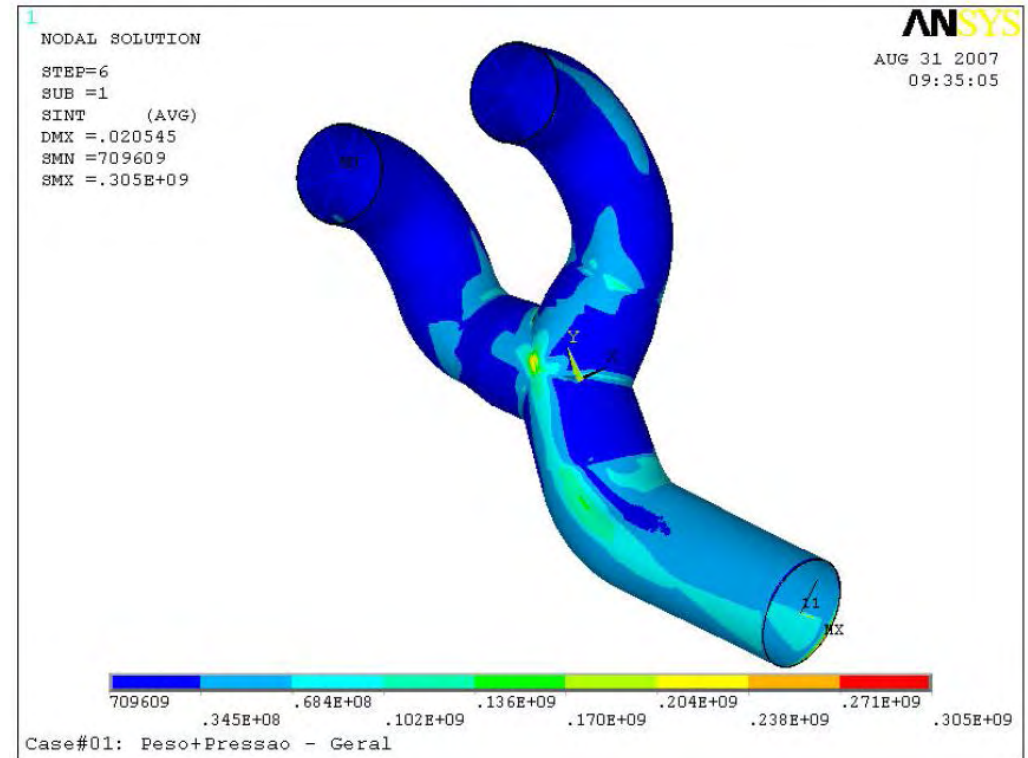
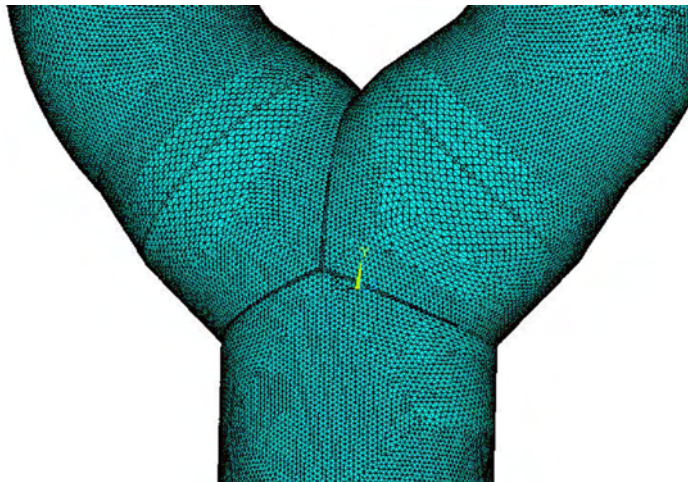


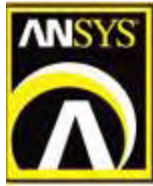
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Design by Analysis Using ANSYS - Examples

Y Pipe Fitting



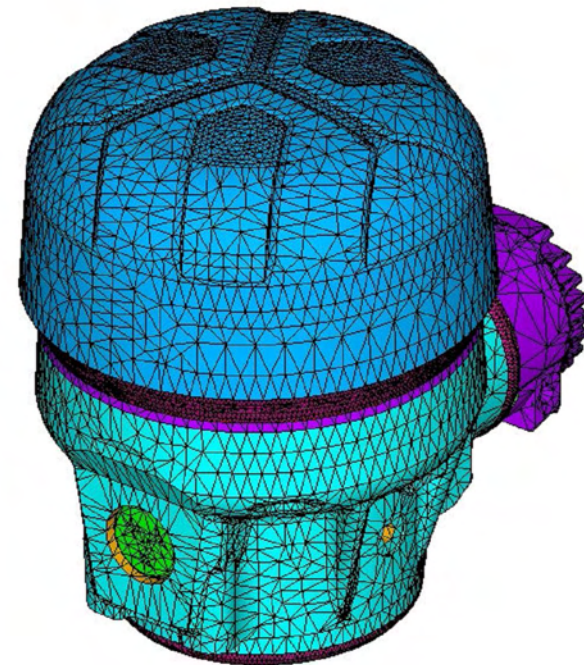


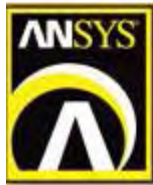
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Design by Analysis Using ANSYS - Examples

Compressor Housing (with EMBRACO)



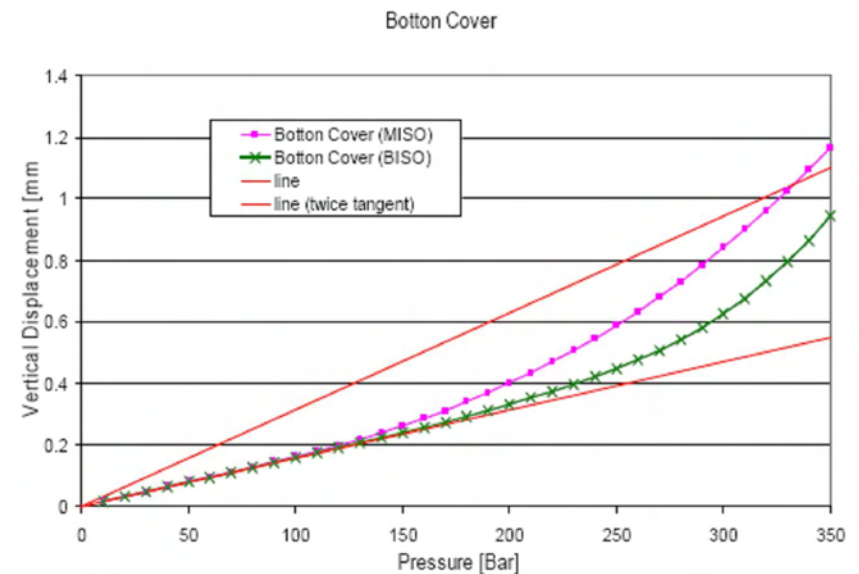
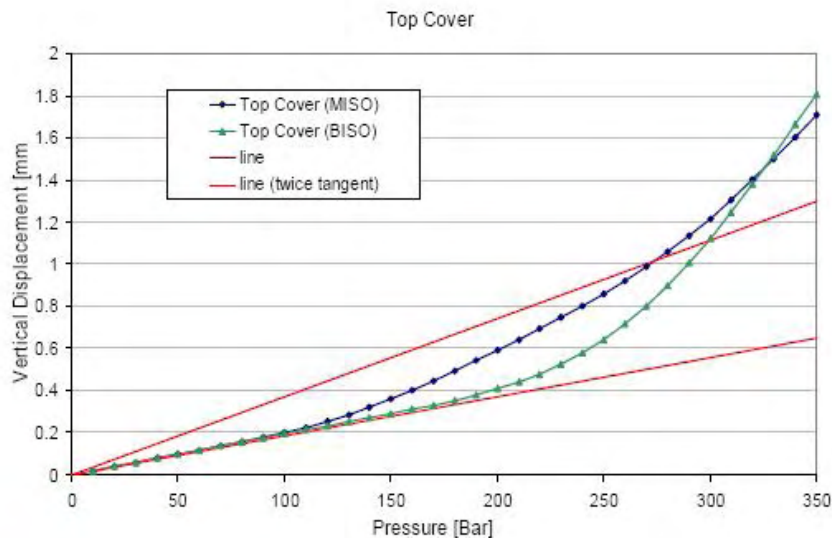


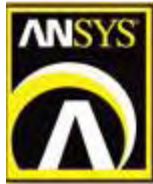
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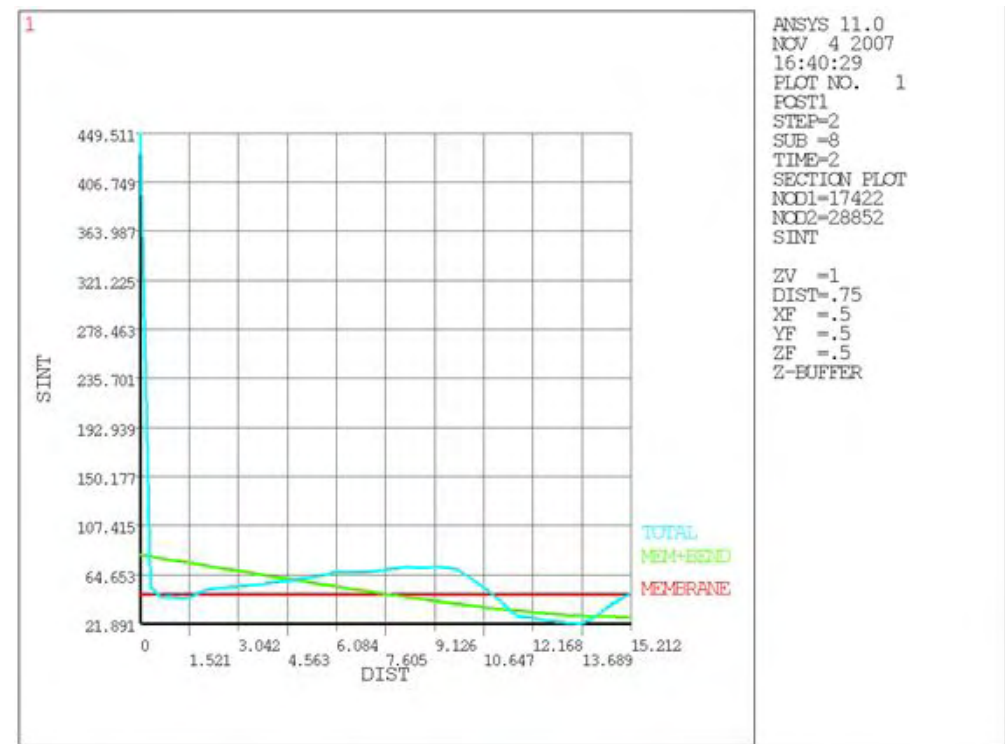
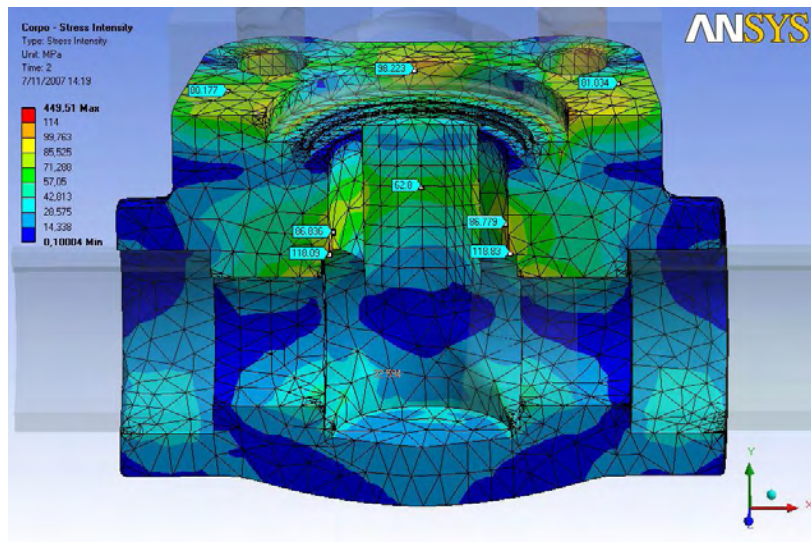


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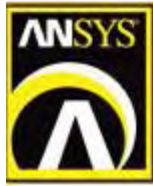
Design by Analysis Using ANSYS - Examples

Industrial Valves (with CONESTEEL)



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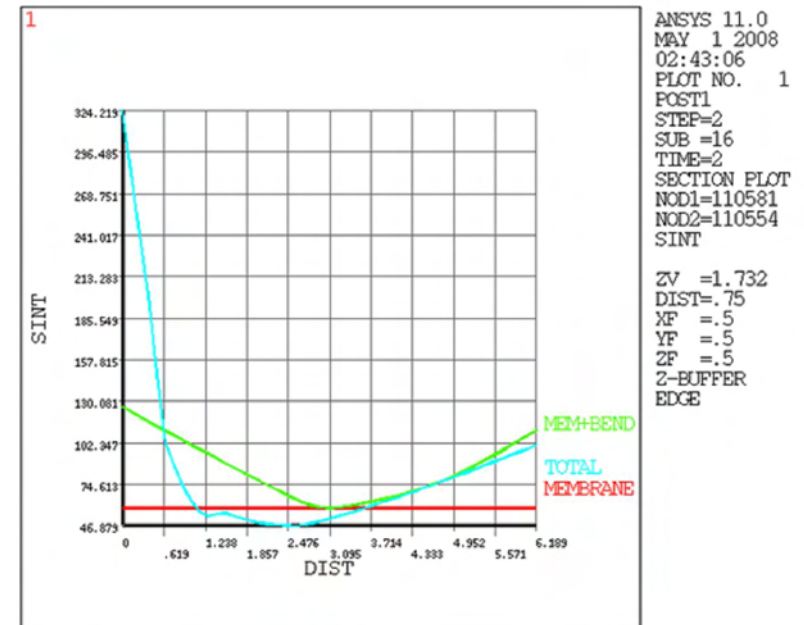
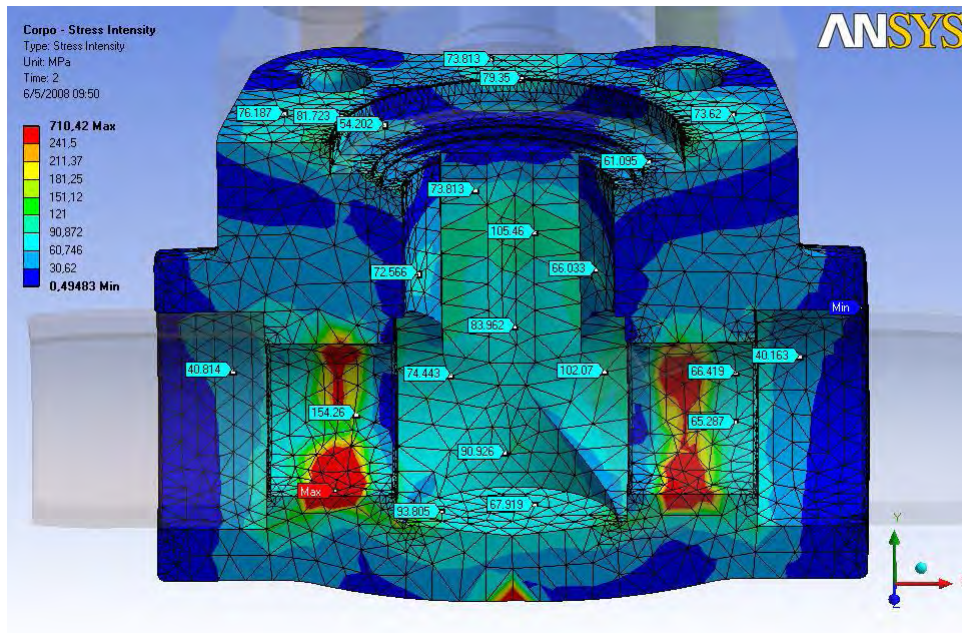


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Industrial Valves (with CONESTEEL)



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