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Finite Element Analysis

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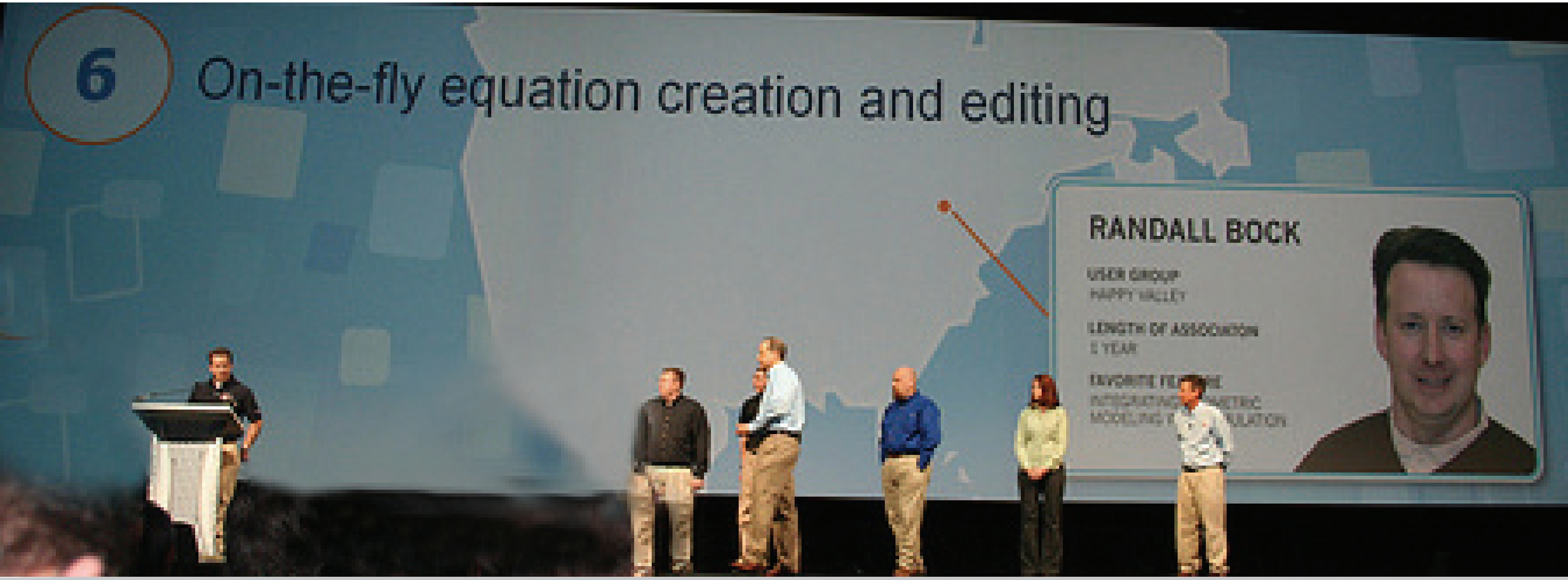
- Research Engineer
- Professor of Continuing Education
- Happy Valley SWUG, Leader
- CSWP



EDSGN 496A: SolidWorks Fundamentals

SolidWorks CERTIFIED PROFESSIONAL

SKETCH: The Design Environment

- Introduction, Objectives, and Goals
- User Interface
- Associative Design
- Design Intent & Constraints
- CommandManager: Sketch & Features
- Extruded Base
- Basic Strategy

real learning

Mission Statement

Students should be proficient in communicating and analyzing designs as 3-D models.

Certificate of Achievement

SolidWorks

85%

we **congratulate you** on your achievement

Randall Bock

has completed the requirements for:

Certified SolidWorks Associate

Jeff Ray | CEO, Dassault Systèmes SolidWorks Corporation

Certificate ID: **C-9RPRCJTJMY**

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www.hvswug.org

Pedagogy

- Instructive theory
- Trainee teachers learn their subject and also the pedagogy appropriate for teaching that subject.

Andragogy

- The art and science of teaching adults.

Here's the Plan

- **SolidWorks Simulation**
  - The Design Cycle
  - Finite Element Method
  - SolidWorks Simulation
  - Defining a Simulation Study
  - Controlling the Mesh
  - Accessing the Results
  - Indentifying Singularities
  - Instructional Examples
  - Tips and Tricks

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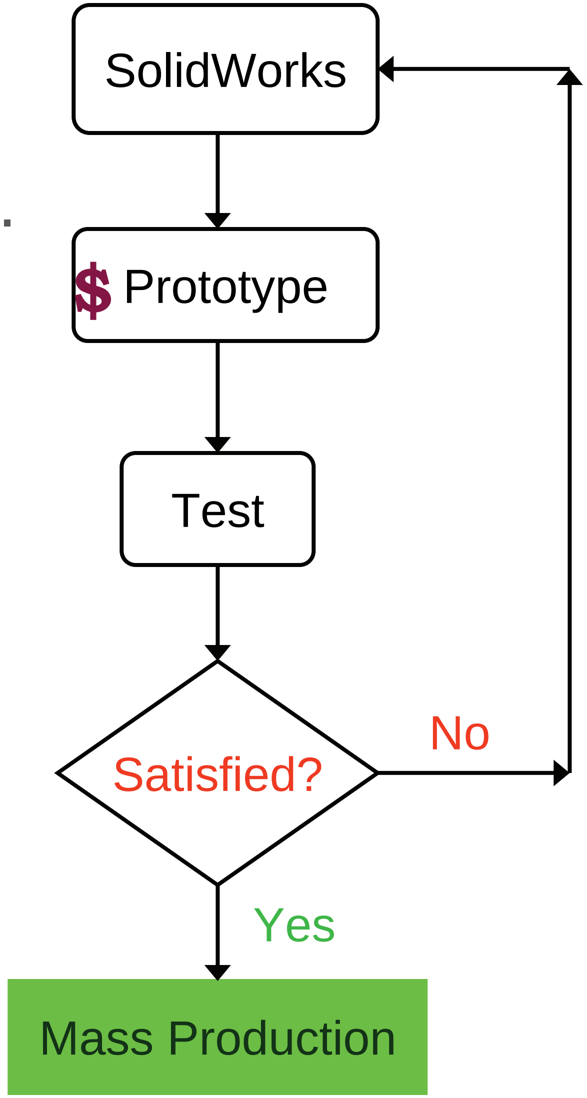
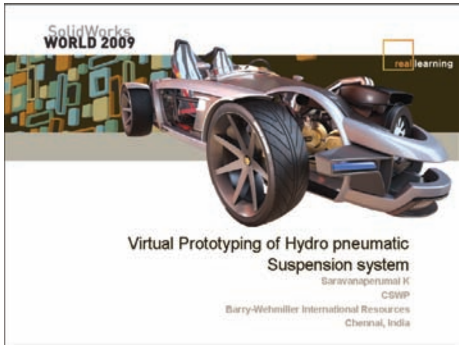
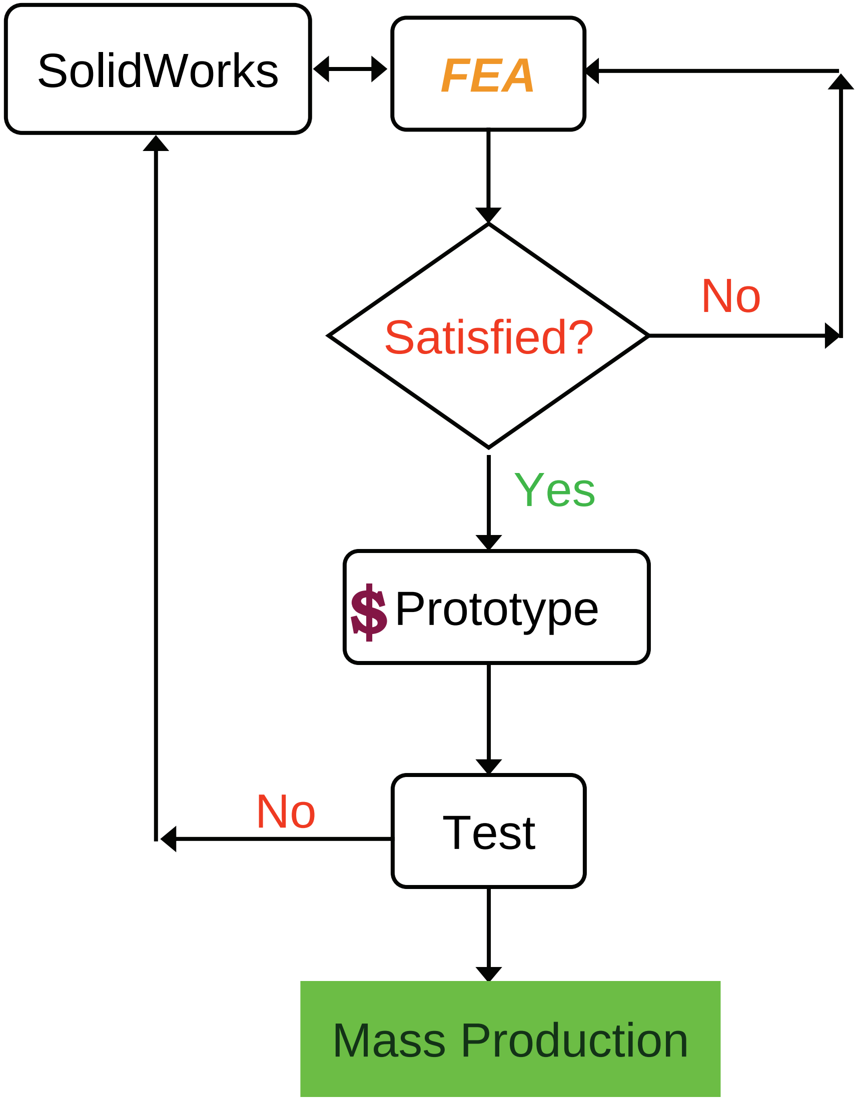
A Traditional Design Cycle

- Build a 3D model.
- Manufacture prototype.
- Test the prototype.
- Analyze results
  - modify the model
  - build a new prototype
  - test it again
  - repeat





FEA Integrated Design Cycle



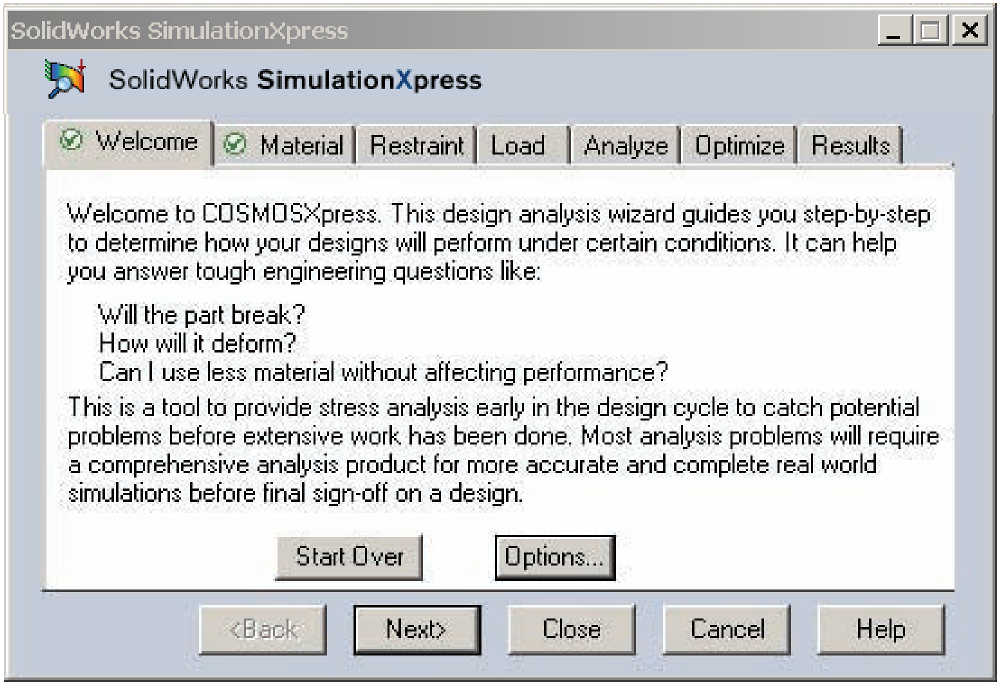
Tools > SimulationXpress

SimulationXpress

Sidebar

- **Limitations**

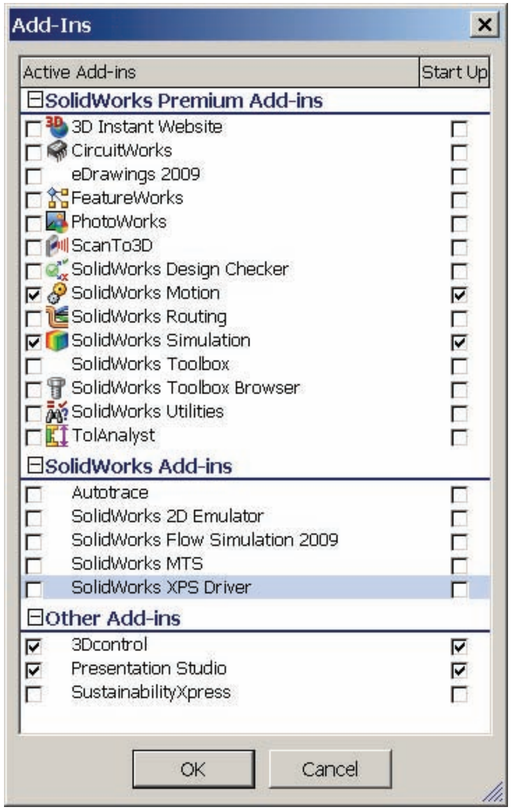
1. PARTs (one solid body)
2. Static analysis only (stress)
3. Optimize one variable
4. Isotropic materials
5. Uniform loads
6. Fixed restraints



Tools > Add-Ins

SolidWorks Simulation

- **Advantages**
  - Parts & Assemblies
  - Non-linear, thermal, buckling, frequency, drop test, optimization, fatigue
  - Isotropic & orthotropic materials
  - Uniform & non-uniform loads
  - Multiple restraints
  - More…



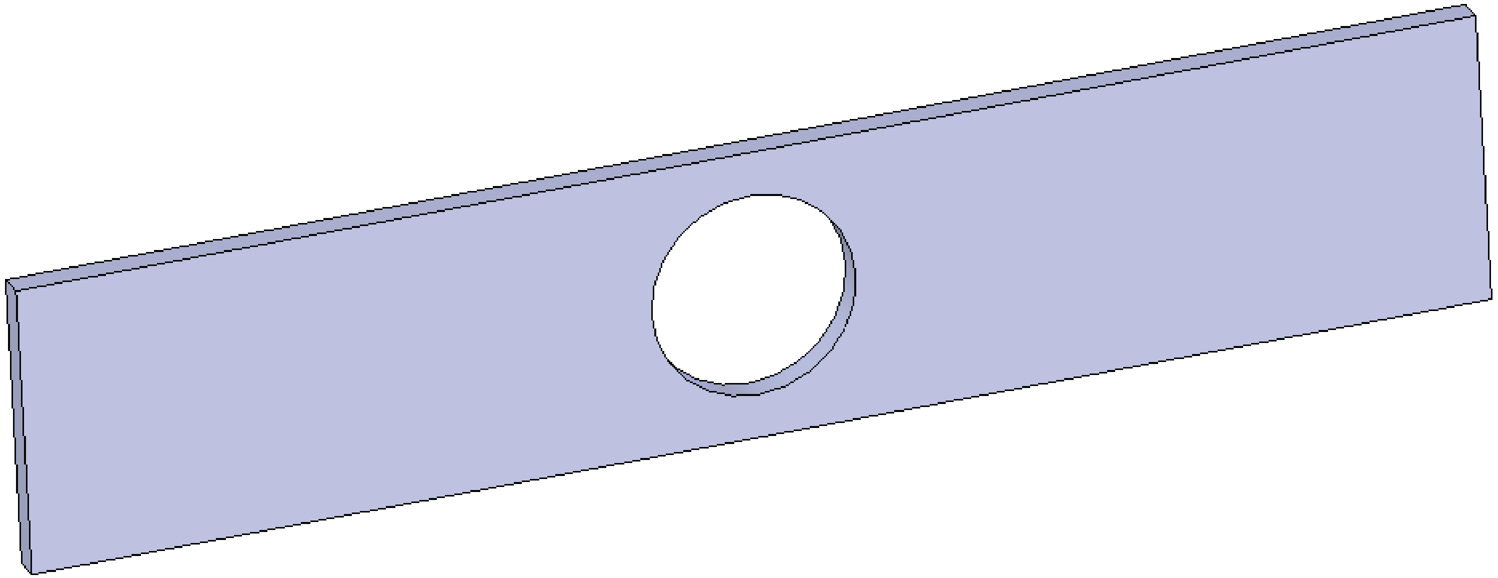
SolidWorks Simulation 2010

FEA Fundamentals

- Define and discretize the domain
- Specify approximating function and B.C.
- Create and converge system of equations
- Resolve for quantities of interest

FEA Fundamentals

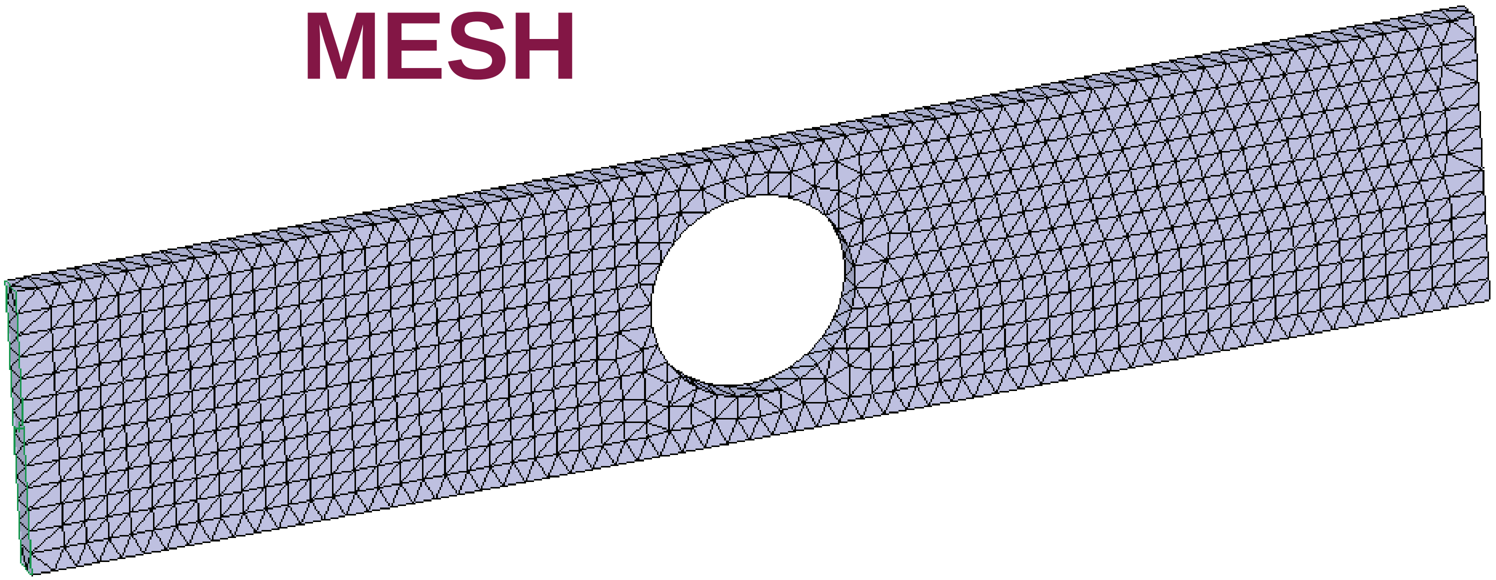
- Define the domain



FEA Fundamentals

- Discretize the domain

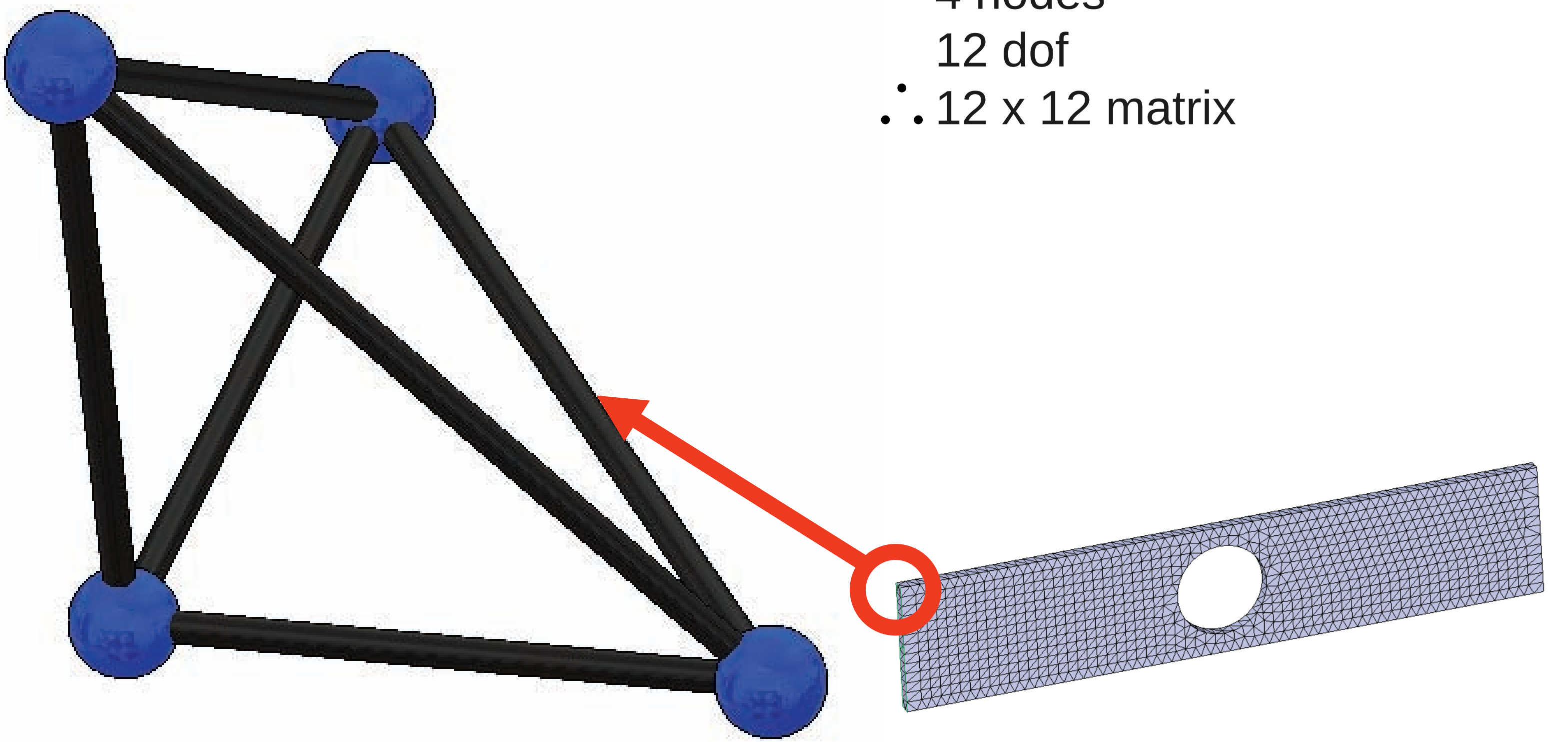
MESH



FEA Fundamentals

- Discretize using tetrahedrons: 1st order (linear)
  - 1 element
  - **4** nodes

First Order Structural Tetrahedron Element:
4 nodes
12 dof
∴ 12 x 12 matrix



FEA Fundamentals

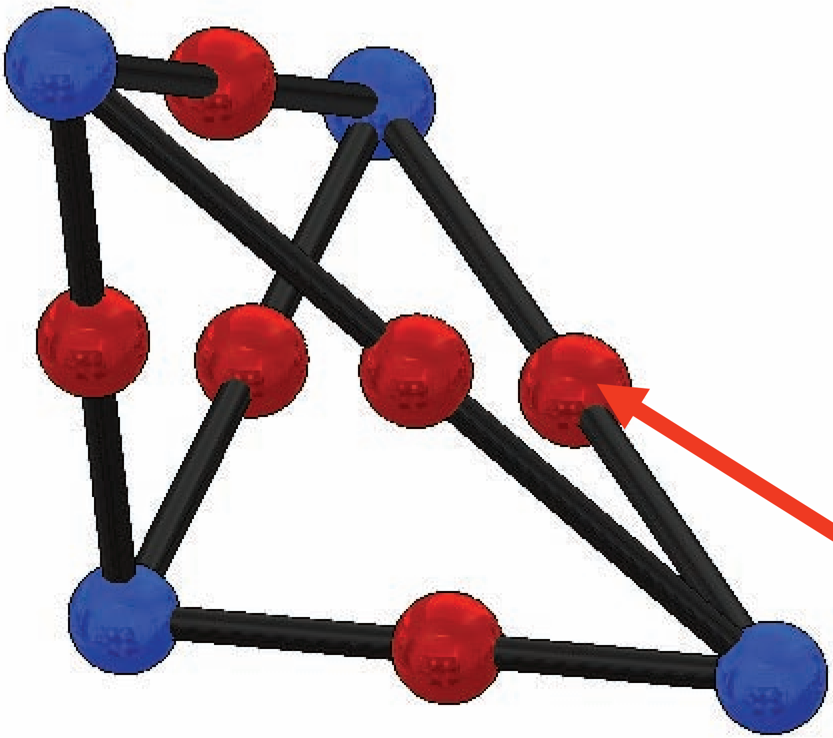
- Discretize using tetrahedrons: 2nd order (quadratic)
  - 1 element
  - **10** nodes

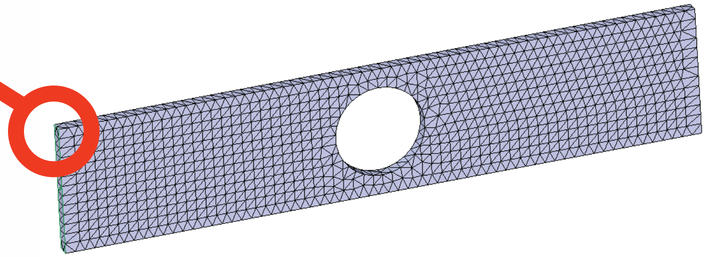
Second Order Structural Tetrahedron Element:

10 nodes

30 dof

∴ 30 x 30 matrix

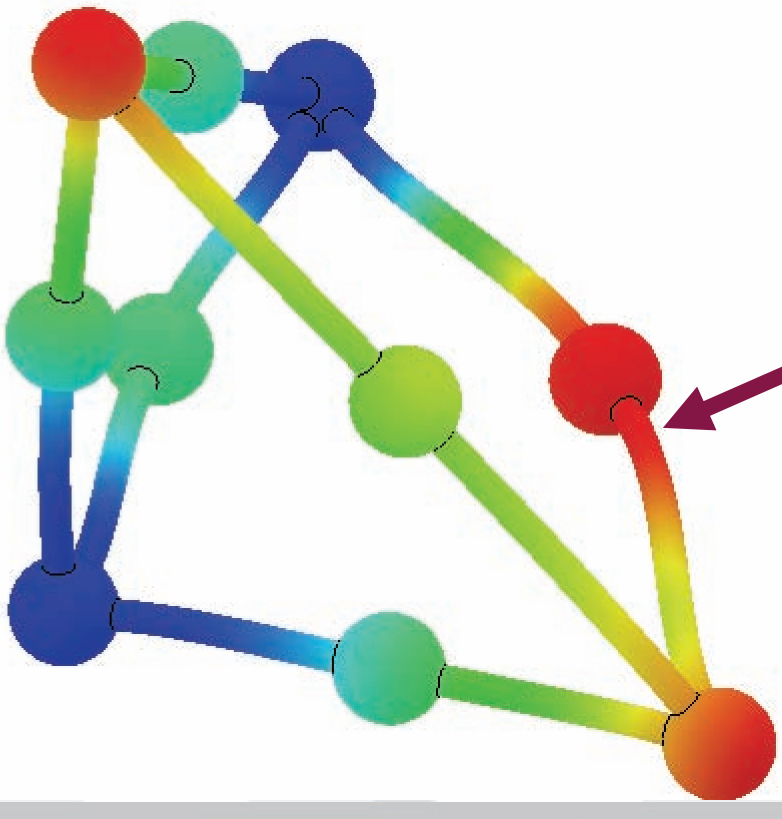




FEA Fundamentals

- Discretize using tetrahedrons: 2nd order
  - 1 element
  - **10** nodes

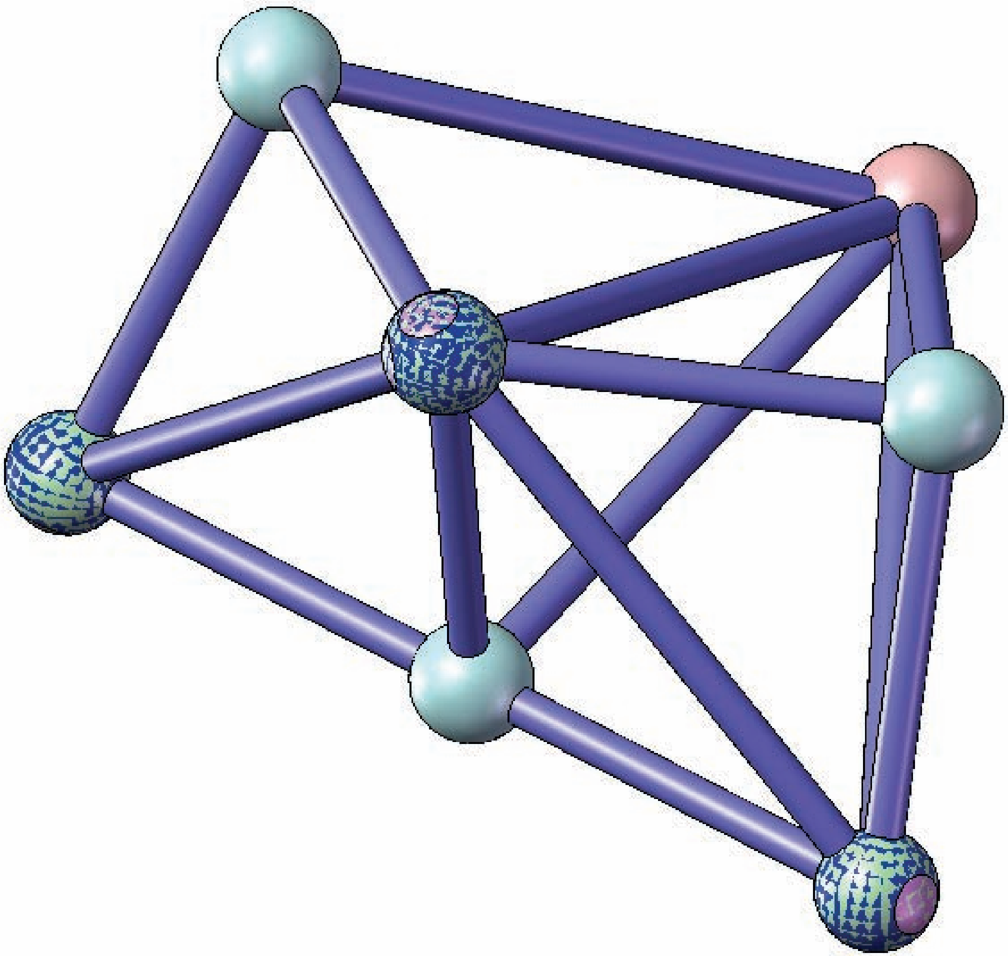
Second Order Structural Tetrahedron Element:
10 nodes
30 dof
∴ 30 x 30 matrix



Curved

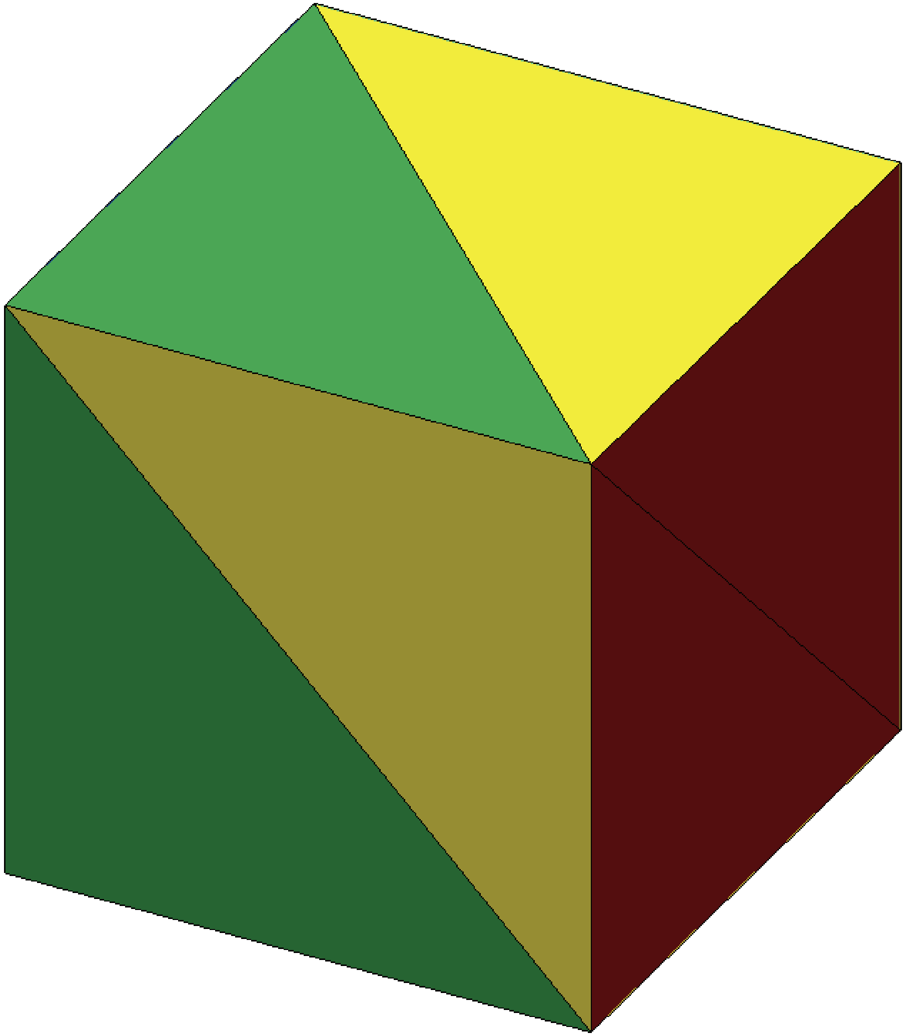
FEA Fundamentals

- Neighboring elements share nodes
  - 4 element
  - 7 nodes
  - DOF ?



FEA Fundamentals

- Cube
  - 12 element
  - 9 nodes
  - DOF ?



FEA Fundamentals

- Specify approximating function

Big Math Warning

And also an…

AVATAR Warning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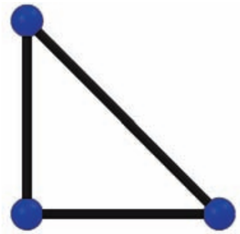
FEA Fundamentals

- Specify approximating function

FEA Fundamentals

- Specify AVATAR function (2D Triangle, linear)

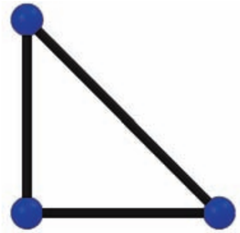


$$u^{(e)}(x,y) = \alpha_o + \alpha_1 x + \alpha_2 y$$

EACH ELEMENT

FEA Fundamentals

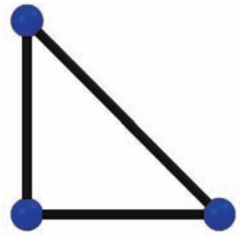
- Specify approximating function (new node values)



$$u^{(e)}(x,y) = \alpha_o + \alpha_1 x + \alpha_2 y$$

FEA Fundamentals

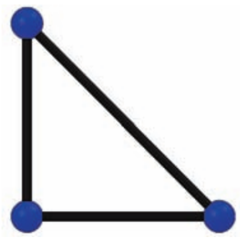
- Specify approximating function (unknown coefficients)



$$u^{(e)}(x, y) = \underline{\alpha_o} + \underline{\alpha_1} x + \underline{\alpha_2} y$$

FEA Fundamentals

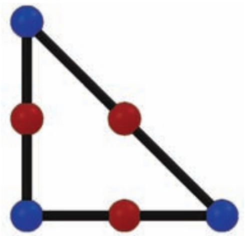
- Specify approximating function (current node values)



$$u^{(e)}(x,y) = \alpha_o + \alpha_1 x + \alpha_2 y$$

FEA Fundamentals

- Specify AVATAR function (2D Triangle, quadratic)



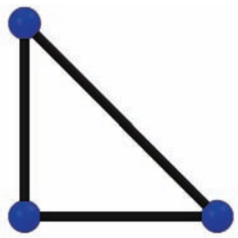
$$u(x,y)=\alpha_o+\alpha_1 x+\alpha_2 y+\alpha_3 x^2+\alpha_4 xy+\alpha_5 y^2$$

$$v(x,y)=\beta_o+\beta_1 x+\beta_2 y+\beta_3 x^2+\beta_4 xy+\beta_5 y^2$$

Sidebar

FEA Fundamentals

- Specify approximating function

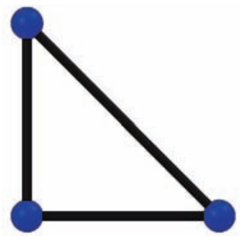


$$u(x, y) = \alpha_o + \alpha_1 x + \alpha_2 y$$

$$v(x, y) = \beta_o + \beta_1 x + \beta_2 y$$

FEA Fundamentals

- Specify approximating function



$$u(x,y) = \alpha_o + \alpha_1 x + \alpha_2 y$$

$$v(x,y) = \beta_o + \beta_1 x + \beta_2 y$$

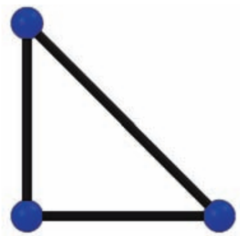
- Equilibrium equations (Hook's Law 2D)

$$+\frac{E}{1-\upsilon^2}\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+G\frac{\partial}{\partial y}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)=0$$

$$+G\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)+\frac{E}{1-\upsilon^2}\left(\upsilon\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)=0$$

FEA Fundamentals

- Specify approximating function



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$$v(x,y)=\beta_o+\beta_1 x+\beta_2 y$$

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FEA Fundamentals

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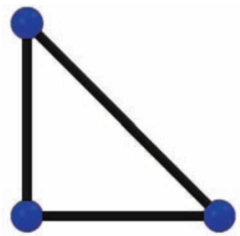

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Moduli conversion

Sidebar

	(λ, G)	(E, G)	(K, λ)	(K, G)	(λ, ν)	(G, ν)	(E, ν)	(K, ν)	(K, E)	(M, G)
$K =$	$\lambda + \frac{2G}{3}$	$\frac{EG}{3(3G-E)}$			$\lambda\frac{1+\nu}{3\nu}$	$\frac{2G(1+\nu)}{3(1-2\nu)}$	$\frac{E}{3(1-2\nu)}$			$M - \frac{4G}{3}$
$E =$	$G\frac{3\lambda+2G}{\lambda+G}$		$9K\frac{K-\lambda}{3K-\lambda}$	$\frac{9KG}{3K+G}$	$\frac{\lambda(1+\nu)(1-2\nu)}{\nu}$	$2G(1+\nu)$		$3K(1-2\nu)$		$G\frac{3M-4G}{M-G}$
$\lambda =$		$G\frac{E-2G}{3G-E}$		$K - \frac{2G}{3}$		$\frac{2G\nu}{1-2\nu}$	$\frac{E\nu}{(1+\nu)(1-2\nu)}$	$\frac{3K\nu}{1+\nu}$	$\frac{3K(3K-E)}{9K-E}$	$M-2G$
$G =$			$3\frac{K-\lambda}{2}$		$\lambda\frac{1-2\nu}{2\nu}$		$\frac{E}{2(1+\nu)}$	$3K\frac{1-2\nu}{2(1+\nu)}$	$\frac{3KE}{9K-E}$	
$\nu =$	$\frac{\lambda}{2(\lambda+G)}$	$\frac{E}{2G} - 1$	$\frac{\lambda}{3K-\lambda}$	$\frac{3K-2G}{2(3K+G)}$					$\frac{3K-E}{6K}$	$\frac{M-2G}{2M-2G}$
$M =$	$\lambda + 2G$	$G\frac{4G-E}{3G-E}$	$3K - 2\lambda$	$K + \frac{4G}{3}$	$\lambda\frac{1-\nu}{\nu}$	$G\frac{2-2\nu}{1-2\nu}$	$E\frac{1-\nu}{(1+\nu)(1-2\nu)}$	$3K\frac{1-\nu}{1+\nu}$	$3K\frac{3K+E}{9K-E}$	

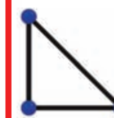
AVATAR

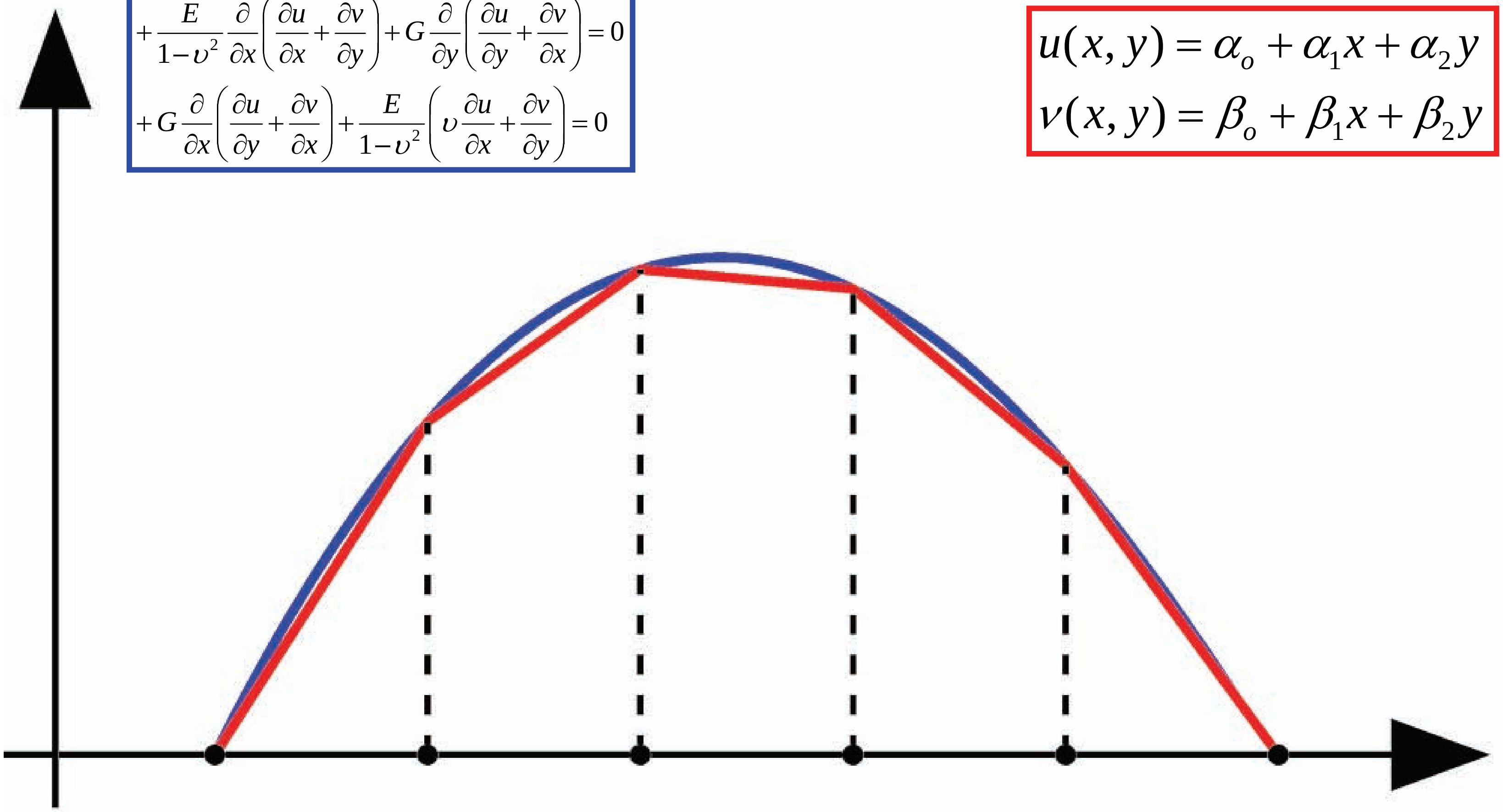
$$+\frac{E}{1-\upsilon^2}\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+G\frac{\partial}{\partial y}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)=0$$

$$+G\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)+\frac{E}{1-\upsilon^2}\left(\upsilon\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)=0$$

$$u(x,y)=\alpha_o+\alpha_1 x+\alpha_2 y$$

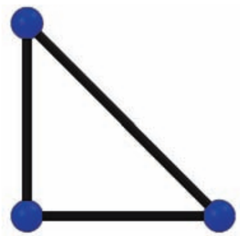
$$v(x,y)=\beta_o+\beta_1 x+\beta_2 y$$





FEA Fundamentals

- Specify approximating function



$$u(x,y) = \alpha_o + \alpha_1 x + \alpha_2 y$$

$$v(x,y) = \beta_o + \beta_1 x + \beta_2 y$$

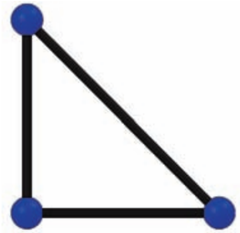
- Equilibrium equations (Hook's Law 2D)

$$+\frac{E}{1-\upsilon^2}\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+G\frac{\partial}{\partial y}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)=0$$

$$+G\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)+\frac{E}{1-\upsilon^2}\left(\upsilon\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)=0$$

FEA Fundamentals

- Specify approximating function



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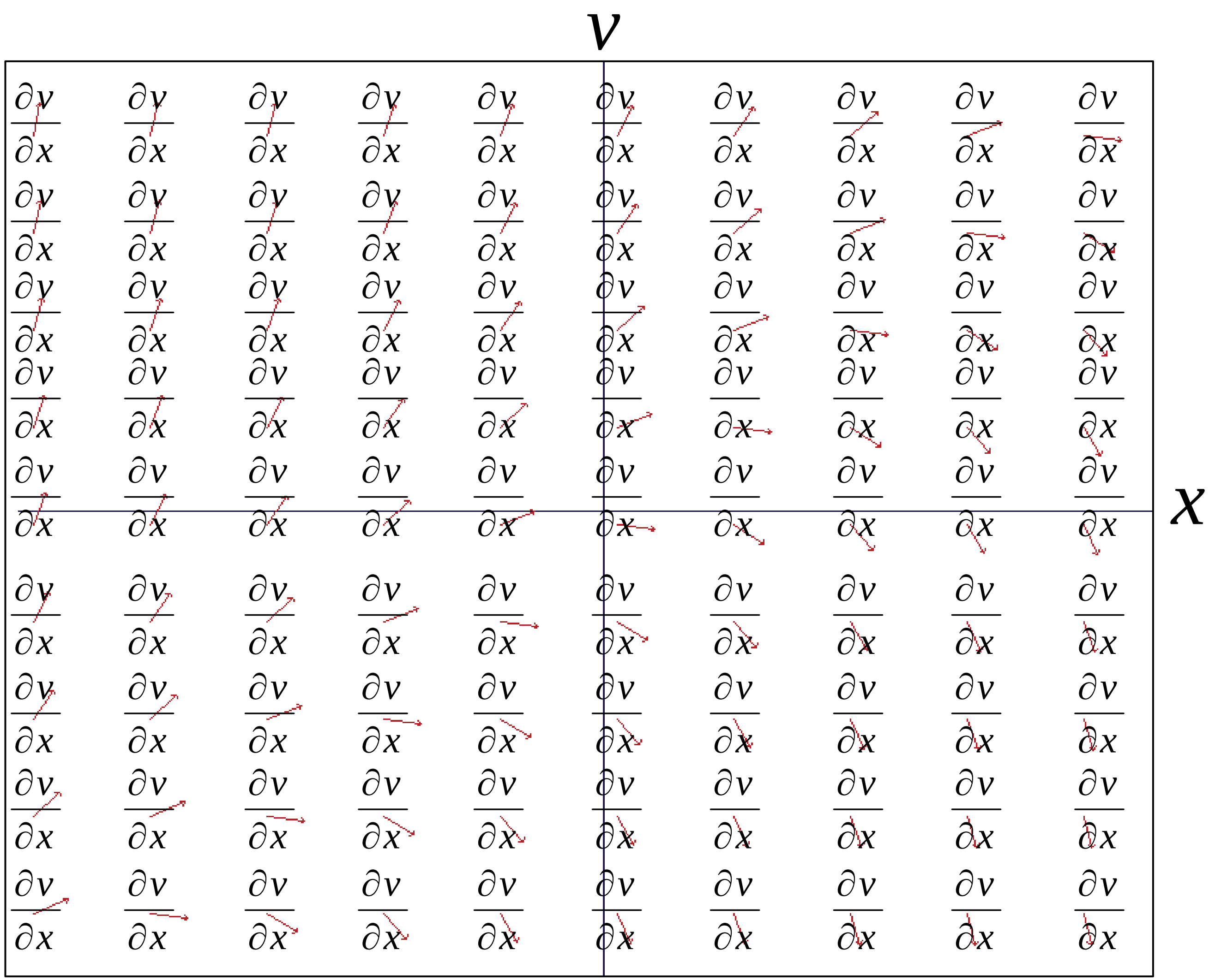
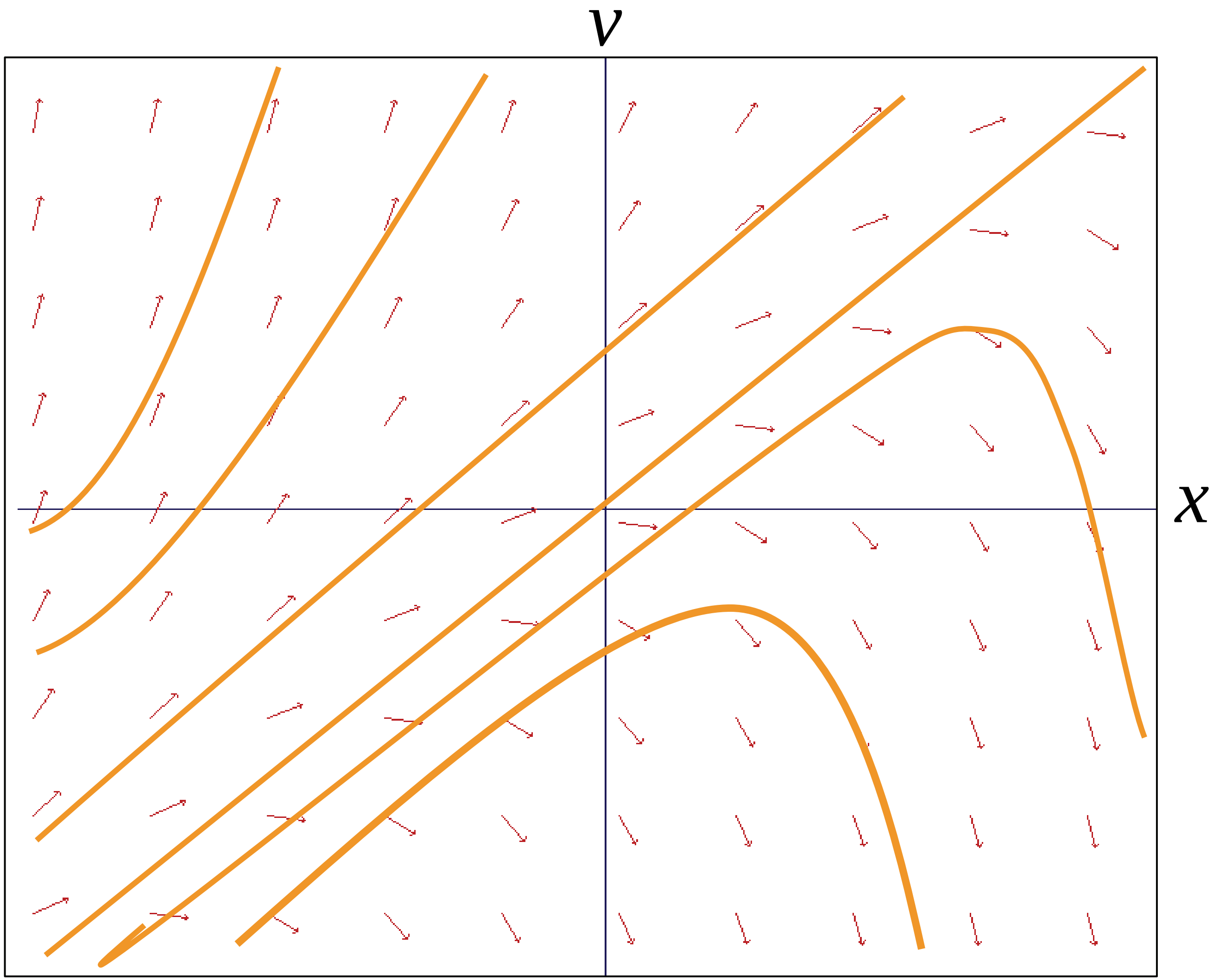
$$+G\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)+\frac{E}{1-\upsilon^2}\left(\upsilon\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)=0$$

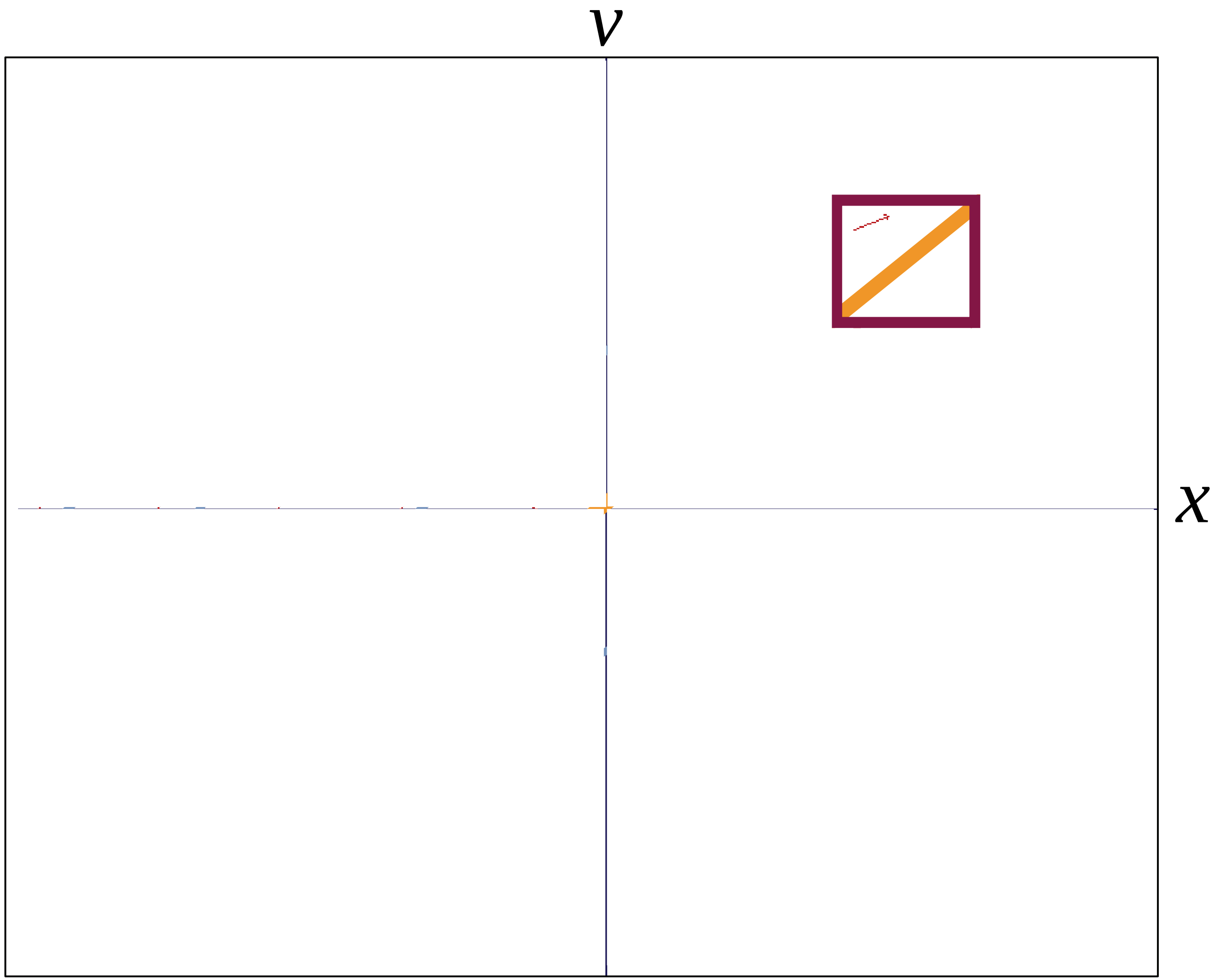
Slope Field: $\frac{\partial v}{\partial x} = v - x$



Solutions: $\frac{\partial v}{\partial x} = v - x$

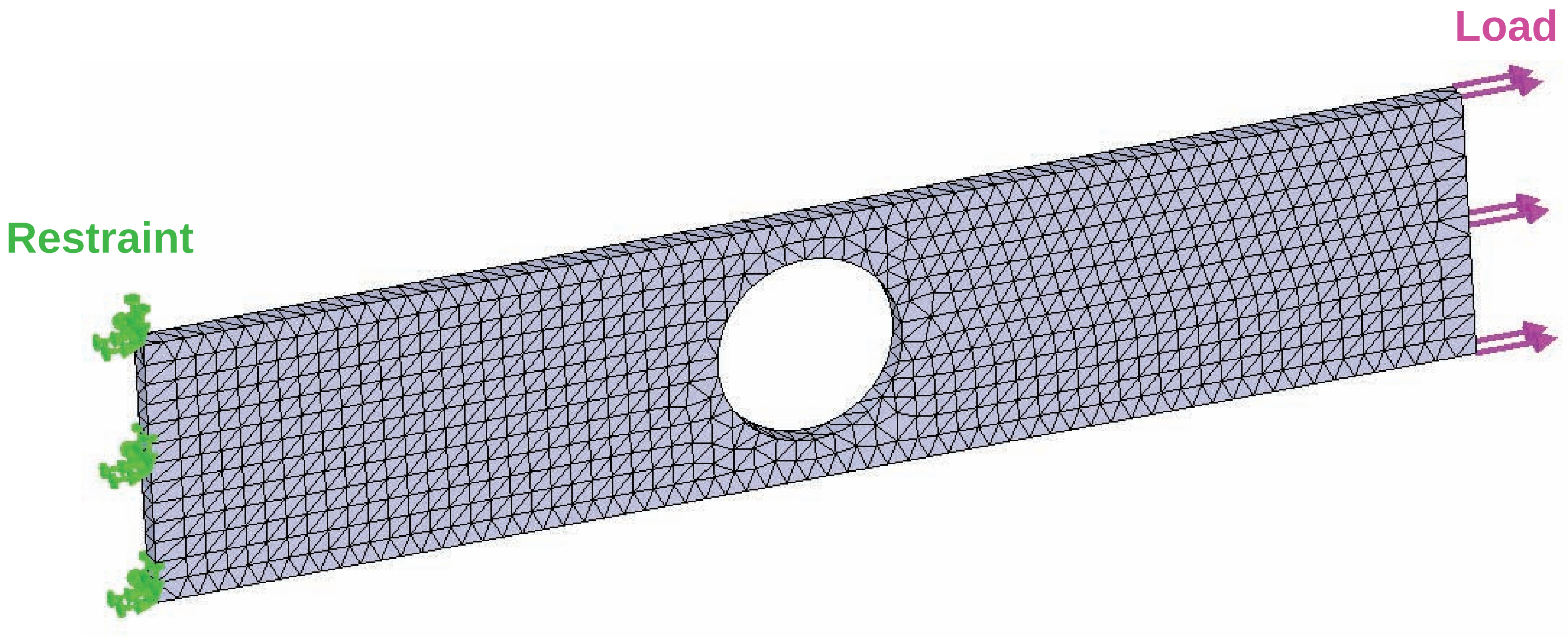


Solutions: $$\frac{\partial v}{\partial x} = v - x$$



FEA Fundamentals

- Specify the boundary conditions



FEA Fundamentals (basic strategy)

- Create and converge system of equations

1) Plug initial mesh geometry into

$$u(x,y)=\alpha_o+\alpha_1 x+\alpha_2 y$$
$$v(x,y)=\beta_o+\beta_1 x+\beta_2 y$$

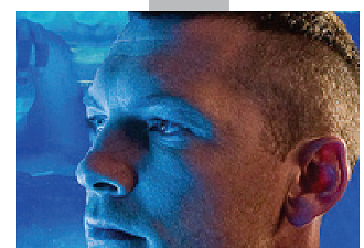
2) Plug new node values from 1) into

$$+\frac{E}{1-\upsilon^2}\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+G\frac{\partial}{\partial y}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)=0$$
$$+G\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)+\frac{E}{1-\upsilon^2}\left(\upsilon\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)=0$$

3) Subtract 1) from 2)

4) Difference 3) drives next iteration

+



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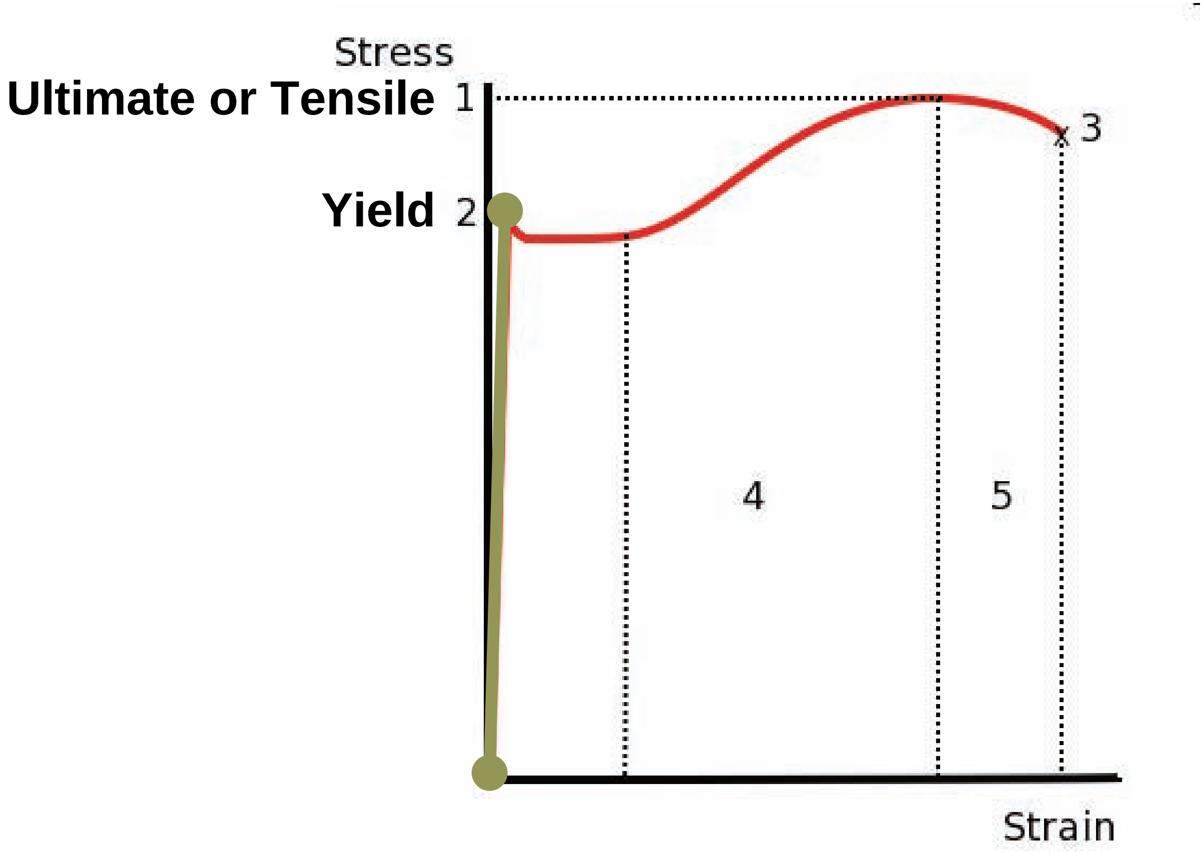
FEA Fundamentals

- Resolve for other quantities of interest
  - Strain (ϵ)
  - Stress (σ)
  - von Mises Stress: $\sigma_{eq} = \sqrt{0.5\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]}$

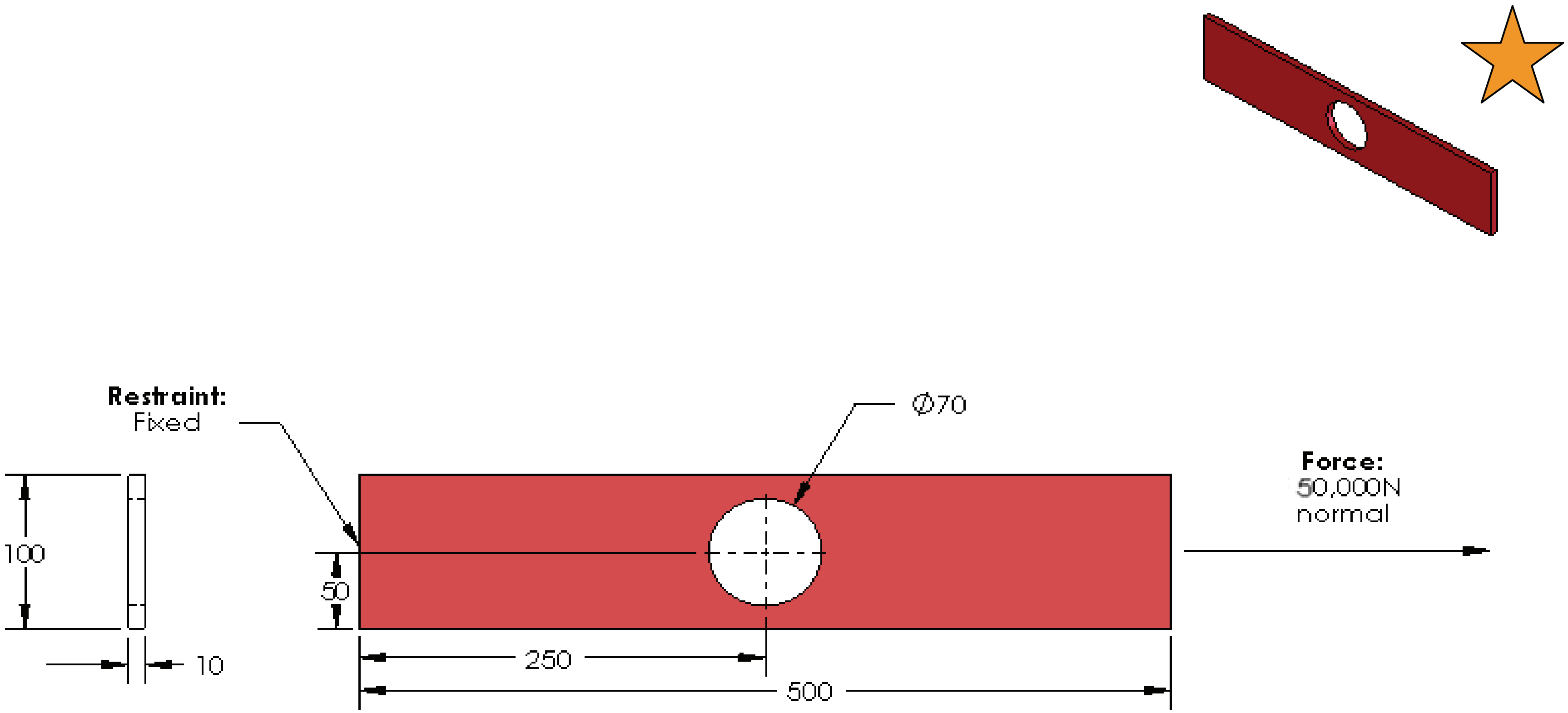
Linear elastic stress analysis

- Small displacements with constant b.c.
- Material properties constant (ductile)



Defining a Study (fea fundamentals)

1. **Define the type of analysis.** (specify approx. function)
2. **Create a study.**
3. **Define material for each component.**
4. **Define *Connections*.** (b.c.: component-component)
5. **Define *Fixtures*.** (b.c.: reduce model DOF)
6. **Define *External Loads*.** (b.c.: force, pressure, torque)
7. **Define the *Mesh*.** (discretize the domain)
8. **Run the analysis.** (solve linear system)
9. **View *Results*.**
10. **Interpret results.**



Material: Alloy Steel   Units: MMGS

TITLE: Example 13.1, SWS Rectangular Plate with Hole		
SIZE A	Course: EDSGN 496A	REV
SCALE: 1:5	RGB	SHEET 1 OF 1

5 4 3 2 1

Analytical vs. FEA (node)

$$\sigma_{max} = K_n \times \sigma_n$$

Stress concentration factor, (flat plate, circular hole, D/W>0.65):

$$K_n = 2 + \left(1 - \frac{D}{W}\right)^3$$

Normal stress, at hole cross section:

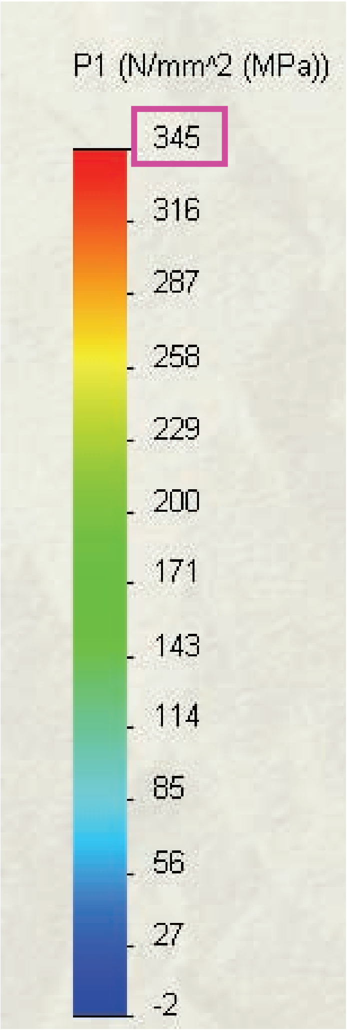
$$\sigma_n = \frac{P}{(W - D) \times T}$$

Plate geometry:
D = hole diameter = 70 mm
W = plate width = 100 mm
T = plate thickness = 10 mm

Load:
P = tensile load = 50,000 N

$$\therefore \sigma_{max} = 338\,MPa$$

FEA Solution



Flat Plate: vonMises (MPa) vs DOF

Mesh	vonMises*	DOF
• Coarse	327	7,944
• Default	341	46,728
• Fine	349	281,142
• Default w/ mesh ctrl.	348	52,368

$$*\sigma_{eq} = \sqrt{0.5\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]}$$

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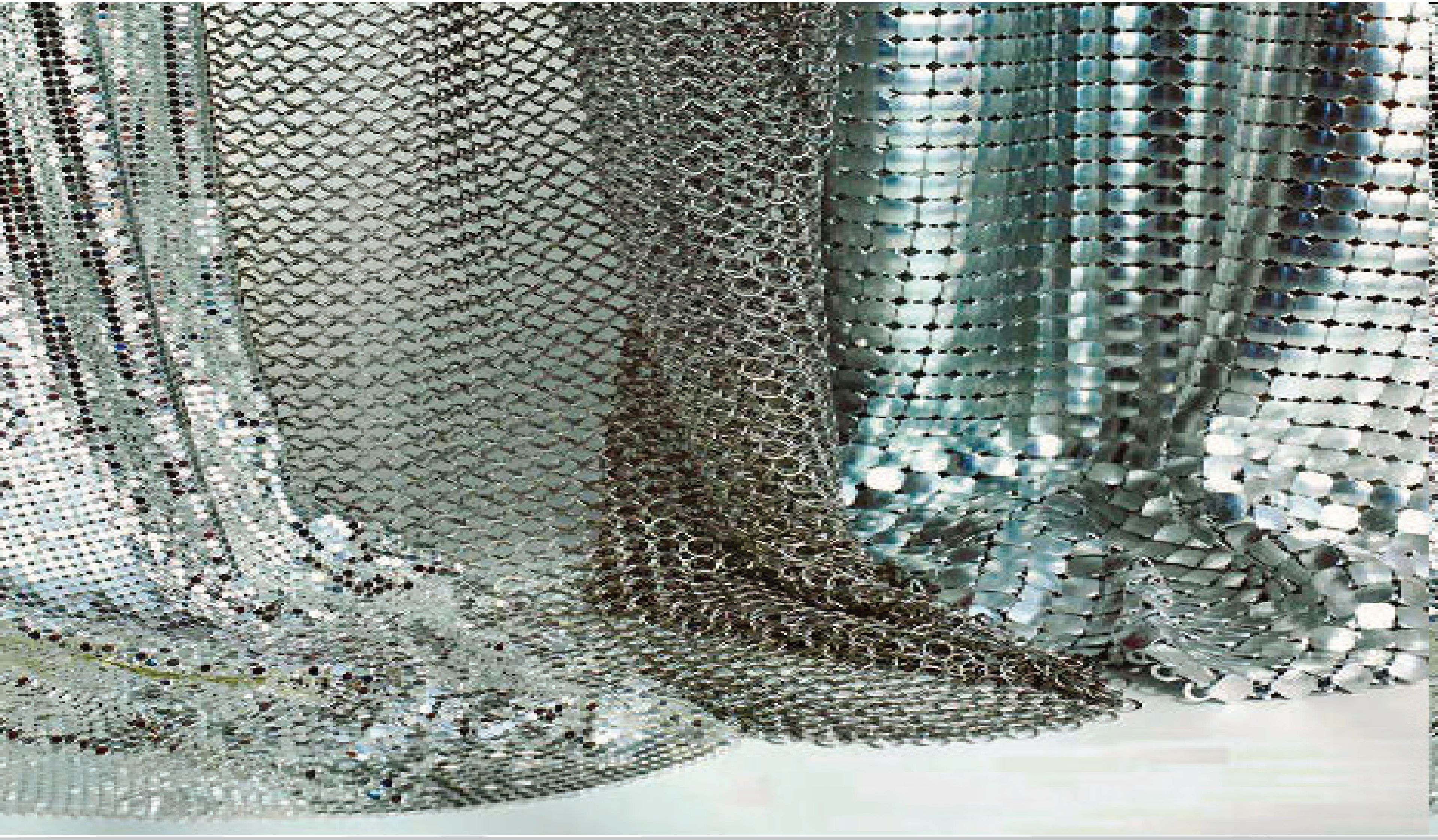
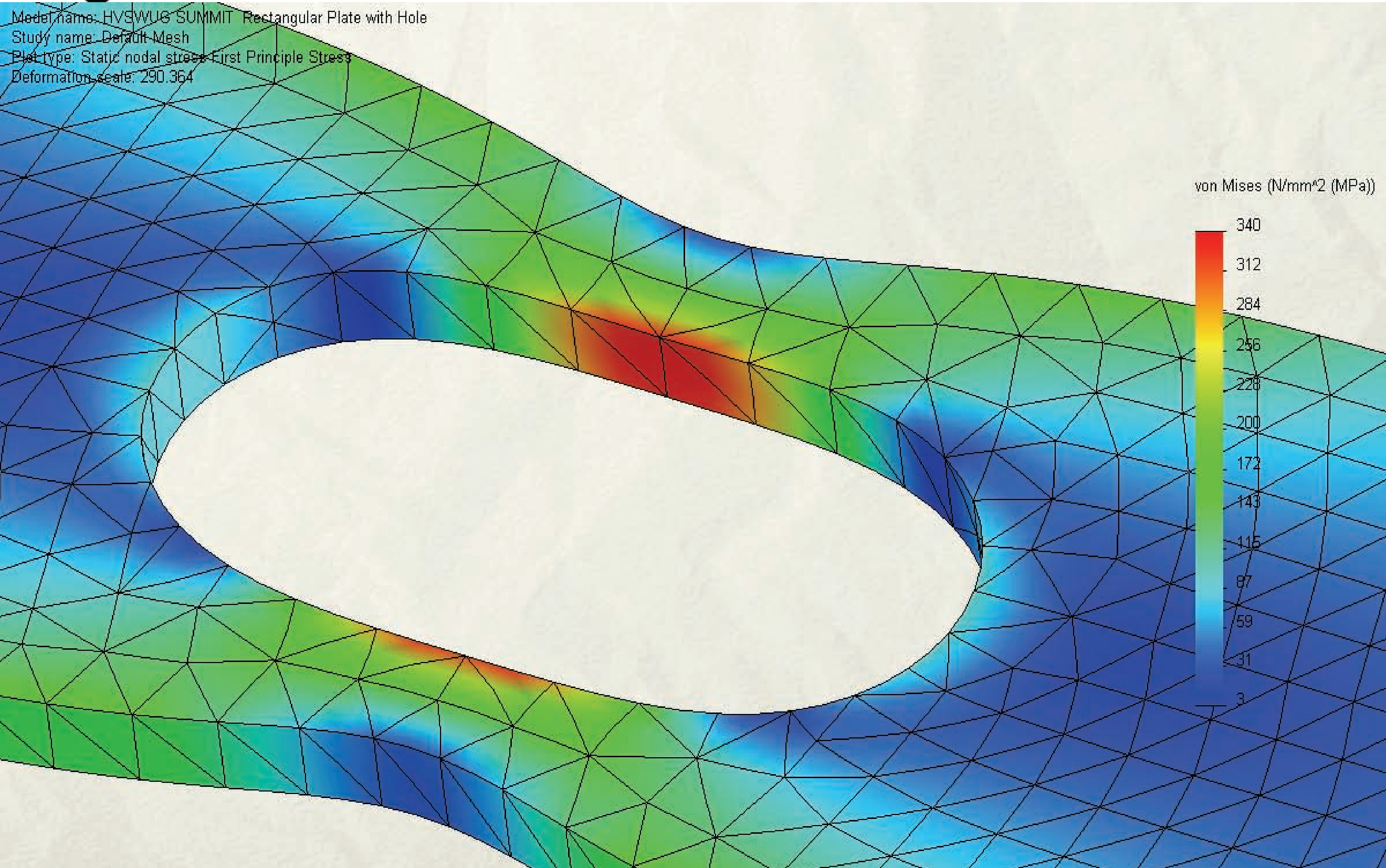
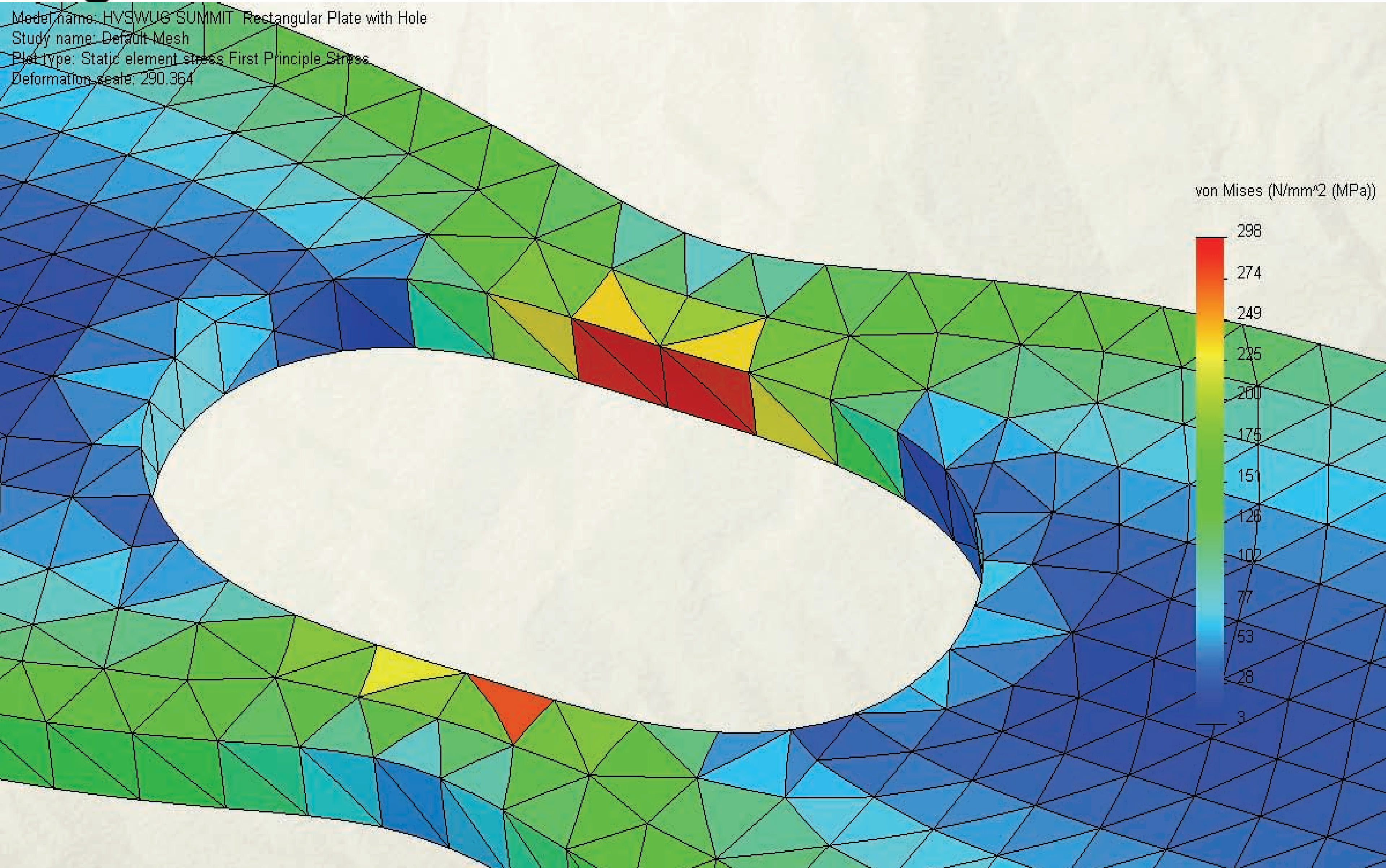
It's all about the Mesh



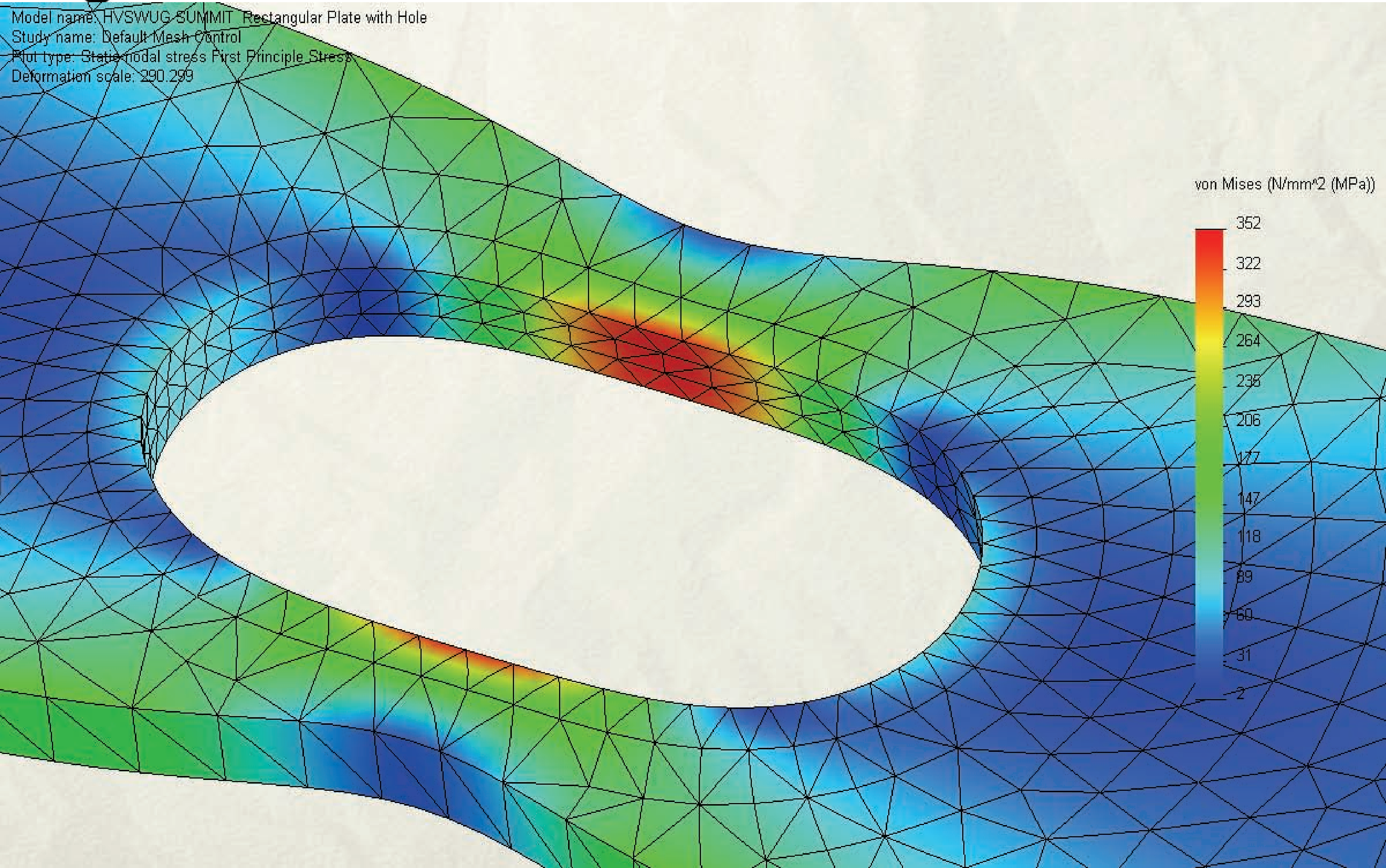
vonMises (MPa): Default Nodes



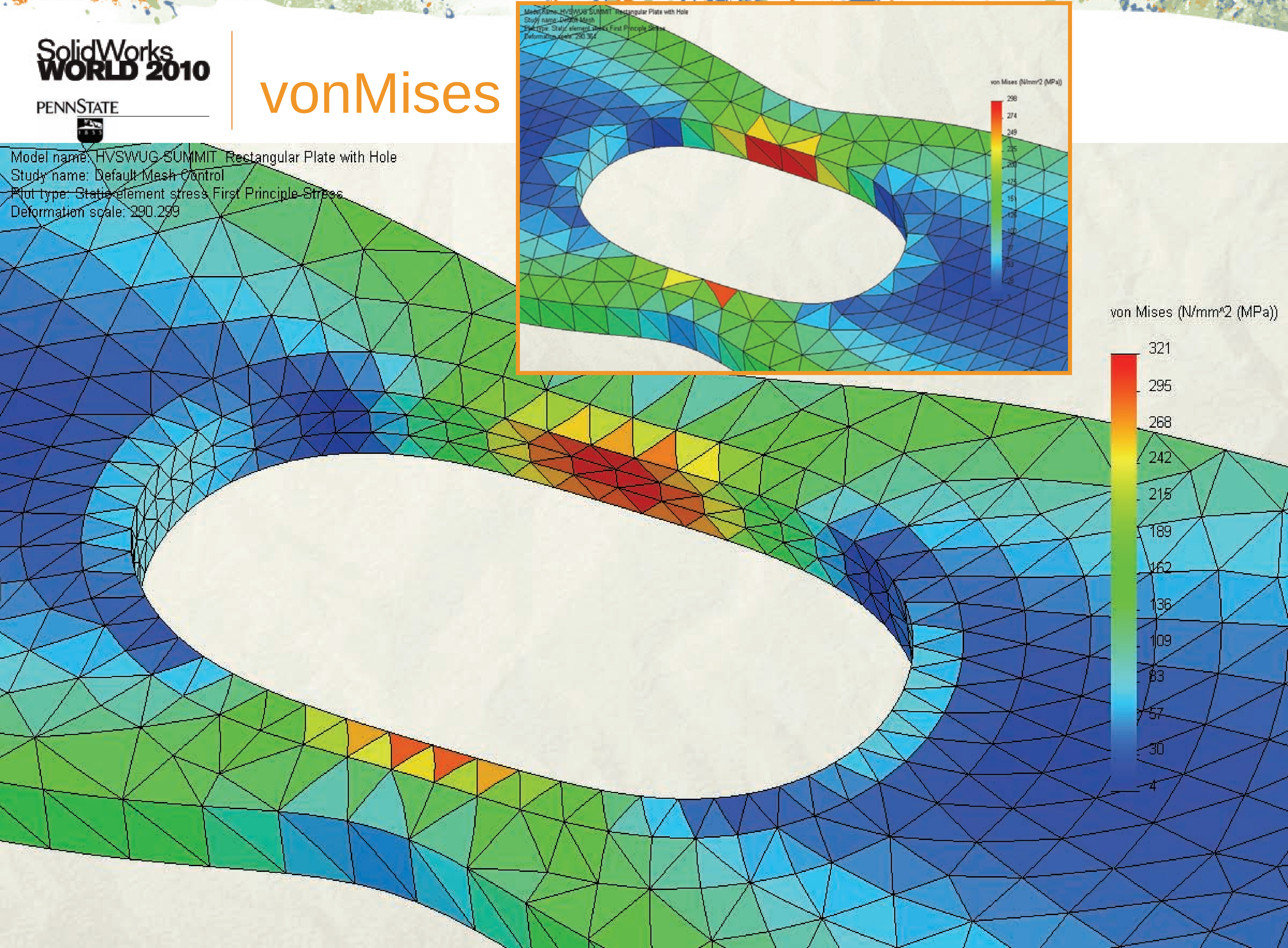
vonMises (MPa): Default Elements



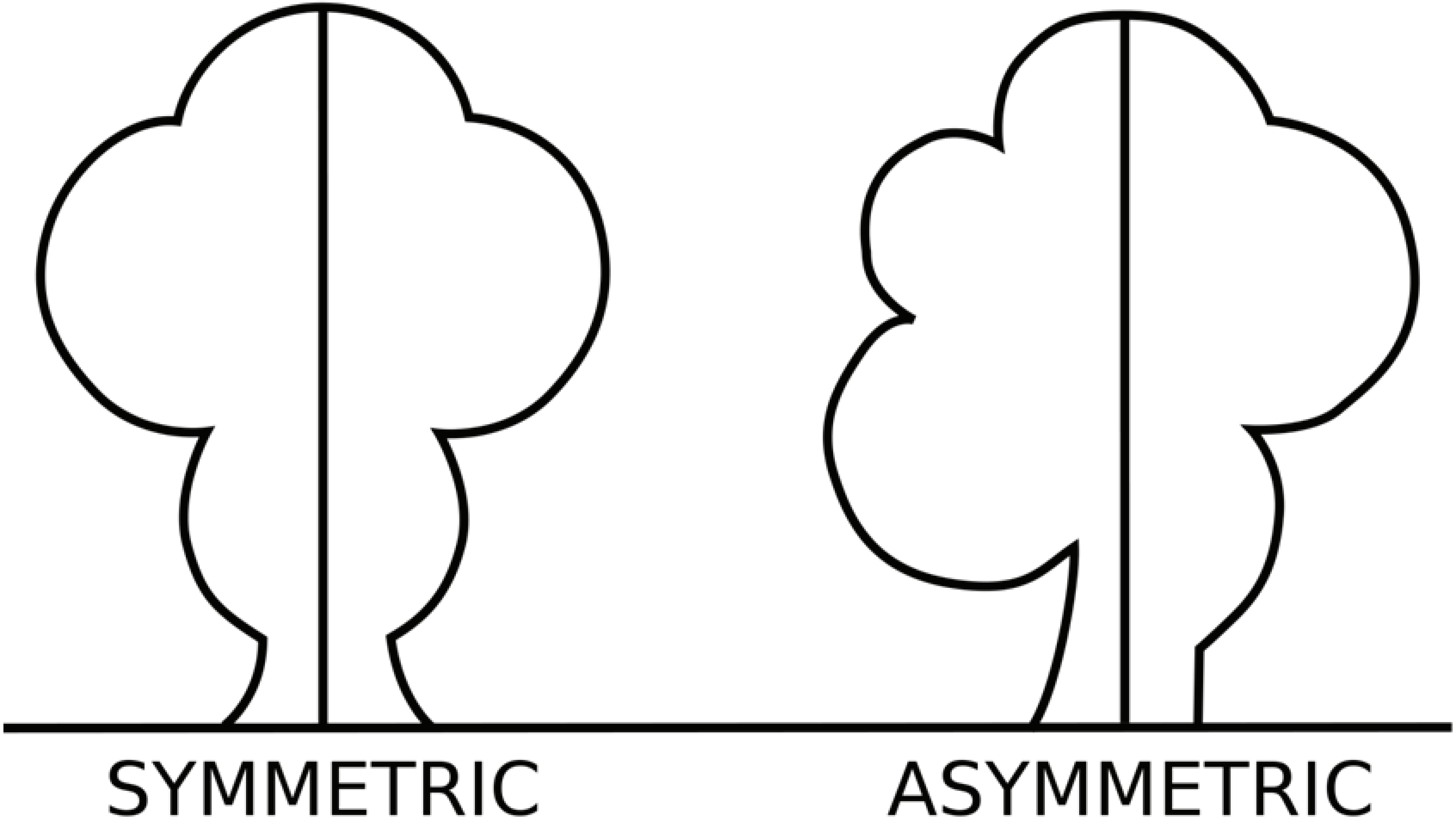
vonMises (MPa): Fine Nodes



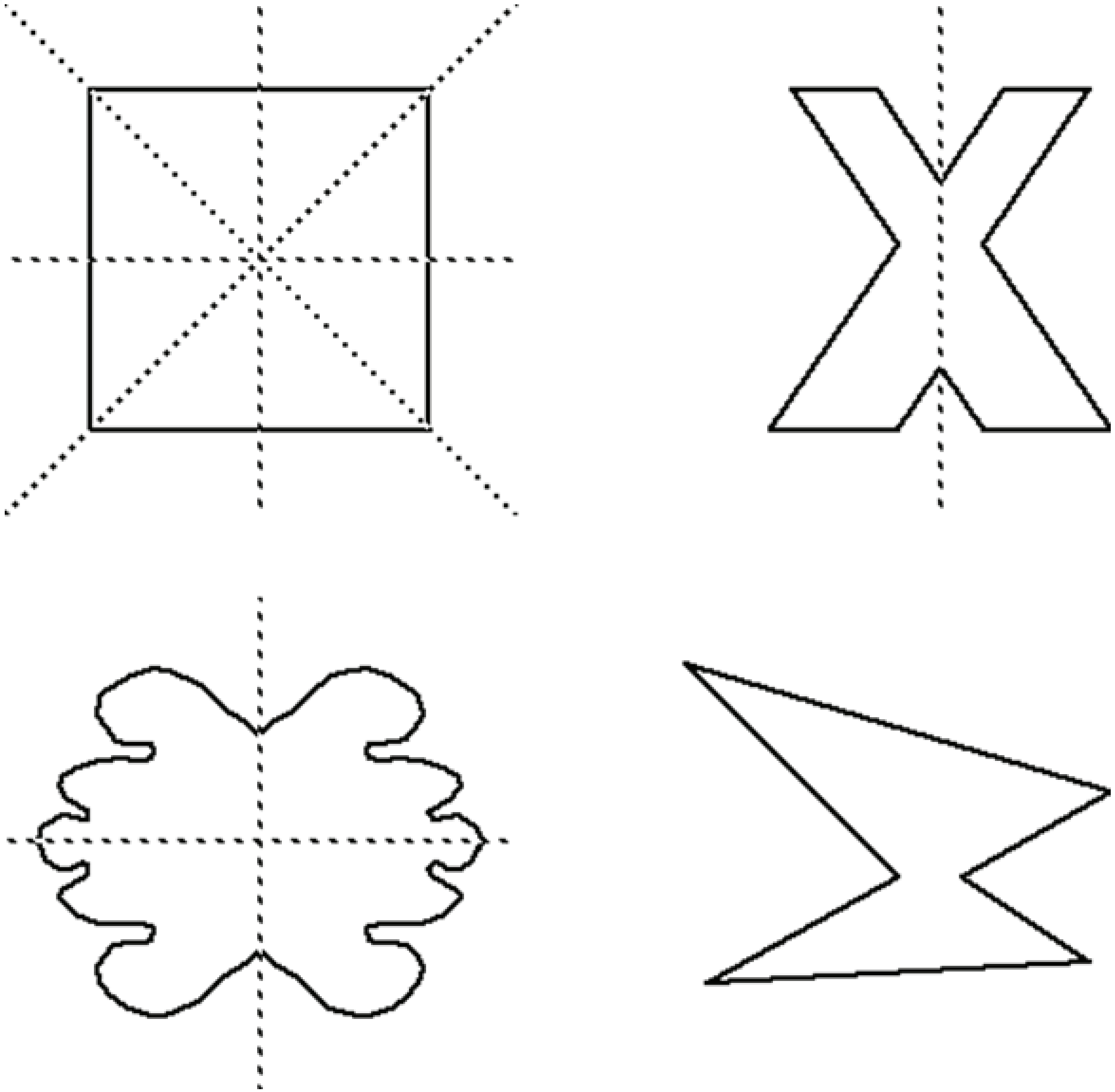
vonMises


Model name: HVSWUG SUMMIT Rectangular Plate with Hole
Study name: Default Mesh Control
Plot type: Static element stress First Principle Stress
Deformation scale: 290.299
von Mises (N/mm^2 (MPa))
321
295
268
242
215
189
162
136
109
83
57
30
4
Rectangular Plate with Hole
von Mises (N/mm^2 (MPa))
298
274
249

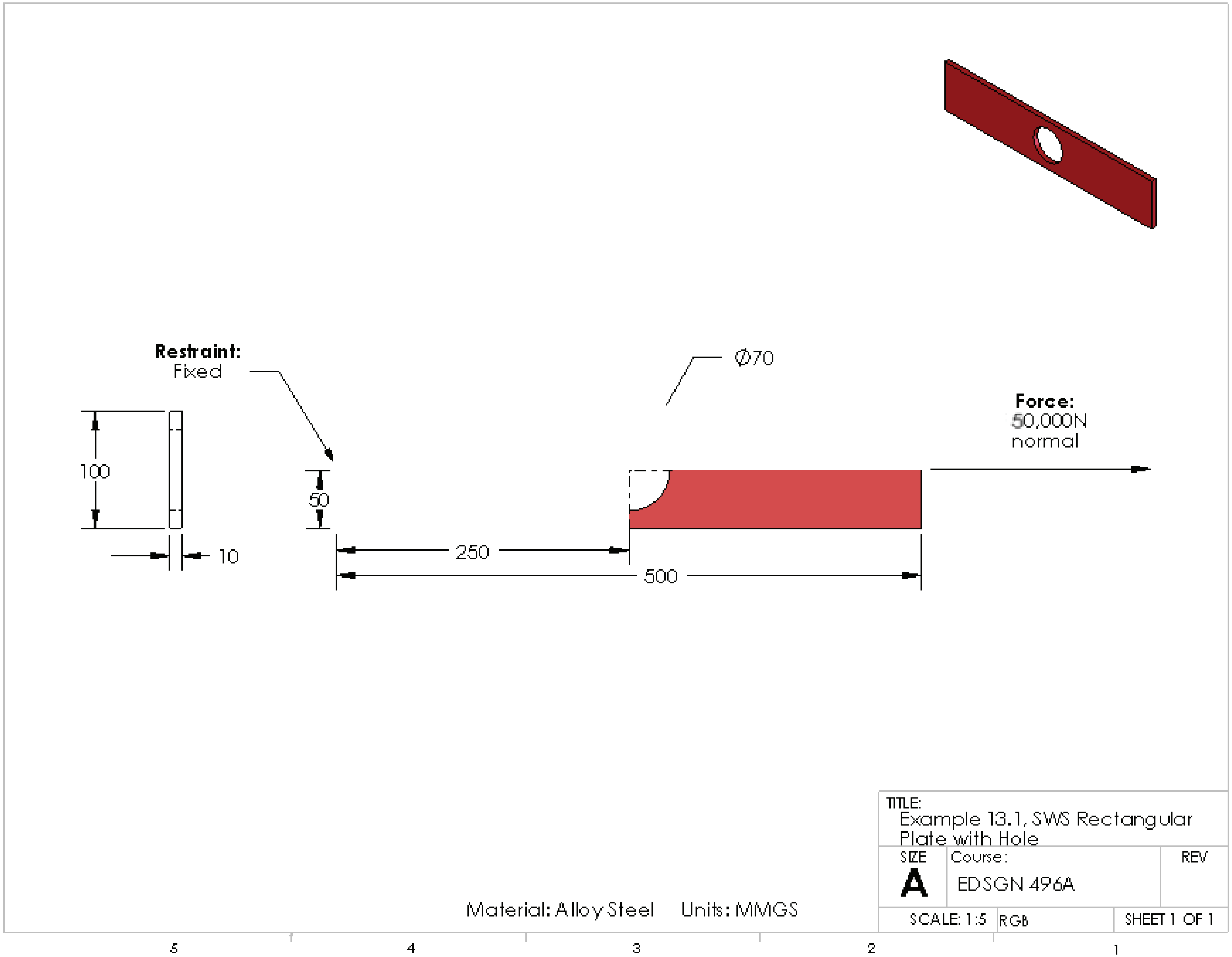
Consider Symmetry



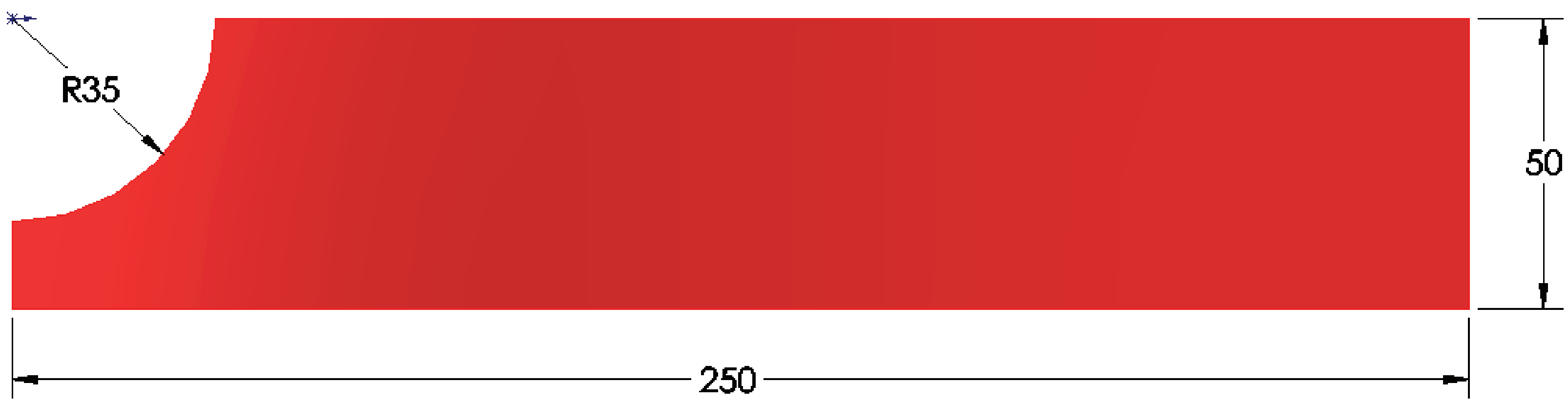
Consider Symmetry



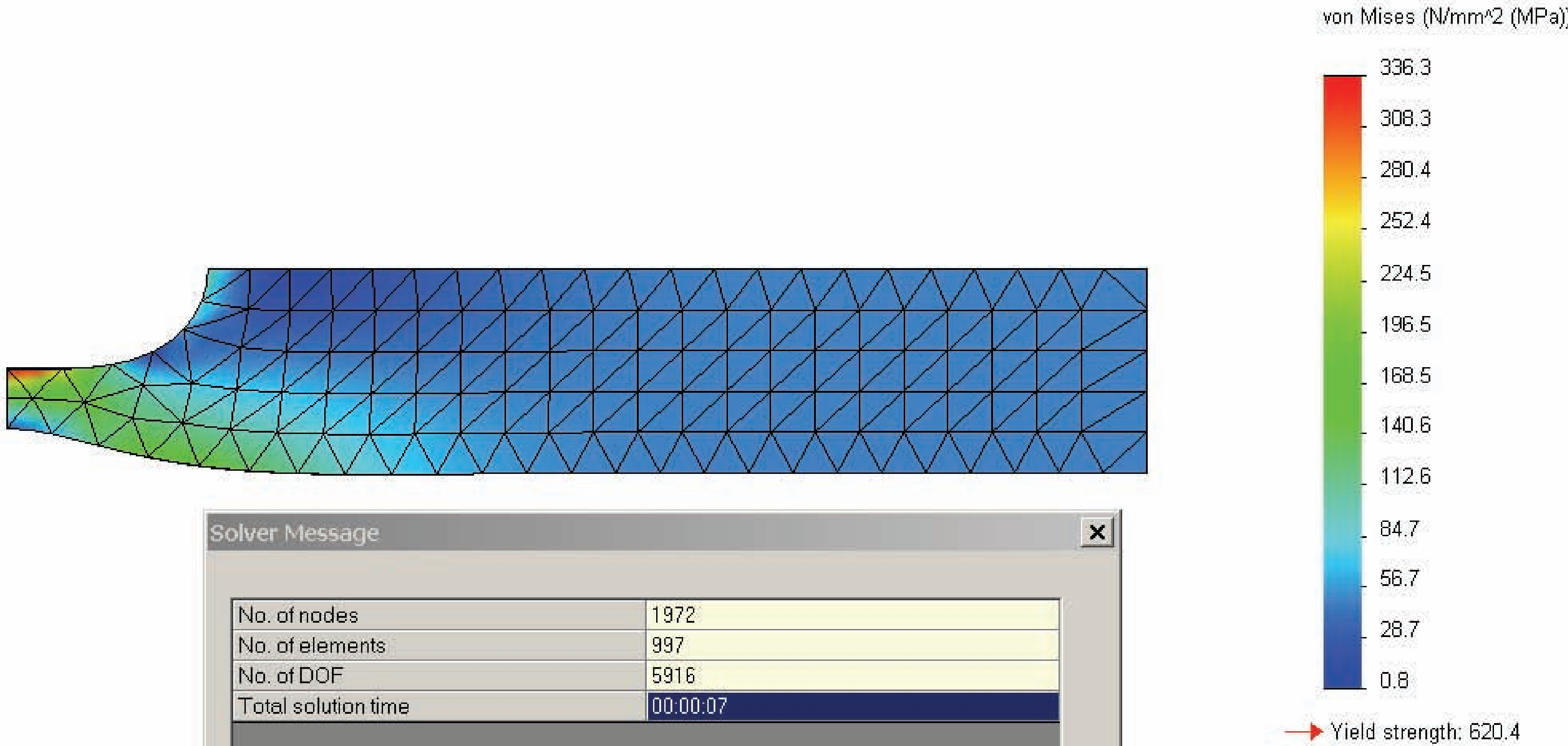
Consider Symmetry



Simplification: ¼ Symmetry



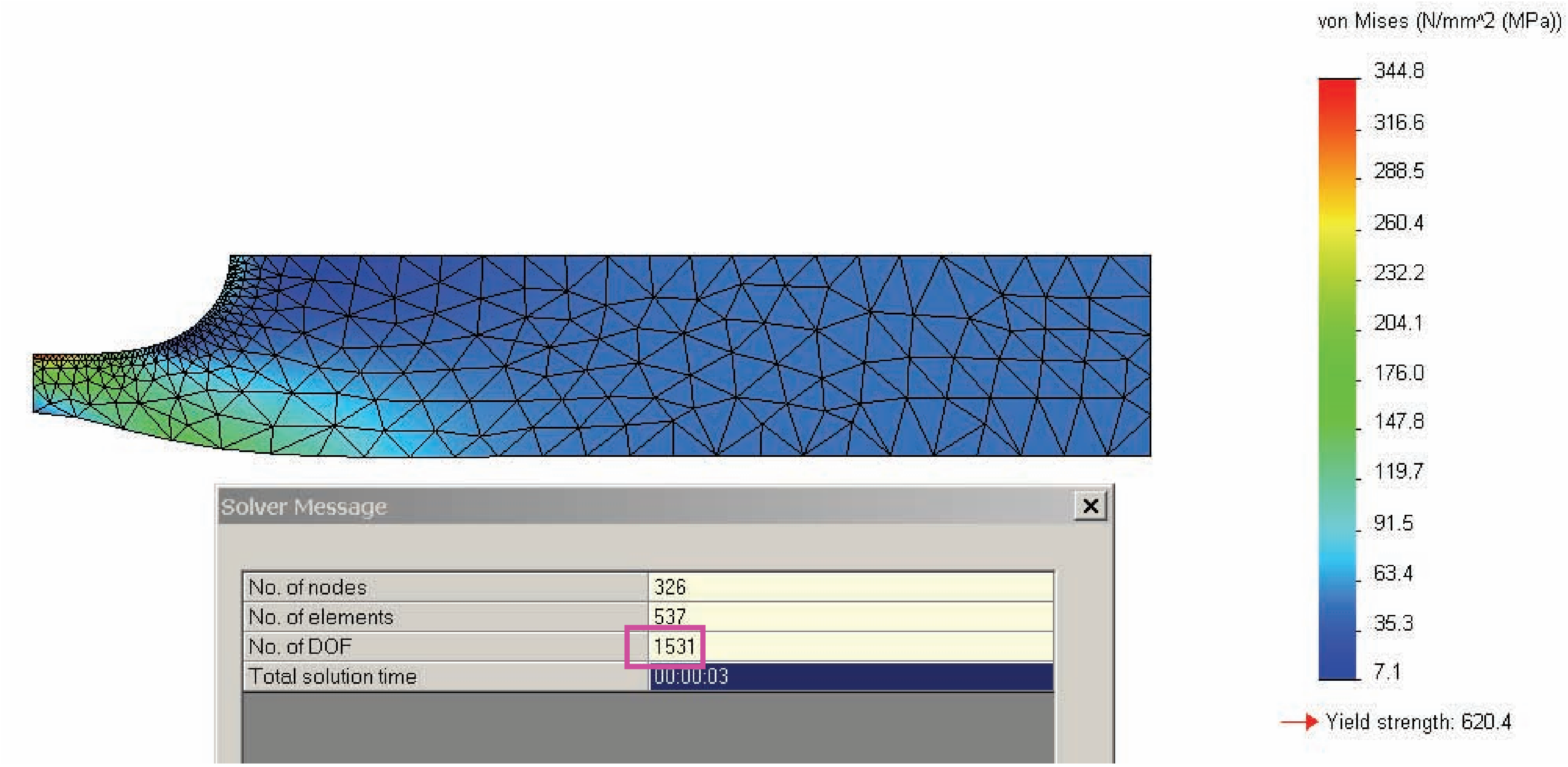
Simplification: ¼ Symmetry & 3D



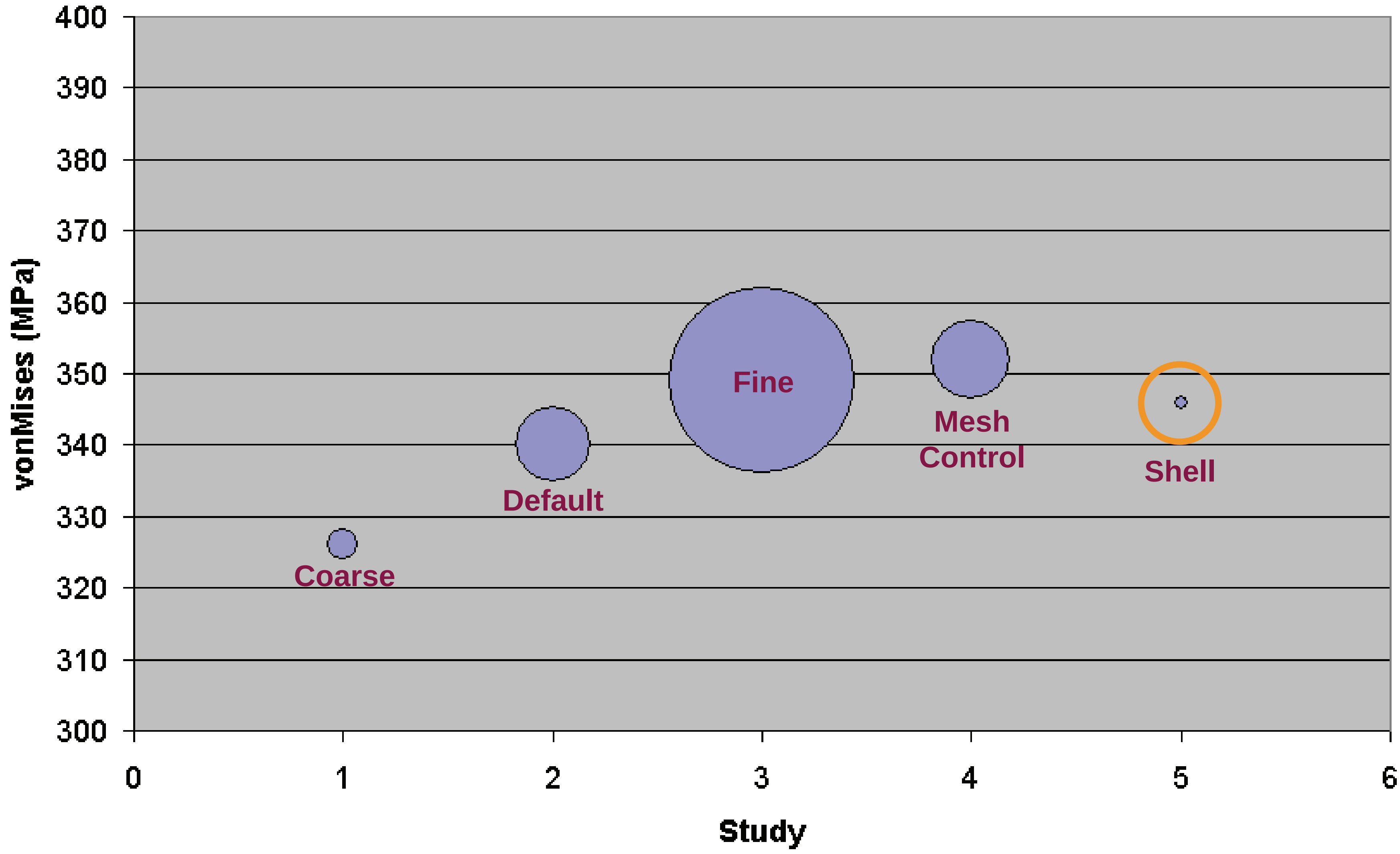
Solver Message

No. of nodes	1972
No. of elements	997
No. of DOF	5916
Total solution time	00:00:07

Simplification: ¼ Symmetry & 2D



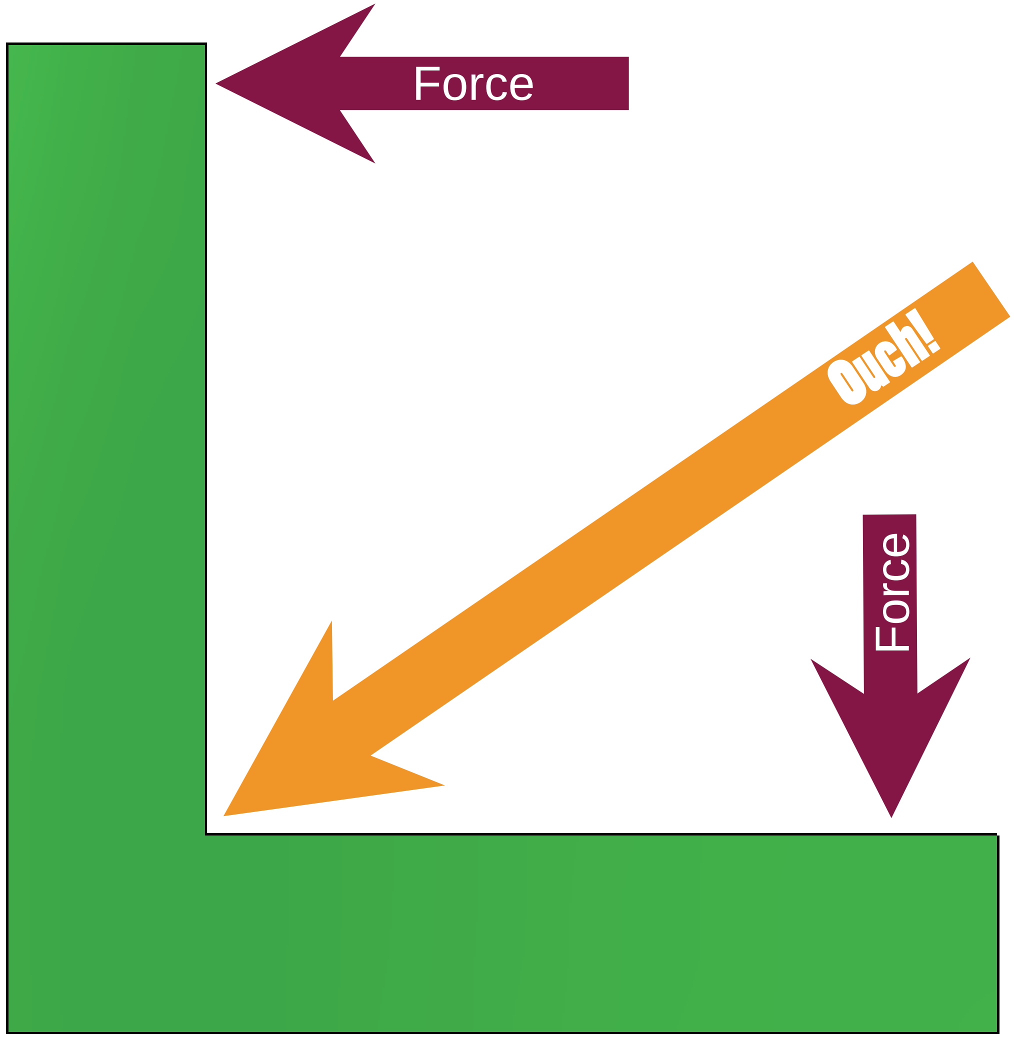
vonMises vs. Degree of Freedom



Flat Plate: vonMises (MPa) vs DOF

Mesh	vonMises	DOF
Coarse	326	7,902
Default	340	46,581
Fine	349	280,218
Default w/ mesh ctrl.	352	52,197
¼ Symmetry Shell	**347**	**1,531**

Singularity: Reentrant Corner



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Consider Singularity: L-Bracket (MPa)

Study	Sharp Corner	Radius Corner
• Mesh Control 1	76	101
• Mesh Control 2	92	101
• Mesh Control 3	194	101
• Adaptive Mesh	-	115

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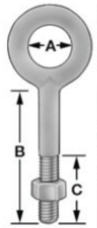
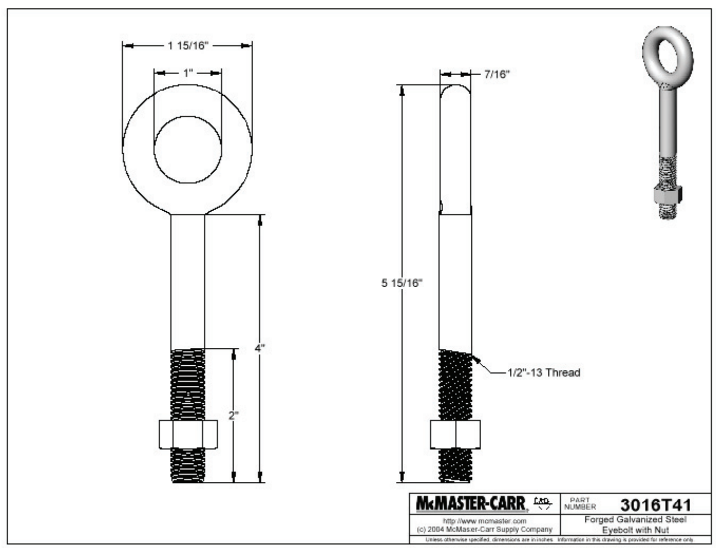
McMaster-Carr

Eyebolts and Eye Nuts



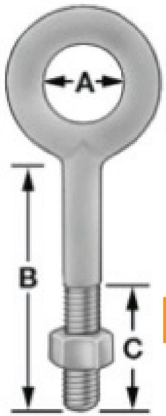
Part Number: **3016T41** $6.86 Each

Type	Eyebolts with Nuts
Shoulder Type	Without Shoulder
Thread Type	Partially Threaded
Material Type	Steel
Finish	Galvanized
Steel Type	Plain Steel
Thread Size	1/2"-13
Work Load Limit	2,100 lbs.
Dimension A	1"
Dimension B	4"
Dimension C	2"
Specifications Met	Not Rated
Furnished With	One hex nut.
WARNING	Do not exceed work load limits for this item. Any eyebolt that has been modified from its original design will have a reduced work load limit and should be discarded.



Work Load Limit Given

Eyebolts and Eye Nuts



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WARNING	Do not exceed work load limits for this item. Any eyebolt that has been modified from its original design will have a reduced work load limit and should be discarded.

Simplify Geometry

Suppress nut & thread

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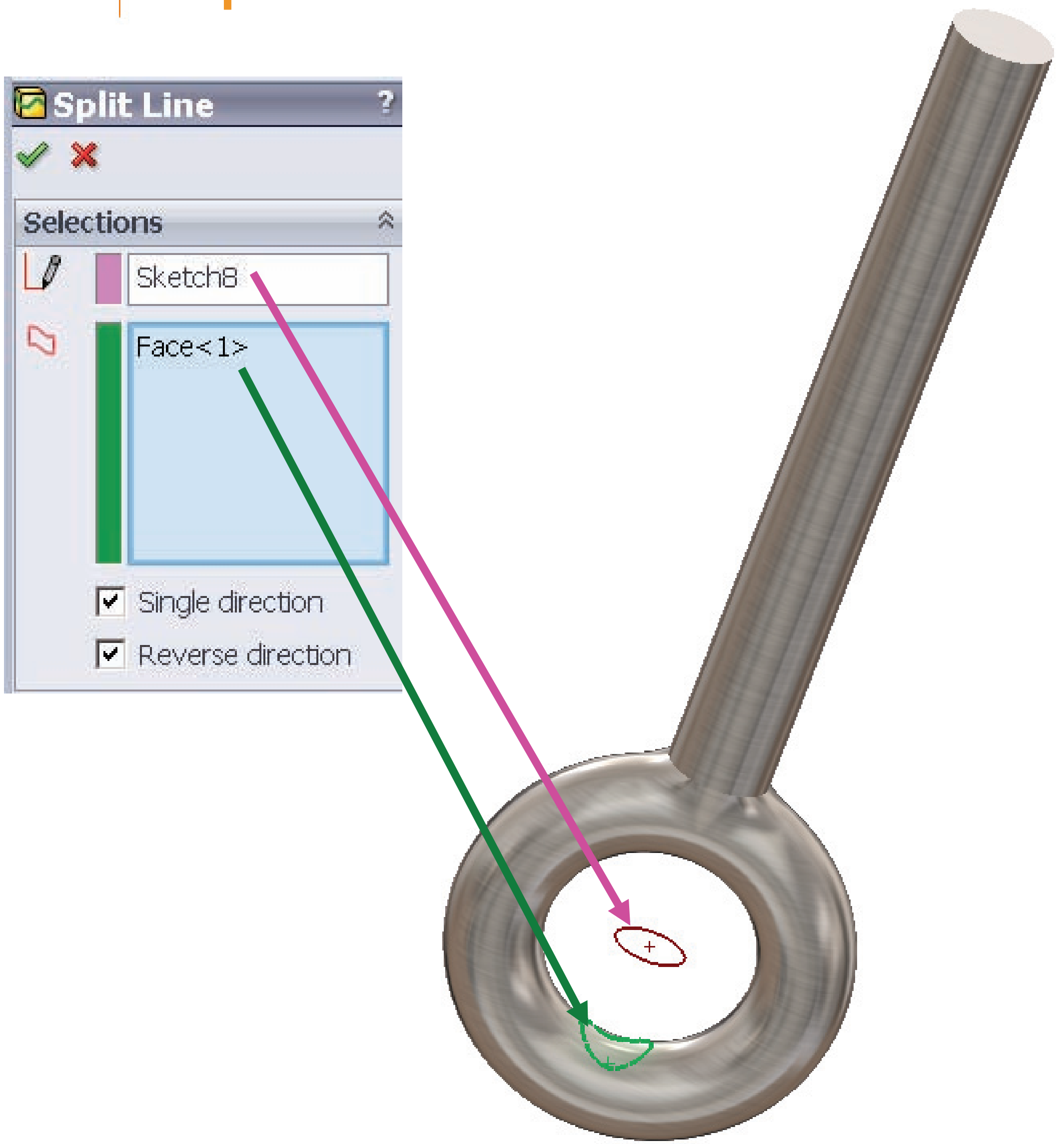
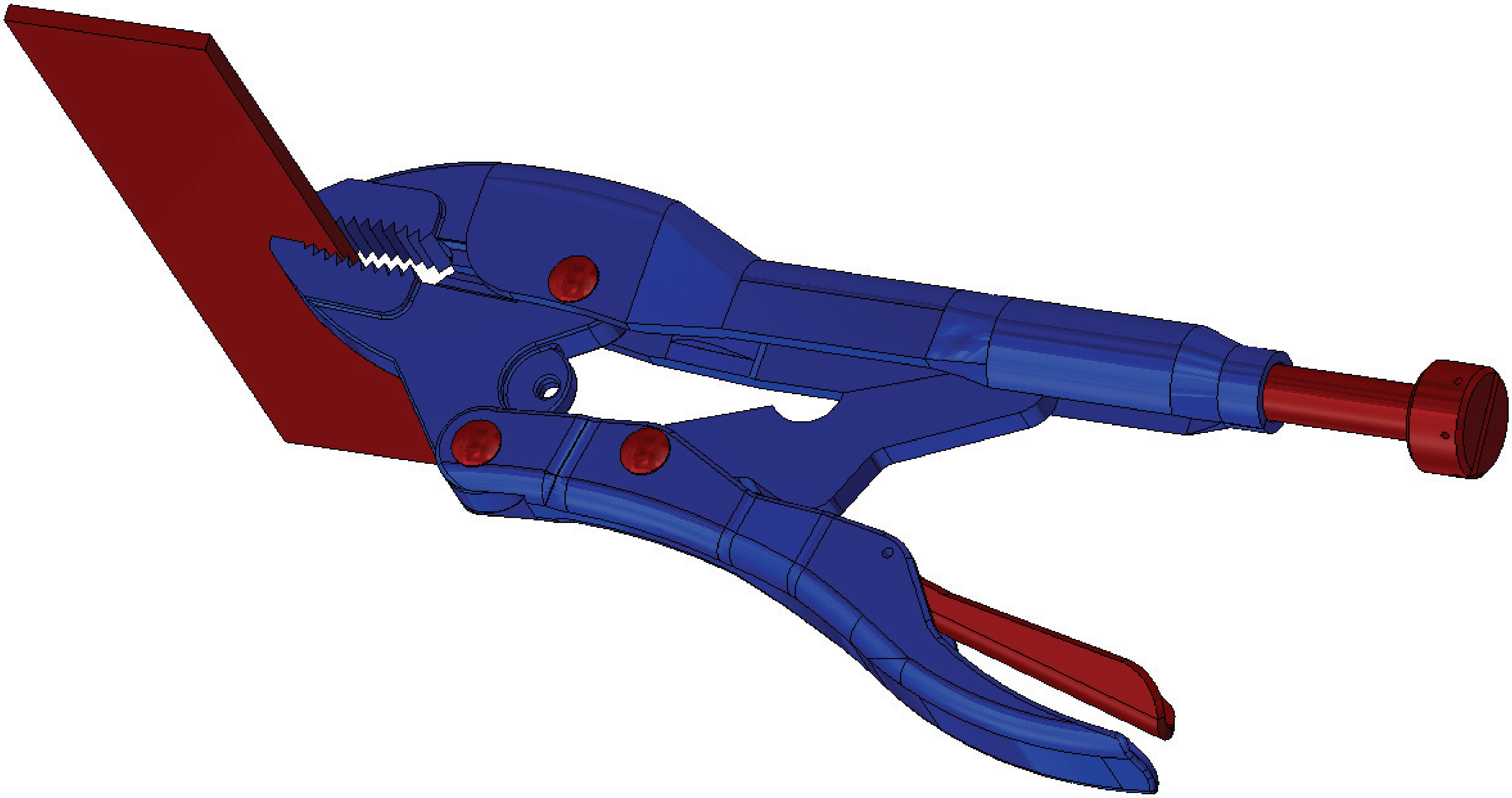
Split Line

Insert > Curve > Split Line



Assembly Analysis



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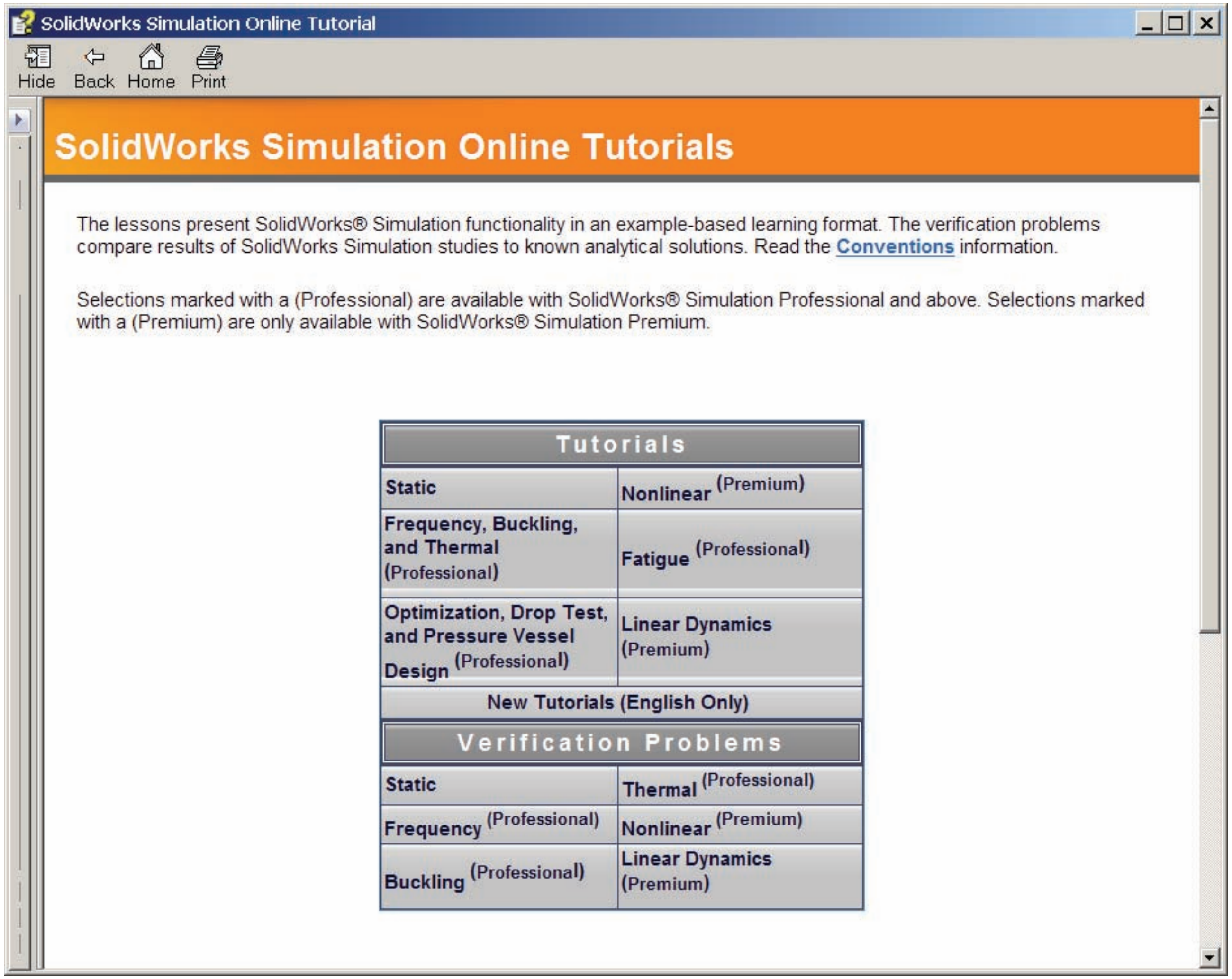
SolidWorks Tutorials



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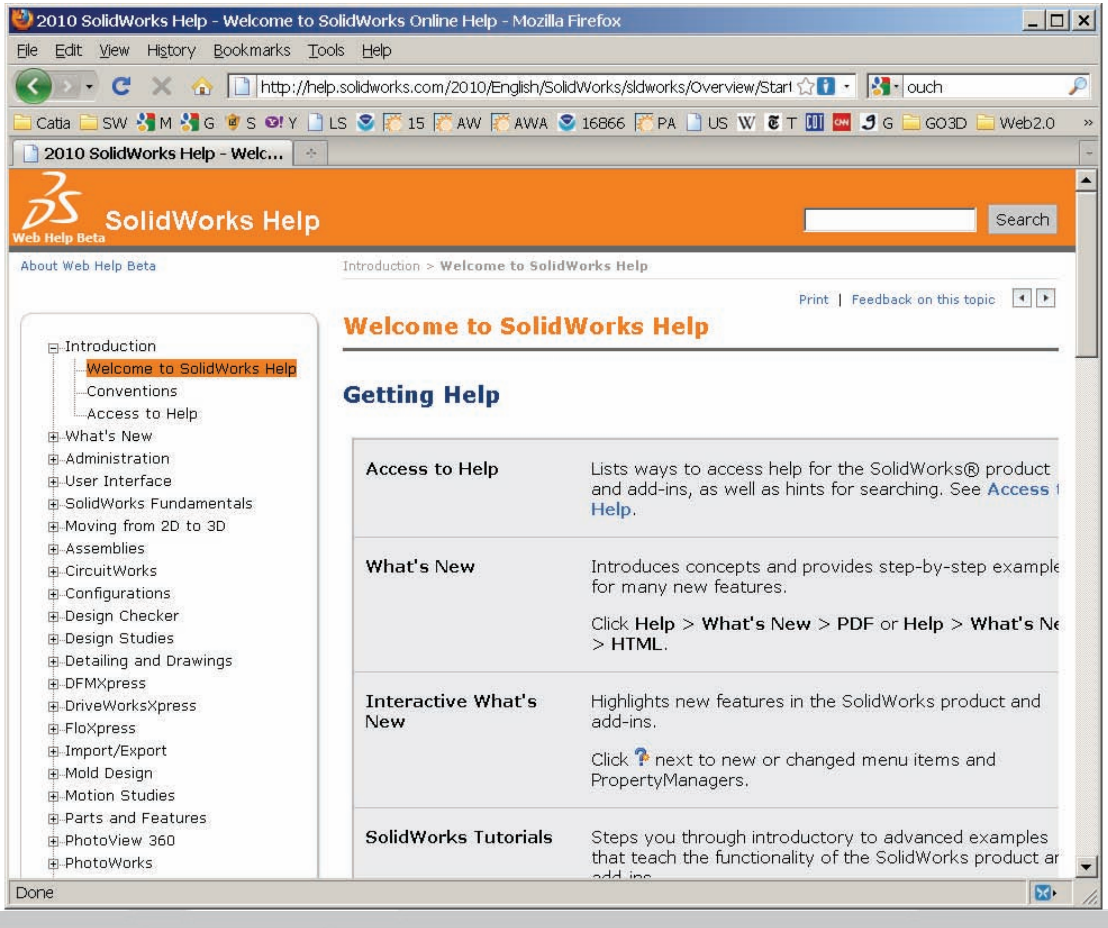
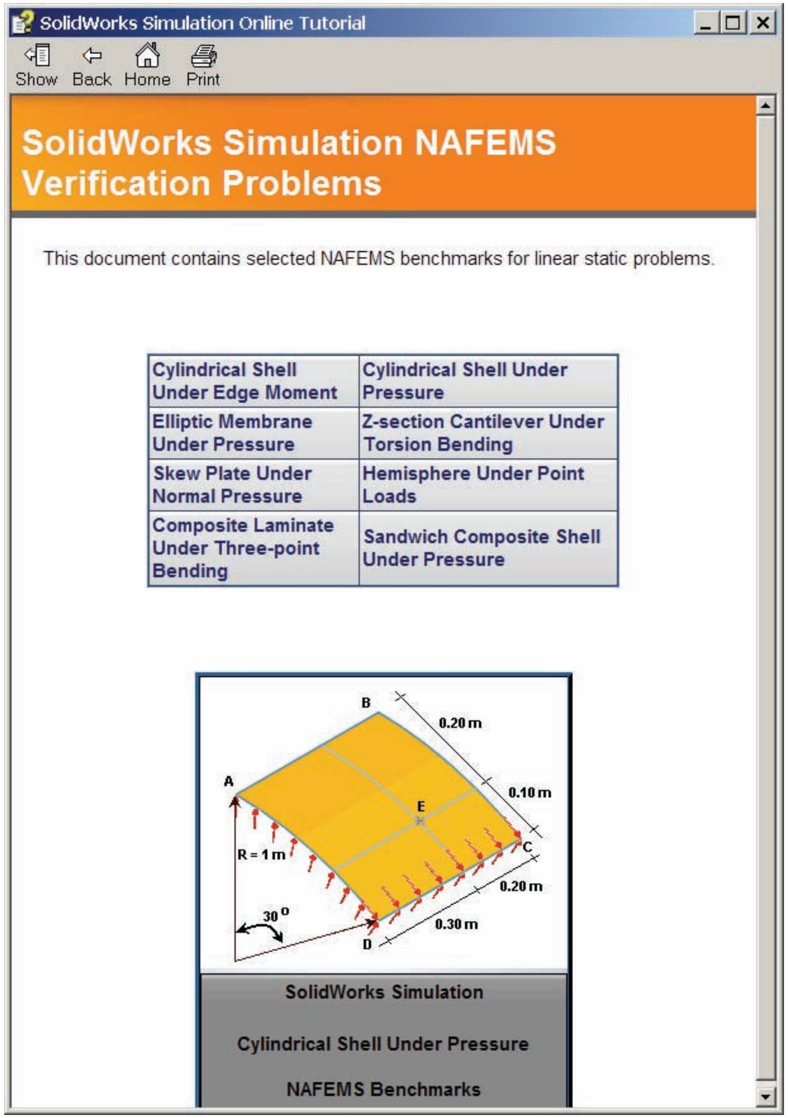
SolidWorks Web Help

- http://help.solidworks.com/2010/English/SolidWorks/sldworks/Overview/StartPage.htm

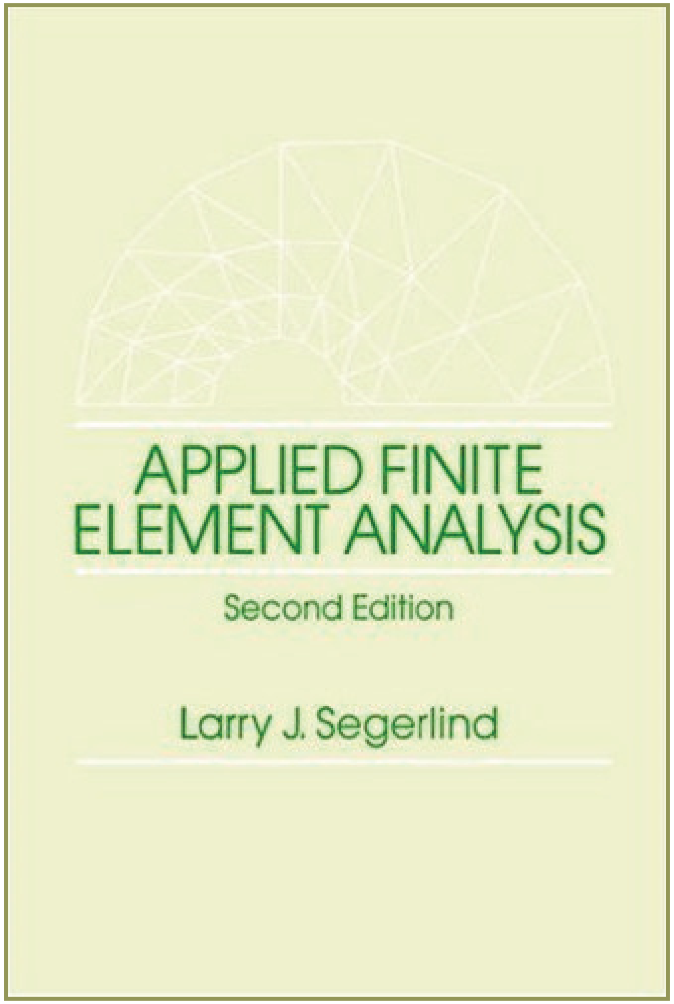


National Agency for Finite Element Methods and Standards

- NAFEMS Benchmarks... Help > SolidWorks Simulation > Validation > NAFEMS Benchmarks.

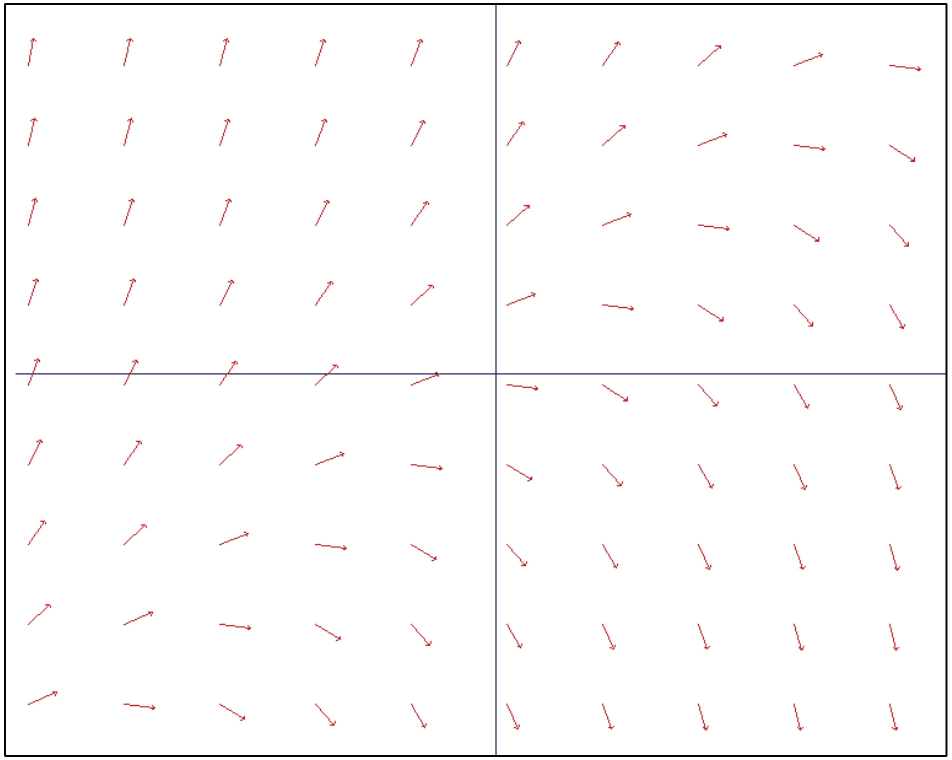


FEA Reference



Make Math Fun w/ Direction Field Plotter

- http://www.math.psu.edu/cao/DFD/Dir.html



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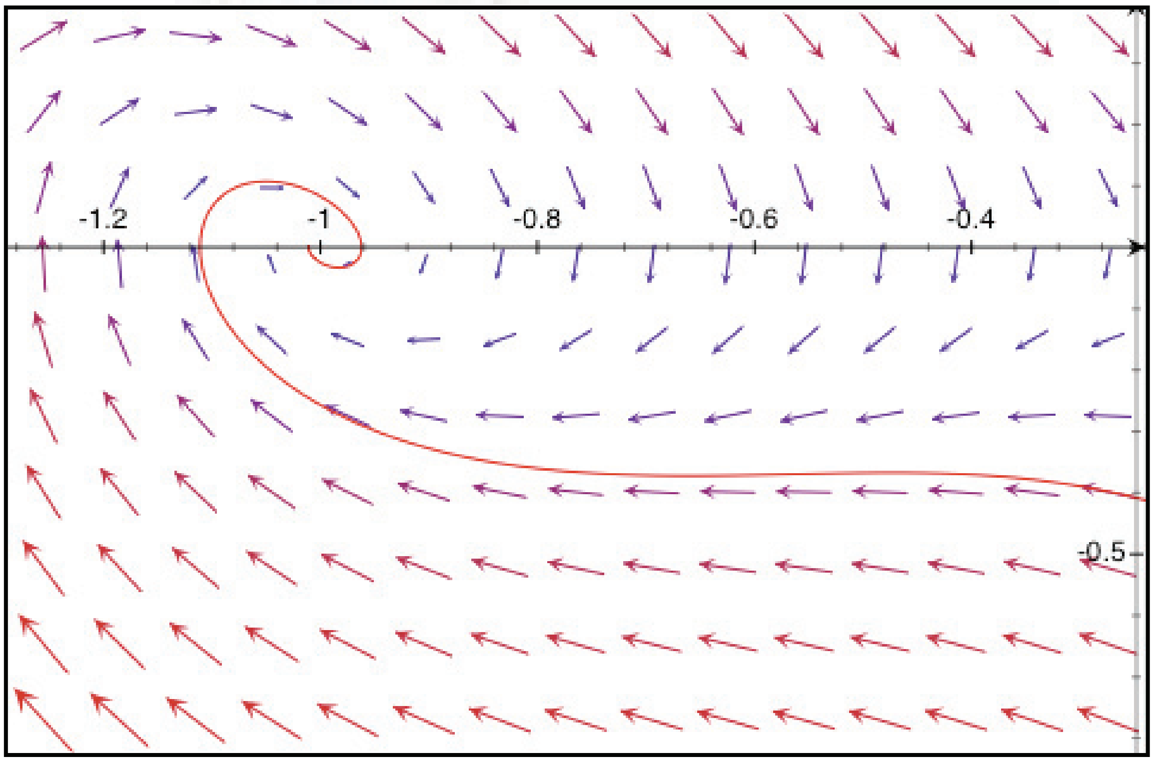
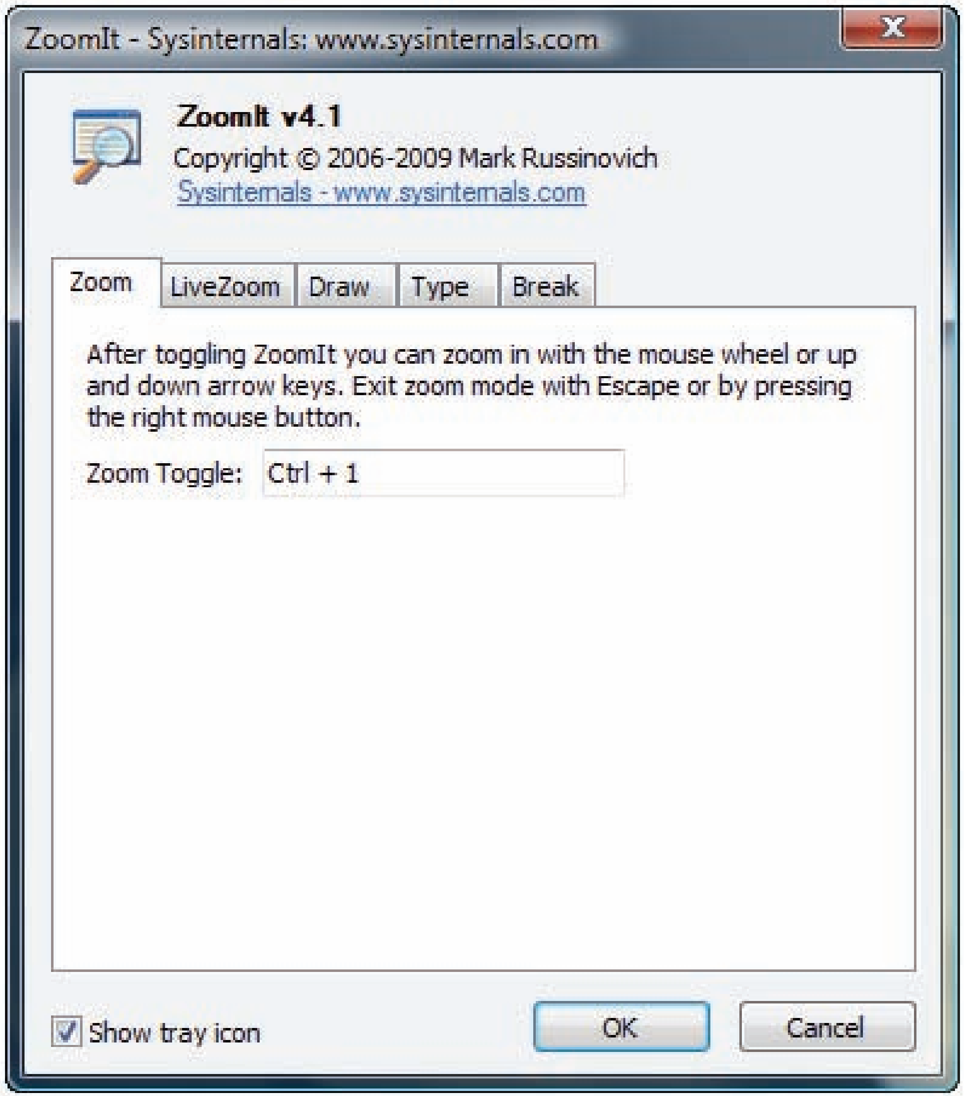
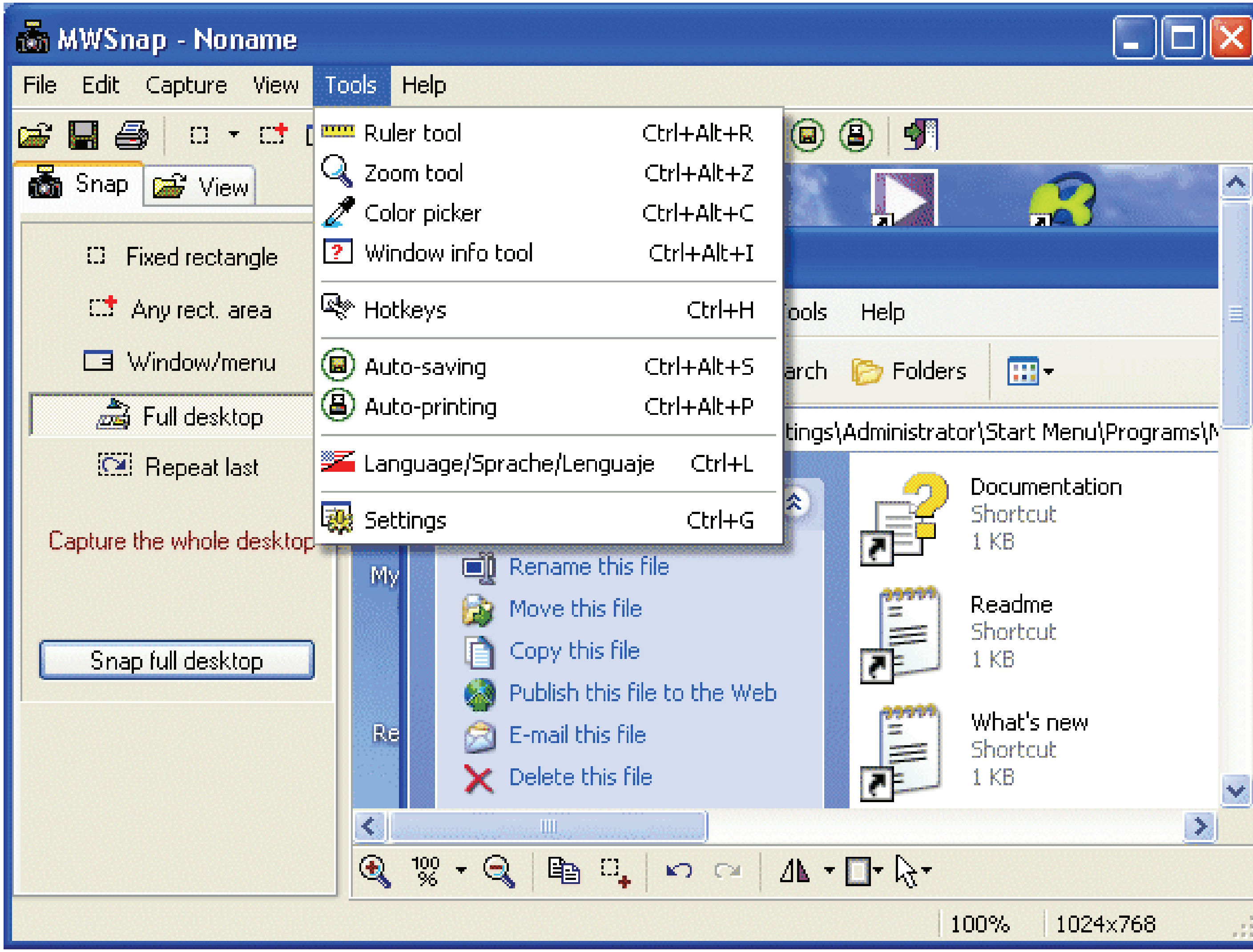
Formula Plotter with Integral Curves



ZoomIt


ZoomIt - Sysinternals: www.sysinternals.com
ZoomIt v4.1
Copyright © 2006-2009 Mark Russinovich
Sysinternals - www.sysinternals.com
Zoom
LiveZoom
Draw
Type
Break
After toggling ZoomIt you can zoom in with the mouse wheel or up and down arrow keys. Exit zoom mode with Escape or by pressing the right mouse button.
Zoom Toggle:
Ctrl + 1
Show tray icon
OK
Cancel

MWSnap


MWSnap - Noname
File
Edit
Capture
View
Tools
Help
Ruler tool Ctrl+Alt+R
Zoom tool Ctrl+Alt+Z
Color picker Ctrl+Alt+C
Window info tool Ctrl+Alt+I
Hotkeys Ctrl+H
Auto-saving Ctrl+Alt+S
Auto-printing Ctrl+Alt+P
Language/Sprache/Lenguaje Ctrl+L
Settings Ctrl+G
Snap
View
Fixed rectangle
Any rect. area
Window/menu
Full desktop
Repeat last
Capture the whole desktop
Snap full desktop
Rename this file
Move this file
Copy this file
Publish this file to the Web
E-mail this file
Delete this file
Documentation
Shortcut
1 KB
Readme
Shortcut
1 KB
What's new
Shortcut
1 KB
Folders
100%
1024x768

This was the Plan

- **SolidWorks Simulation**
  - The Design Cycle
  - Finite Element Method
  - SolidWorks Simulation
  - Defining a Simulation Study
  - Controlling the Mesh
  - Accessing the Results
  - Indentifying Singularities
  - Instructional Examples
  - Tips and Tricks

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Questions