Introduction to Section Analysis and Design of Vehicle Structure Components

- For Crush Strength (Safety) and Stiffness (NVH)

Agenda

1. Technical background and beam theory review.
2. Section design for safety and stiffness (NVH).
3. Using CAE tools Section D – techniques, tips and demo.
4. Q & A.

Background: Why Section Analysis/Design

1) Section reflect the characteristics of body structural components in
   a) Stress (Durability/Fatigue). The major factors: material, size.
   b) Stiffness (NVH). The major factors: size, shape, reinforcements.
   c) Strength (Crash Safety). The major factors: material, size, shape.

2) Master sections are the base for vehicle structural construction.

3) Sections are 2D, which means
   a) Straightforward, simple and quick to analyze, design and modify.
   b) The analysis results are simplified, approximate and best for trend design purposes.

Section Analysis Foundation and Limitation

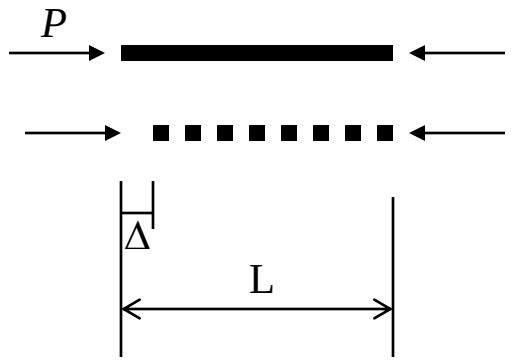
- Section analysis is based on the beam theory therefore, can only be applied to beam-like components – pillars, roof rails and headers, front/rear rails and shotguns…
- Stiffness properties are based on linear beam theory.
- Crush strengths are based on the thin-wall buckling and nonlinear strength-hardening theory with experimental factors.
- Formulae are closed form enabling speedy computation.

Beam Theory – Axial Loading

Axial crush strengths:

$$P_{cr} = \sigma_{cr} A$$

$$P_{\max} = \sigma_{\max} A$$

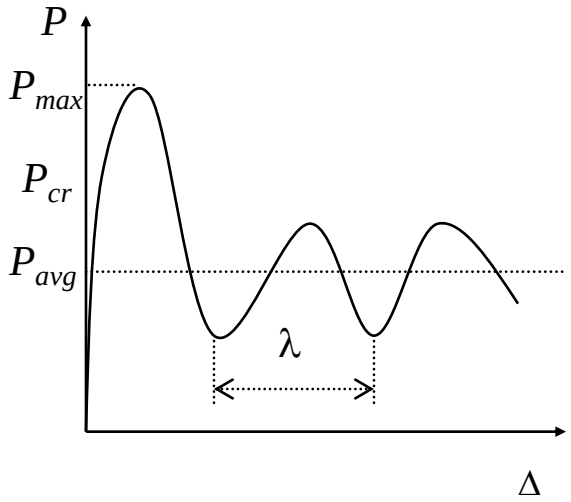


P_{cr} and σ_{cr} are the force and stress at the elastic limit.
P_{max} and σ_{max} are the force and stress at the failure.
A is the section area that represents weight.

Axial deformation:

$$\Delta = \frac{PL}{EA}$$

L is the beam length.
A is the section area that represents axial stiffness.
E is Young's modulus that represents material effect.

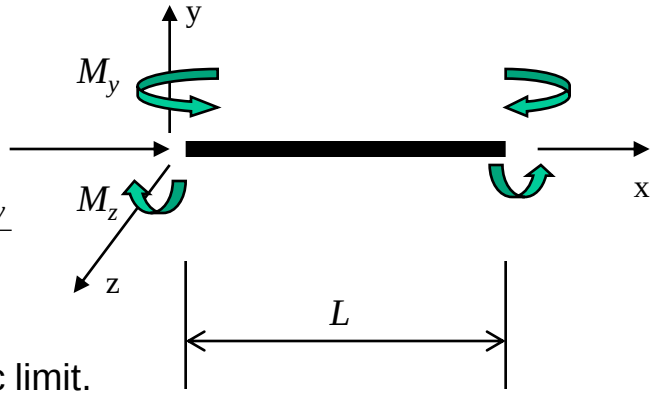


Buckling Force-Displ. Relationship

Beam Theory – Bending

Bending crush strengths:

$$\sigma_{cr} = \frac{M_{cr-y} c_z}{I_y} + \frac{M_{cr-z} c_y}{I_z} \qquad \sigma_{\max} = \frac{M_{\max-y} c_z}{I_y} + \frac{M_{\max-z} c_y}{I_z}$$

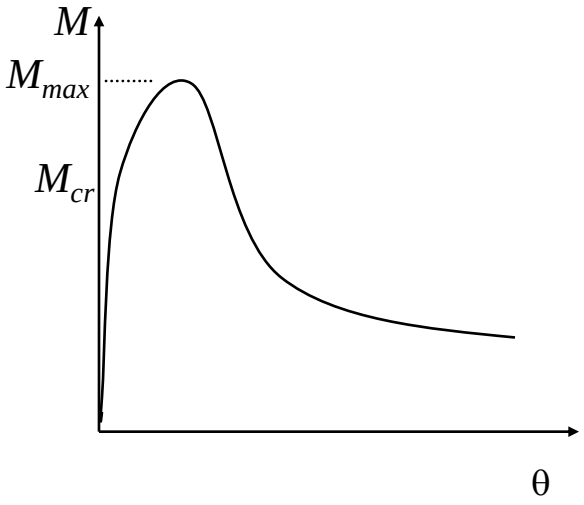


$M_{cr\text{-}y}$ and $M_{cr\text{-}z}$ are bending moments about y and z axes at the elastic limit.
$M_{max\text{-}y}$ and $M_{max\text{-}z}$ are bending moments about y and z axes at the failure.
I_y and I_z are section moment inertia about y and z axes.

Bending deformation:

$$\theta_y = \frac{M_y L}{E I_y} \qquad \theta_z = \frac{M_z L}{E I_z}$$

I_y and I_z represent bending stiffness about y and z axes.



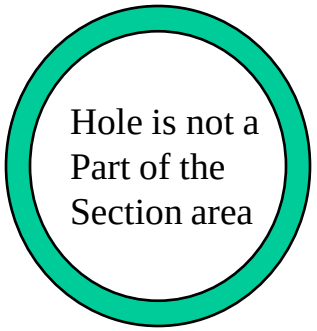
Bending Moment-Rotation Relationship

Geometric Properties - Area

Section area:

$$A = \int_A dA$$

1. Proportional to the axial stiffness.
2. Affects the axial strength (crush load).
3. Represents component self-weight.

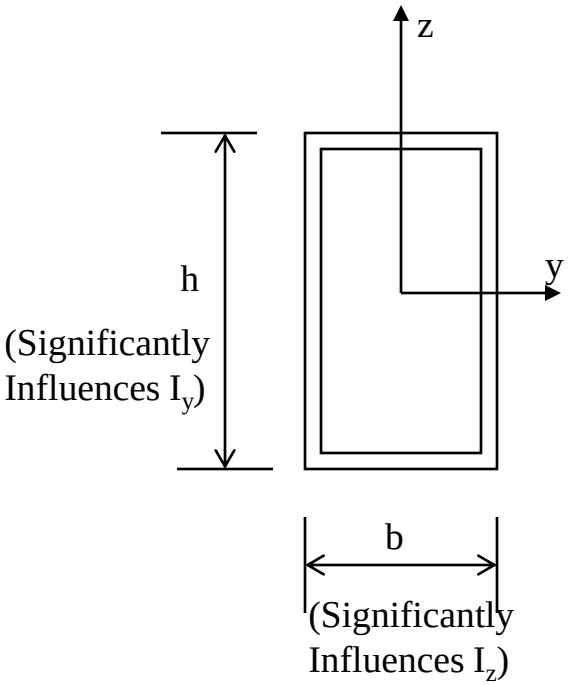


Geometric Properties – Moment Inertia

Bending moments inertia:

$$I_y = \int_A z^2 dA$$

$$I_z = \int_A y^2 dA$$

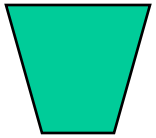


1. Proportional to bending stiffness.
2. Proportional to bending strength.
3. Square relation ship with the section size.

Geometric Properties – Torsion Constant

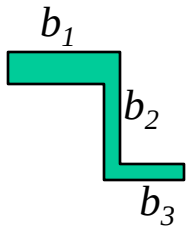
Solid section (ineffective with respective to weight):

$$J = \int_A r^2 dA$$



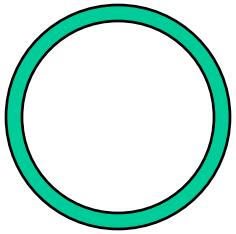
Thin-wall open section (weak torsion rigidity):

$$J = \sum \frac{1}{3} b t^3$$



Thin-wall closed section (strong and effective):

$$J = \frac{4A_m^2}{\oint \frac{ds}{t}}$$



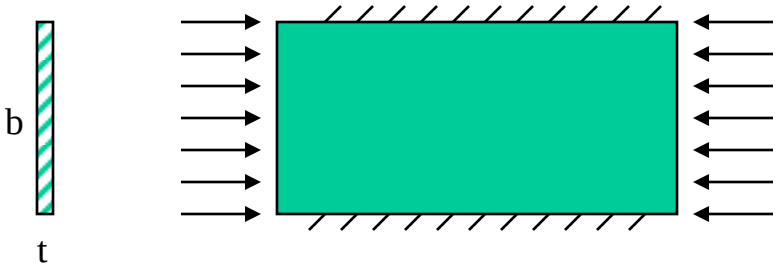
J is sensitive to the hole area A_m

1. Proportional to the torsion stiffness.
2. Proportional to the torsion strength.

Thin-Plate Buckling Stress - Theory

Based on the thin-wall buckling theory, a plate buckles at stress level:

$$\sigma_{cr} = k\frac{\pi E}{2(1+\nu)}\left(\frac{t}{b}\right)^2$$

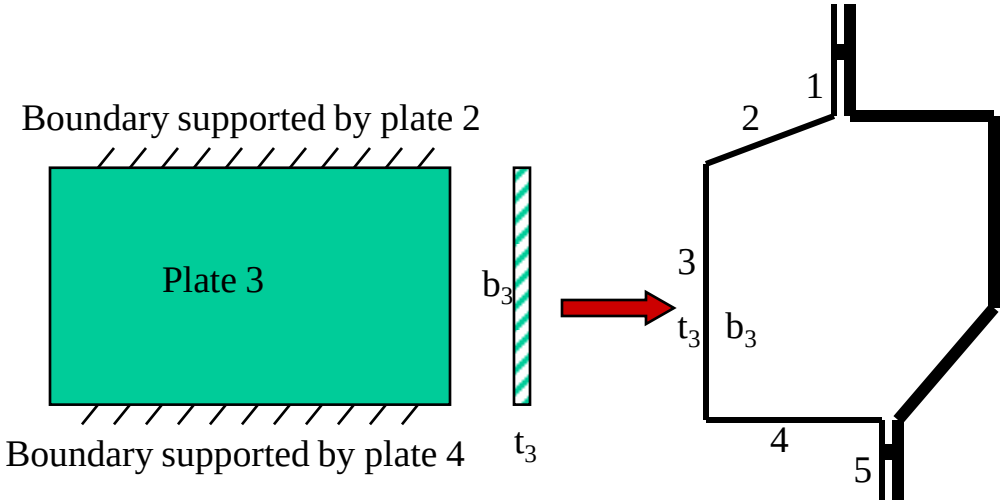


k is the boundary support factor – shape factor
v is poison's ratio, *E* is Young's modulus – material properties
t is thickness, *b* is the width – geometric factors

Section Strength = Buckling Strength of All Plates

-Automotive body components almost always fail in buckling.
-Section can be viewed as a combination of thin-wall plates (segments).

$$\sigma_{cr} = k\frac{\pi E}{2(1+\nu)}\left(\frac{t}{b}\right)^2$$



Crush Property – Axial Strength

Compression – buckling mode dominates

Upper limit: $P_{\max} = \sum_{i=1}^{n} (\sigma_{cr})_i A_i$ -assume all segments reach buckling

Lower limit: $P_{\max} = \sigma_{cr-\min} A$ -weakest segment reaches buckling
-adopted in Section D2.0

where A_i is the area of segment i and A is the total area of the section.

Tension – yielding mode governs

$$P_{\max} = \sigma_y A$$

Crush Property – Bending Strengths

About y axis: $M_{\max-y} = \frac{\sigma_{cr} I_y}{c_z}$ - Compression side buckles

About z axis: $M_{\max-z} = \frac{\sigma_{cr} I_z}{c_y}$ - Compression side buckles

The above equations are based on symmetric sections (I_{yz}=0) and are for demonstration purpose. The equations are more complex for general shape of sections.

Crush Property – Summary

In NVH and durability design look for 5 geometric properties:

A, I_y, I_{yz}, I_z and J

For safety considerations, look for 5 crush strengths:

P_{max}, $M_{max\text{-}y}$, $M_{max\text{-}z}$, and M_{max+y}, M_{max+z}

Section Design and Optimization

Property	Action	Results	Effective Means
A	decrease	light weight	reduce thickness, section size, use high-strength material.
I_y and I_z	increase	high stiffness	increase size; move material far away from center.
J	increase	high stiffness	adopt closed section.
P_{max}	increase	strong crush strength	increase thickness, reduce size, add corners, reinforcements.
M_{max}	increase	strong crush strength	increase thickness and add corners, reinforcements on compression side.

Conflict Between Safety and NVH

NVH Objectives:
Maximize I_y, I_z and J, Minimize A

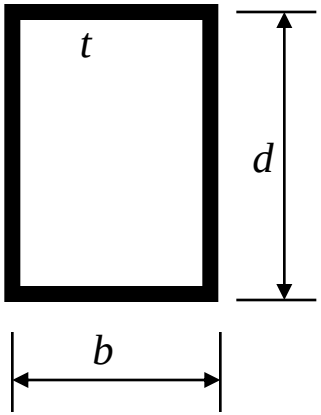
Maximize

Minimize

$$I_y = \int_A z^2 dA$$
$$I_z = \int_A y^2 dA$$
$$A = \sum bt + \sum dt$$

Maximize b and d
Minimize t

Fight



Fight

Minimize b and d
Maximize t

Safety Objectives:
Maximize P_{max}, $M_{max\text{-}y}$ $M_{max\text{-}z}$

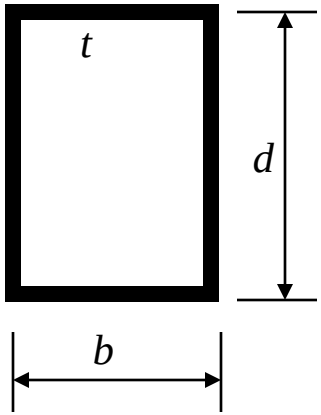
Maximize

Minimize

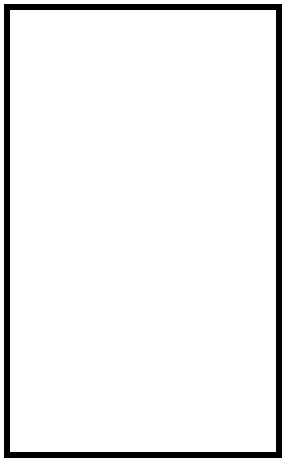
$$\sigma_{cr} = k \frac{\pi E}{2(1+\nu)} \left(\frac{t}{b} \right)^2$$
$$P_{\max} = \sigma_{cr} \left(\sum tb + \sum td \right)$$

Section Design for Both Safety and NVH

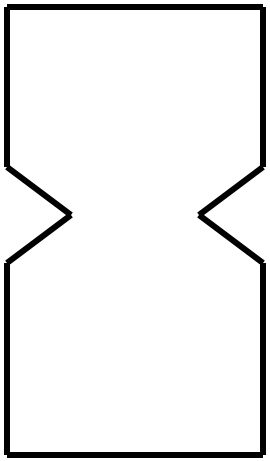
1) Use maximum space allowed for section to maximize stiffness I_y, I_z.
2) Reduce thickness as much as possible to minimize weight A.
3) Add corners on compressed plates to maximize crush strengths P_{max}, M_{max}.
4) Add reinforcements if adding corners can not meet crush requirements.



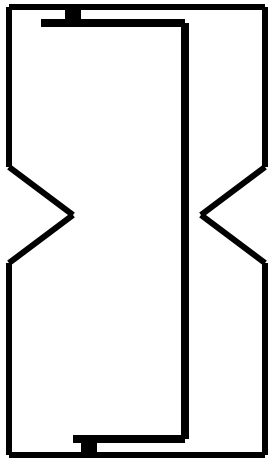
Baseline



NVH consideration: Increase size *b* and *d* with the same area



Safety consideration: Add corners, reduce *b*

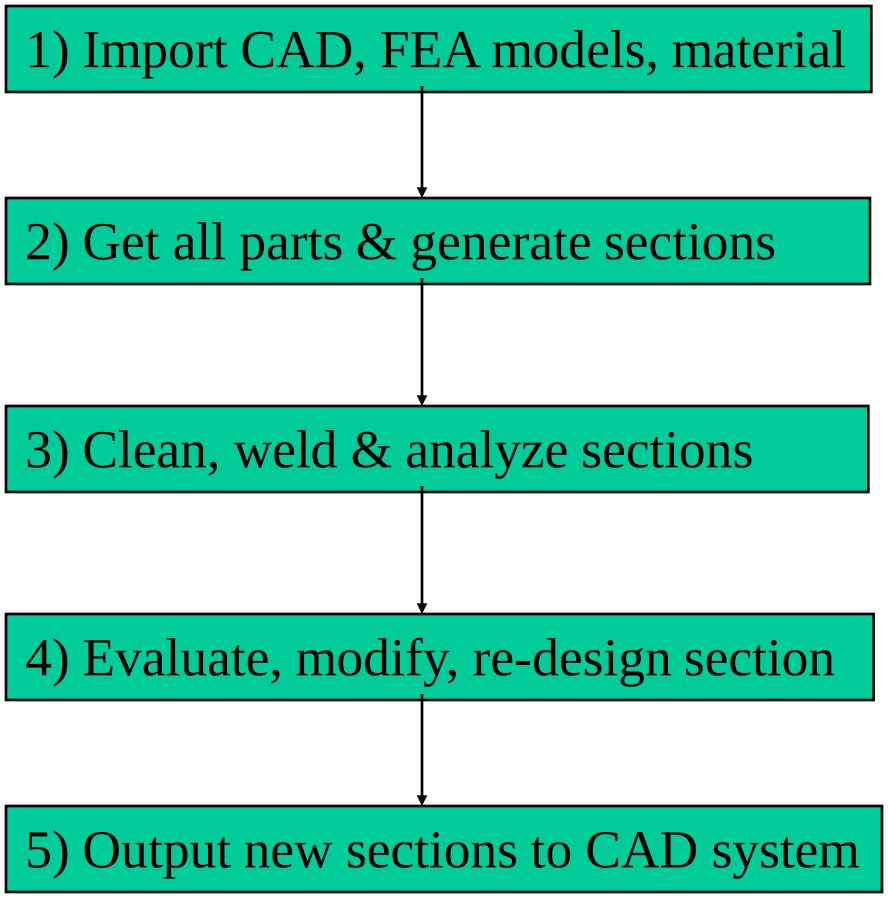


If safety target not met: Add reinforcements

Section D 4.0 Major New Features

1. Compatible with Dyna3D, Radioss (Fix and Block Format) Inputs
   - Large models up to 1 million elements.
2. Section Part Sensitivity/Optimization:
   - Sensitivity to part thickness.
   - Sensitivity to part weight.
   - Part optimization.
3. Section Analysis Under Combined Loads:
   - Stress at any load combination.
   - Buckling & ultimate levels.
   - Failure segment prediction.
4. Baked-in Material Database (Mild, HSLA, DP & Boron steels!)
5. Improved Section Design/Modification Functions:
   - On-screen modifying thickness, material and part ID.
   - Complete tables listing material, part properties & elements.
   - Hypermesh-like view handling (dynamic zoom, rotation…)

Section Design/Analysis – General Process



FEA models: Nastran, Radioss, Ideas.
CAD data: Ideas surface, lines. PDGS lines.

Cut sections: FEA models, CAD lines.
Sketch sections: directly draw, copy-paste.

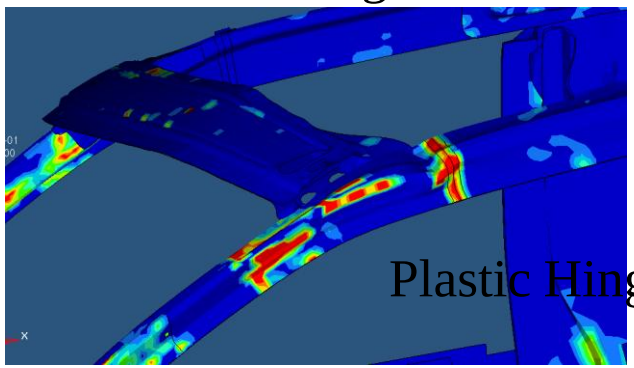
Weld all parts, check material properties.
Get geometric properties I, J, A….
Get crush strengths Pmax, Mmax…

Modify or re-design sections to meet objective.
Means: shape, materials and reinforcement.

Save files in Section D or database formats.
Print section analysis results and new shapes.
Convert, output new sections to CAD system.

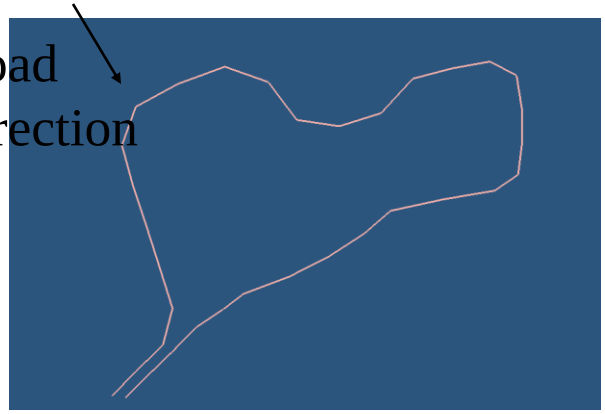
Example-P415 Roof Rail Tube Section Design

Initial CAD section design resulted concentrated plastic hinge, undesirable mode and significantly lower roof strength.

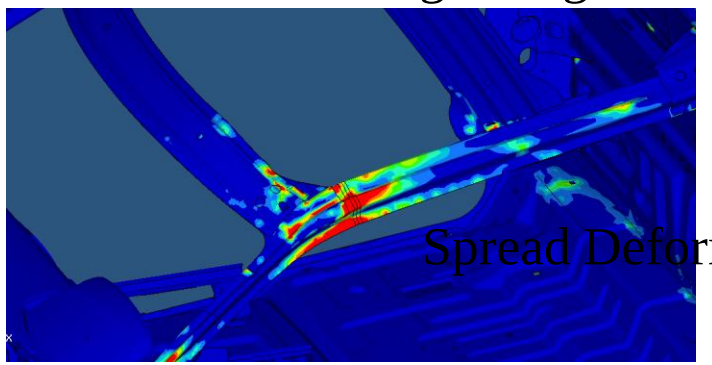


Plastic Hinge

Load direction

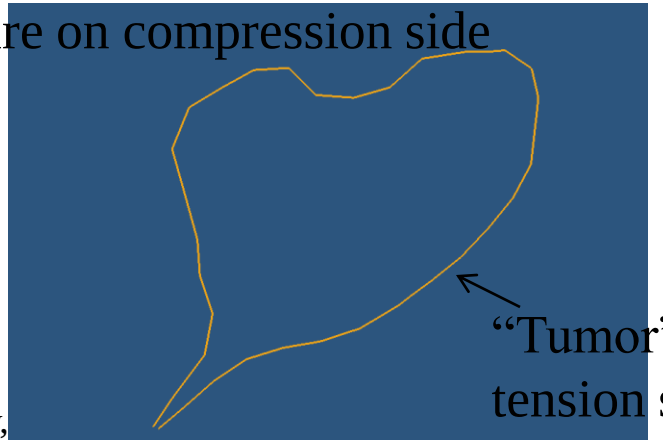


After several iteration of section analysis “tumor is added to increase I value by 20% + in the loading direction and maintain compression feature for buckling strength.



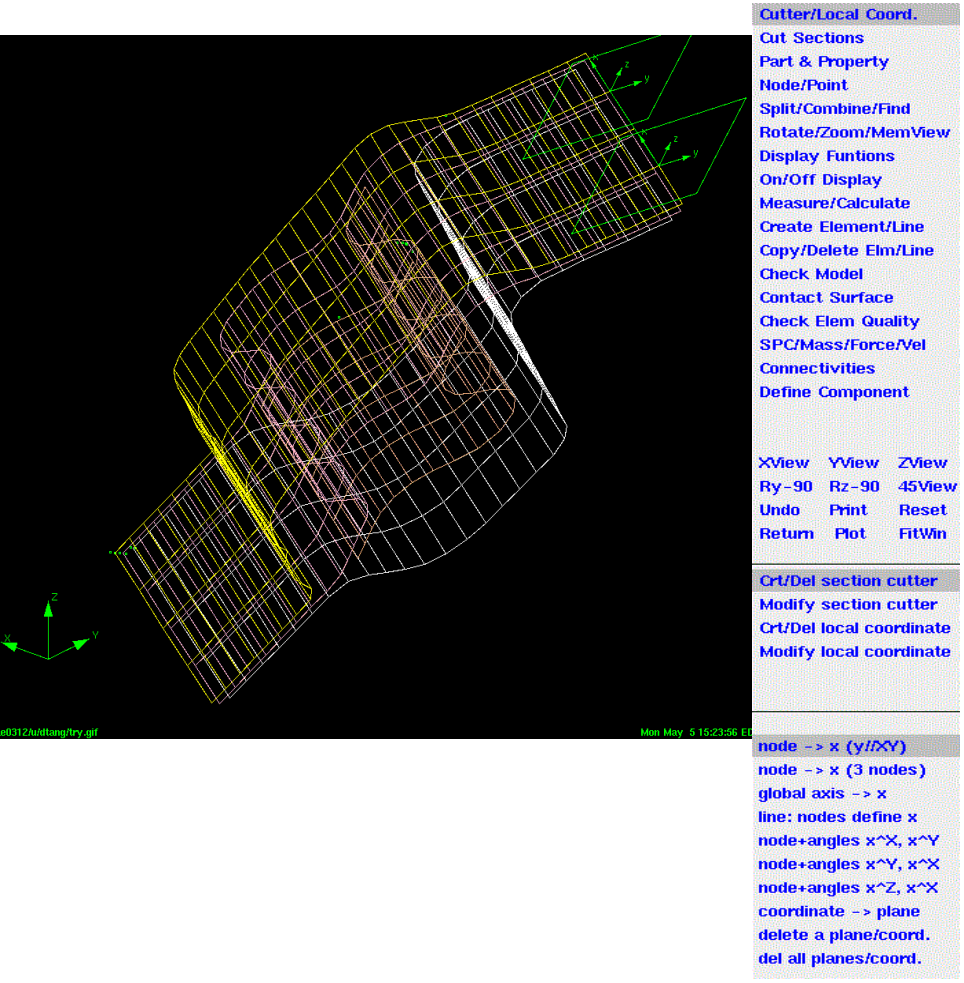
Spread Deformation

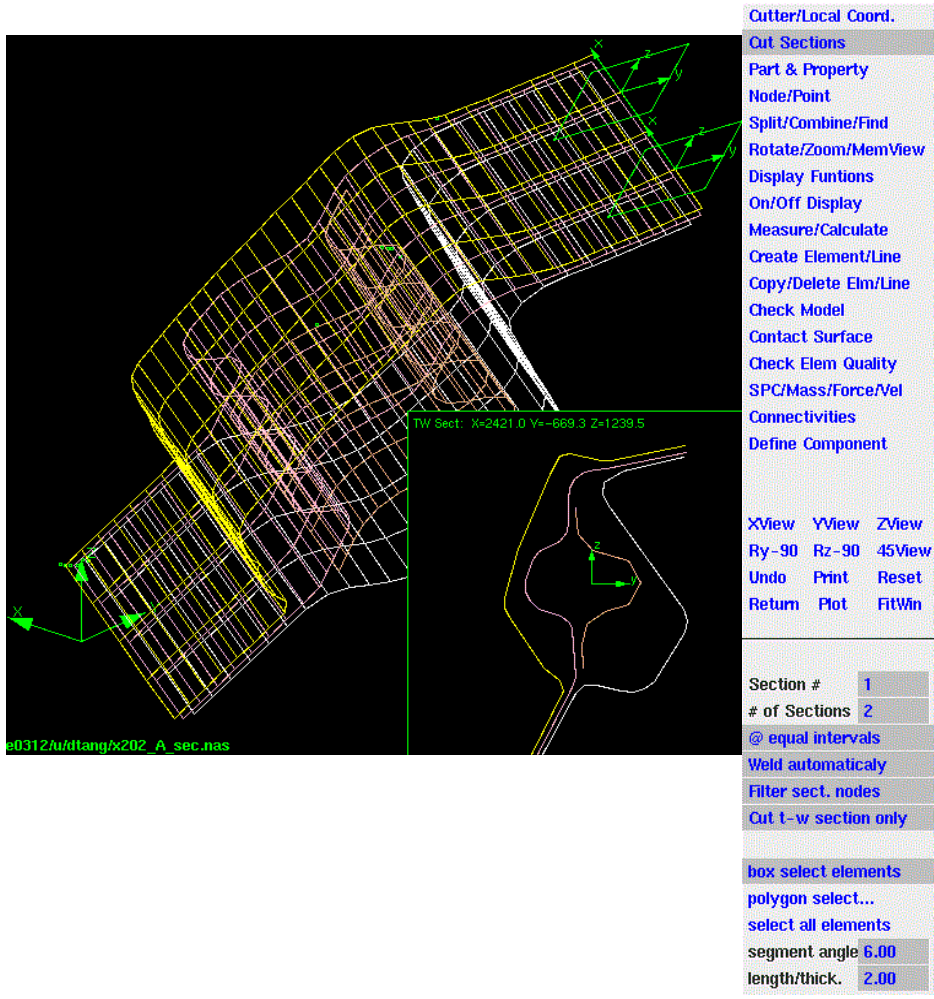
Feature on compression side



“Tumor” on tension side

DEMO


Cutter/Local Coord.
Cut Sections
Part & Property
Node/Point
Split/Combine/Find
Rotate/Zoom/MemView
Display Funtions
On/Off Display
Measure/Calculate
Create Element/Line
Copy/Delete Elm/Line
Check Model
Contact Surface
Check Elem Quality
SPC/Mass/Force/Vel
Connectivities
Define Component
XView YView ZView
Ry-90 Rz-90 45View
Undo Print Reset
Return Plot FitWin
Crt/Del section cutter
Modify section cutter
Crt/Del local coordinate
Modify local coordinate
node -> x (y//XY)
node -> x (3 nodes)
global axis -> x
line: nodes define x
node+angles x^X, x^Y
node+angles x^Y, x^X
node+angles x^Z, x^X
coordinate -> plane
delete a plane/coord.
del all planes/coord.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Cutter/Local Coord.
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Contact Surface
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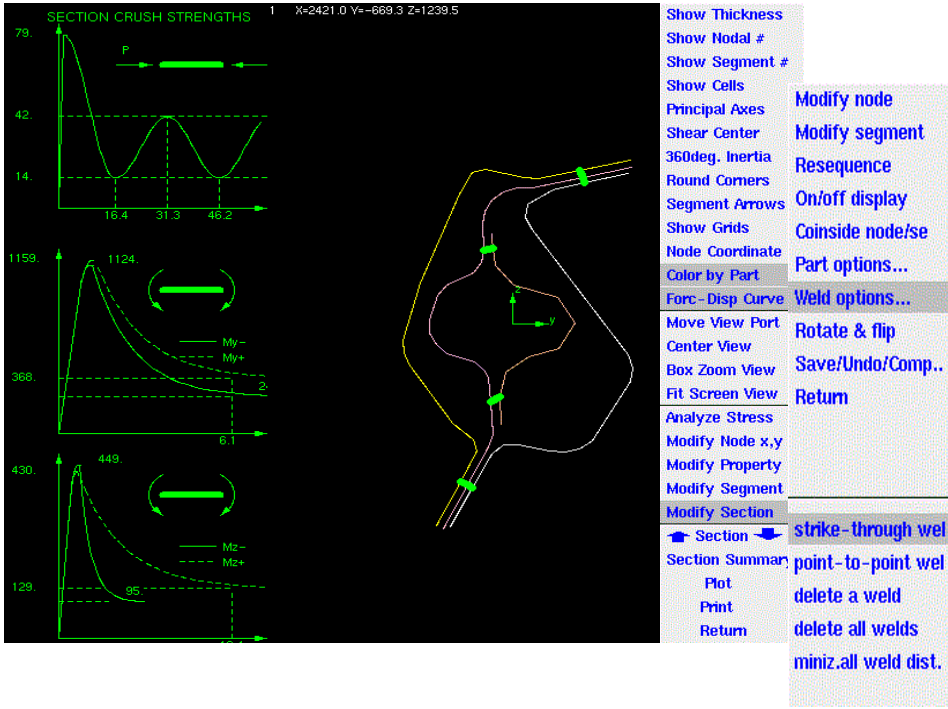
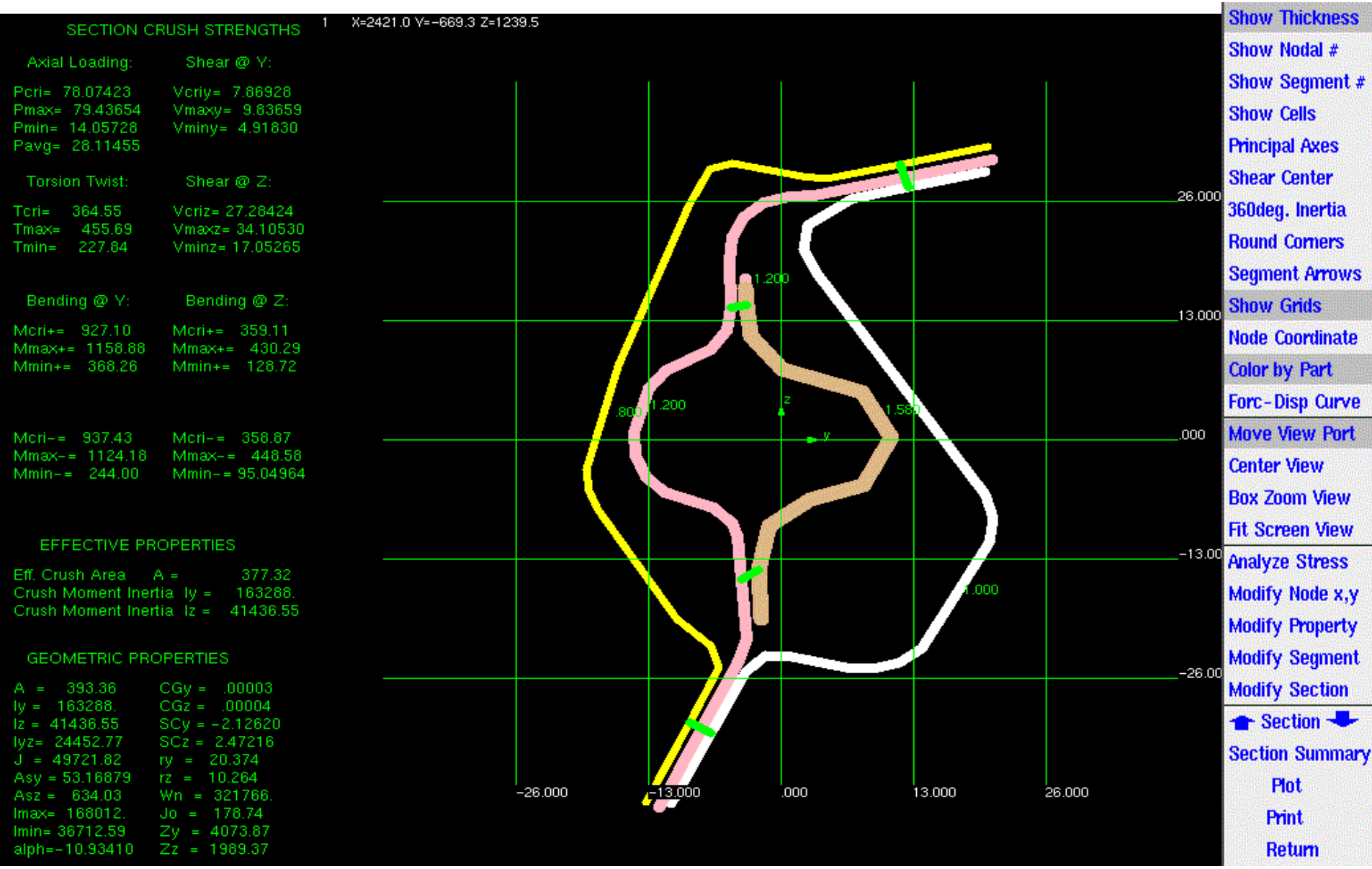
SPC/Mass/Force/Vel
Connectivities
Define Component
XView YView ZView
Ry-90 Rz-90 45View
Undo Print Reset
Return Plot FitWin
Section # 1
# of Sections 2
@ equal intervals
Weld automaticaly
Filter sect. nodes
Cut t-w section only
box select elements
polygon select...
select all elements
segment angle 6.00
length/thick. 2.00

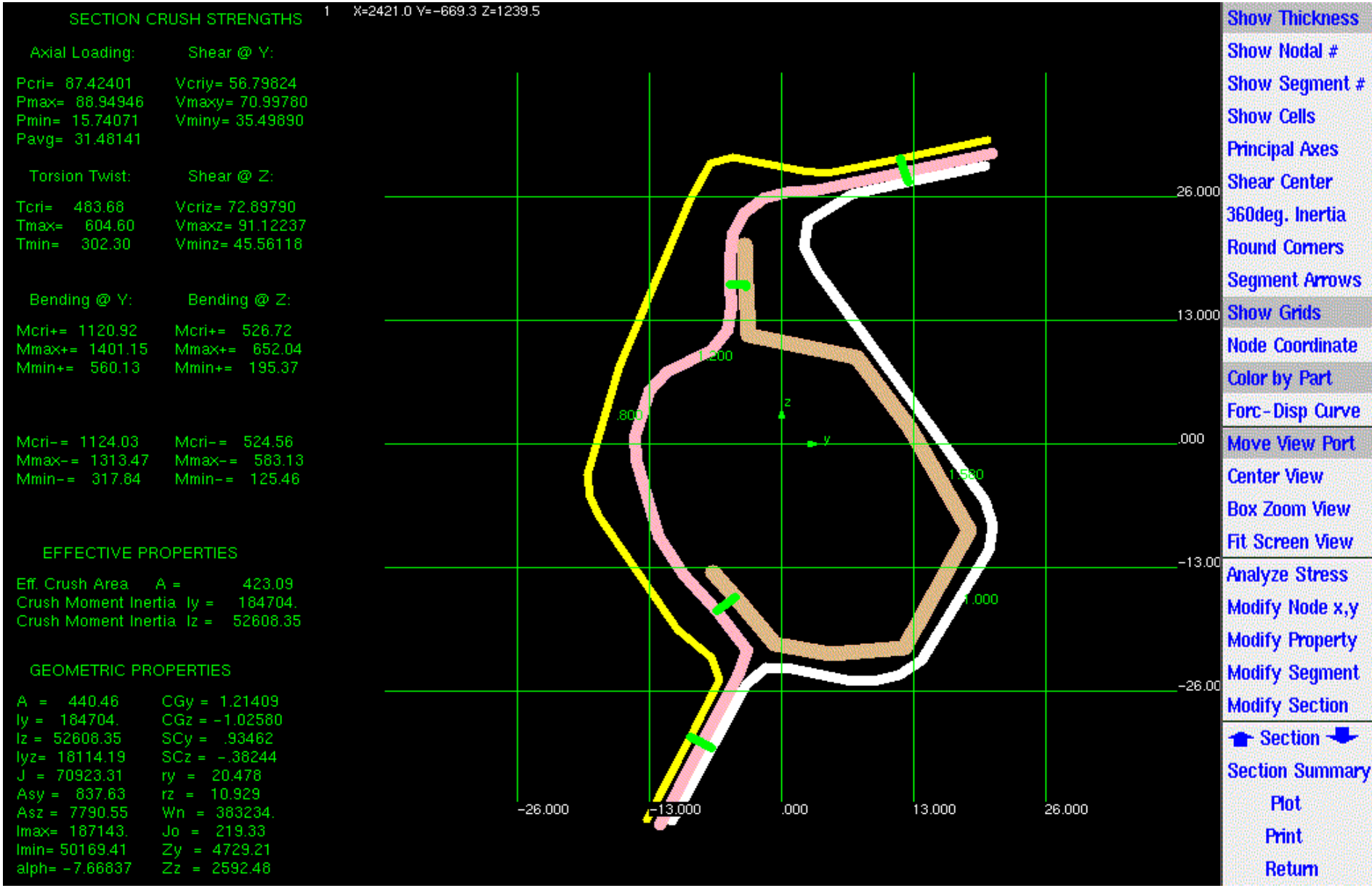
Section Analysis – Clean, Weld Parts



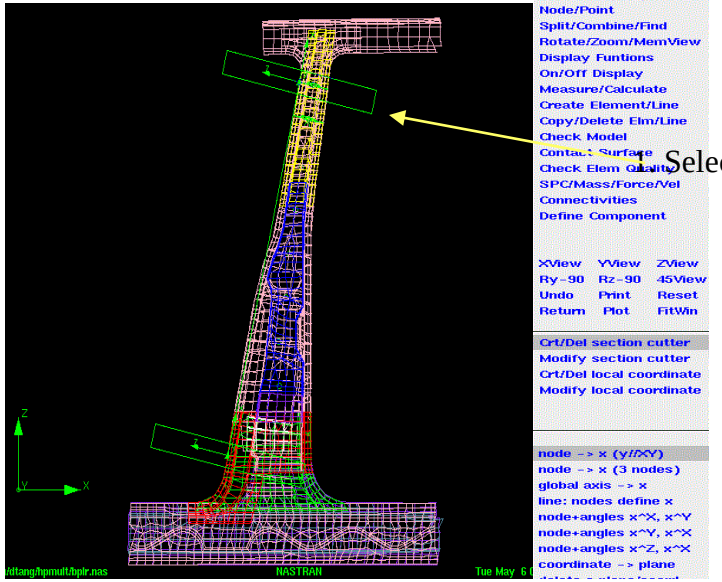
Section Analysis – Read and Print Results



Modification – Shape, Material/Thickness, Reinforcement

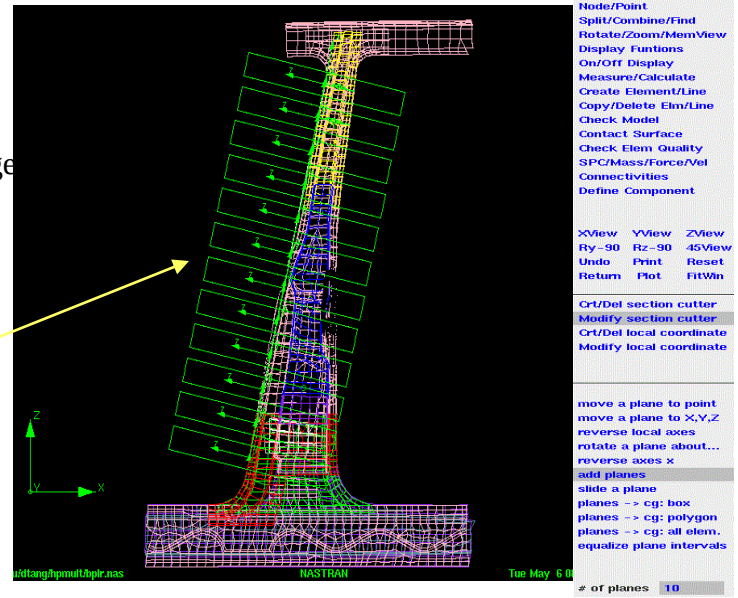


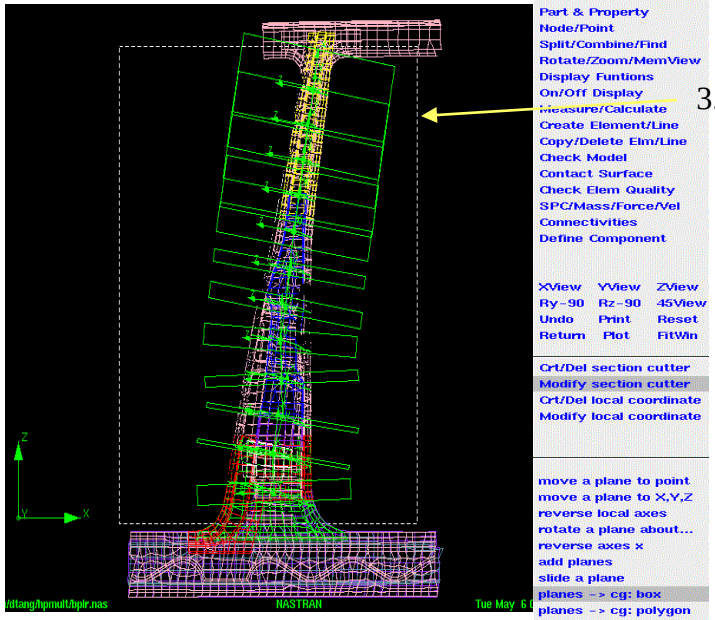
Cutting Sections – Multiple Cutting Planes



1. Select 2 points to specify range

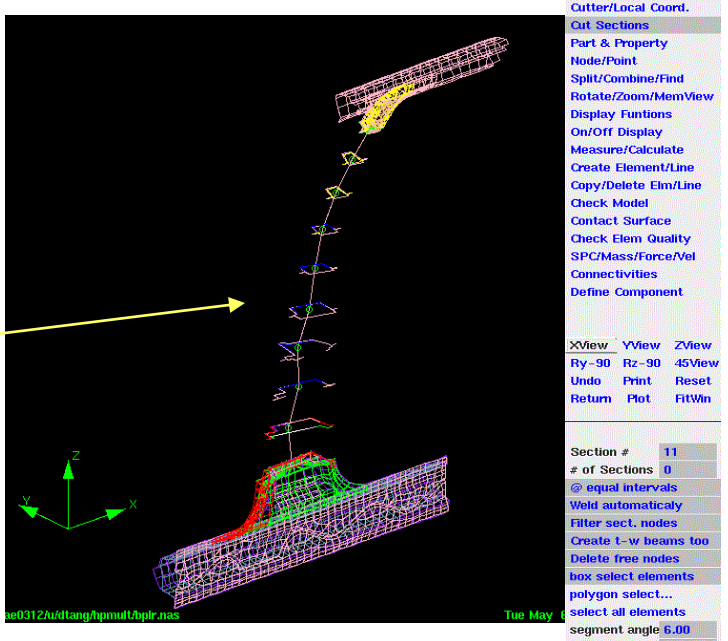
2. Add planes



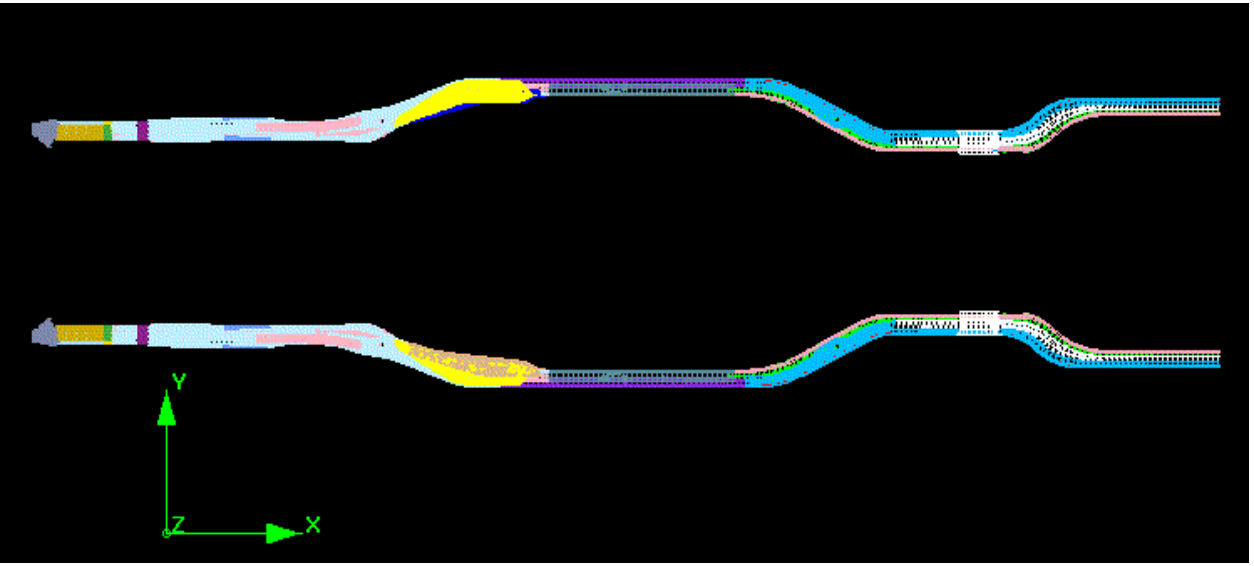


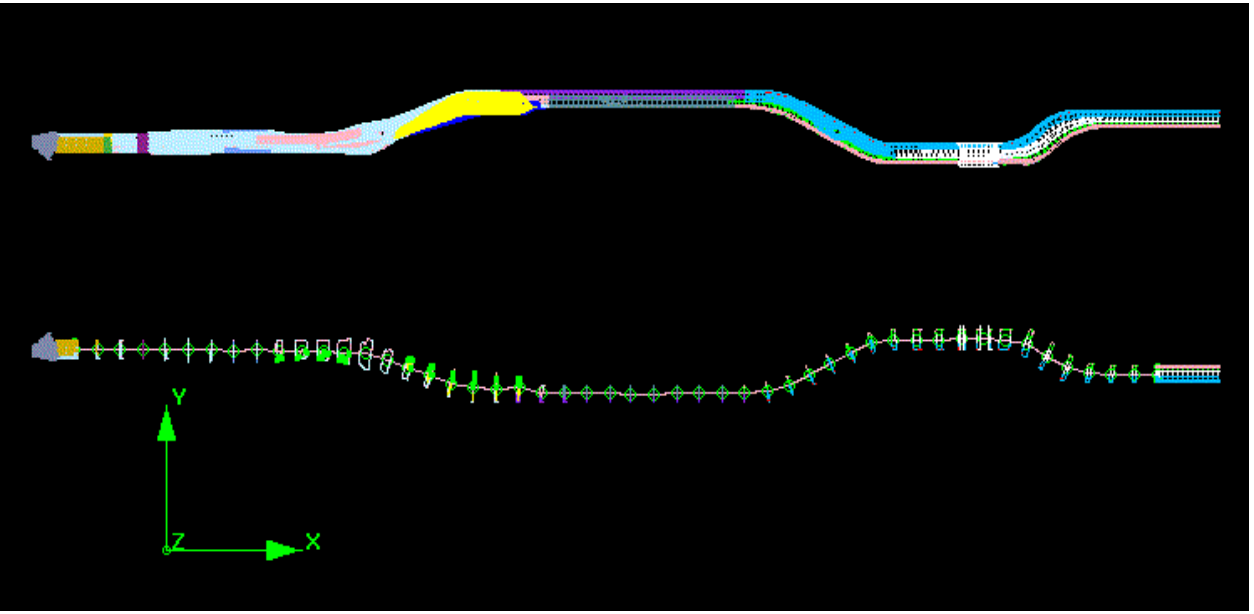
3. Move planes to CG

4. Cut sections



Component Analysis- Cut Section & Create Beams





Cutter/Local Coord.
Cut Sections
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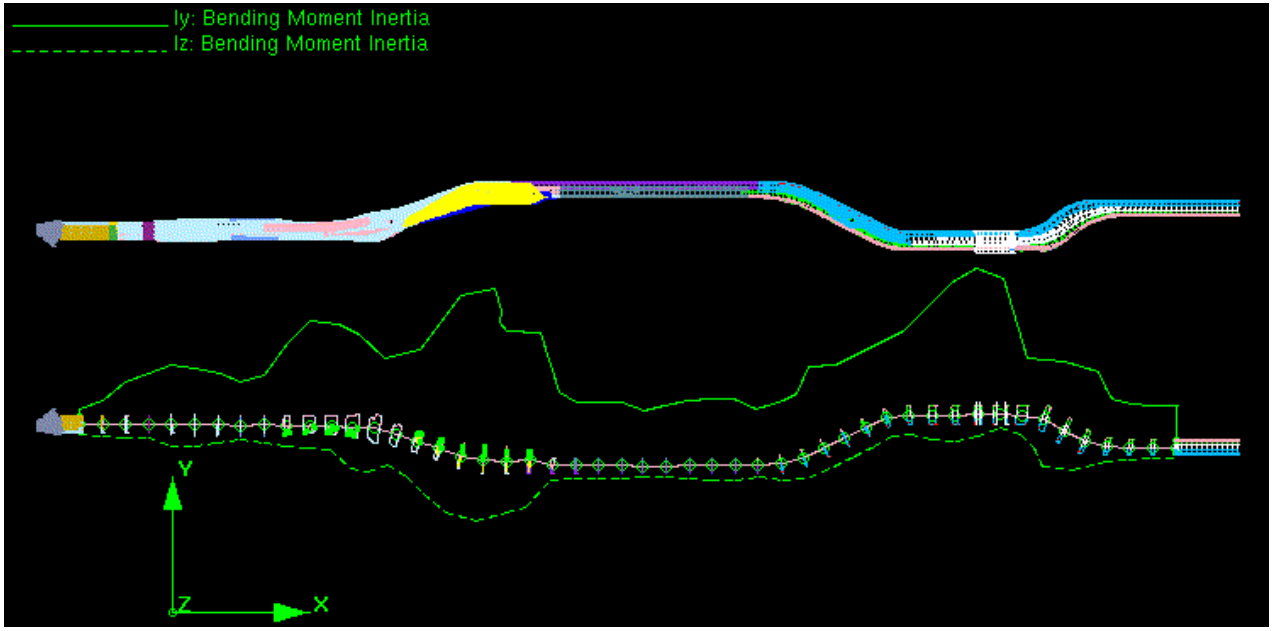
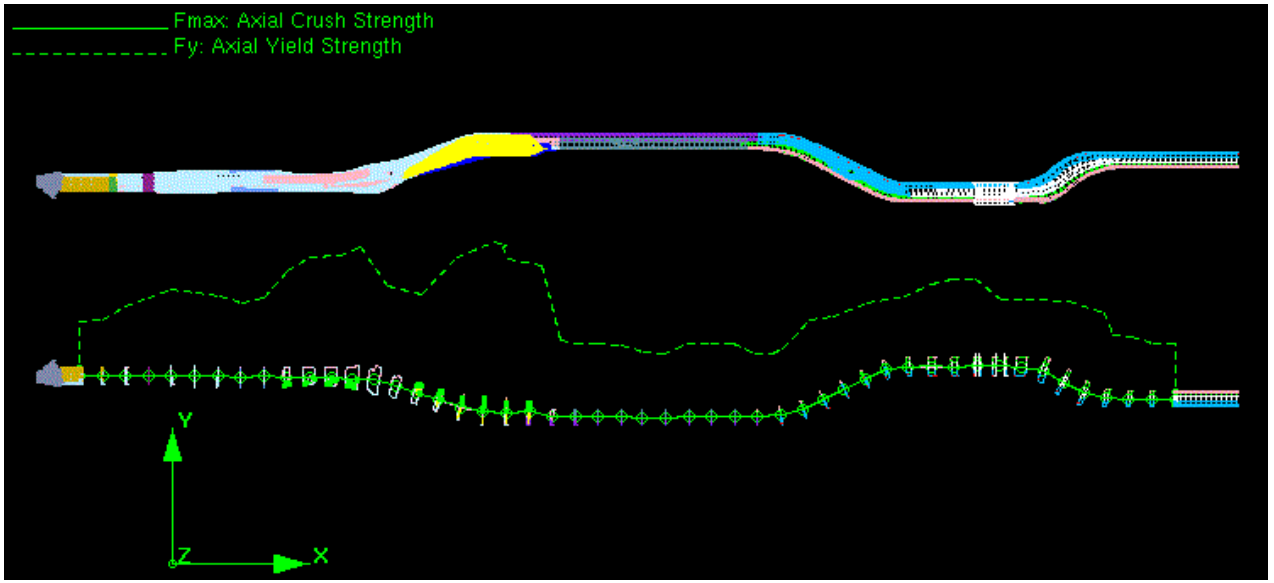
Check Elem Quality
SPC/Mass/Force/Vel
Connectivities
Define Component

XView YView ZView
Ry-90 Rz-90 45View
Undo Print Reset
Return Plot FitWin

Component Analysis- Display Component Performance





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XView YView ZView
Ry-90 Rz-90 45View
Undo Print Reset
Return Plot FitWin

Display modes
Options
Fonts
Misc. items
Display #s
Colors

contact interfaces
rigid wall
failure sequence
moment inertia diagrm
Pmax axial diagram
My bending diagram
Mz bending diagram
section/TWbeam cutter
part border
mesh border
spring/bar/beam end
bar-quad common node
title, file & date

When Section Analysis Adds Values….

1. New program - When design targets are set, sketch or modify a similar section to meet the requirements
2. Quick assessment for a design change – Find the implications for crush strength.
3. Design a reinforcement to meet an increased target or as a remdy for strength gap.
4. Use of high-strength or light-weight materials – Find the equivalent section size, thickness or shape to deliver the same performance.
5. Assess the load path – Use the component profile to make sure the desired strength distribution along the component (rail, pillar…).
6. ……

Section D User Tips

1) If section is open and very stiff and later closed with weak segment using Section D, the overall section strength will be much much smaller than the open section as Section D considers section fails when the weak segment fails. In this case use only open section to compute its strength.

2) Use your judgment in how to use P_{cr}, P_{avg} *or* P_{max} but it is recommended to use P_{avg} in case of side rails where crush is axial and P_{max} when crush is bending such as B pillar.

3) Use rails/pillars etc. without reinforcements when the capacity of structure is needed so that minimum load capacity is measured to be used for path load.

4) Make sure that the correct material and thickness is used when creating new segments in Section D. In this case a new material has to be created in Section D for the new created segments.

5) Section D that is installed now in our server is not the latest version to read Radioss ver. 4.1. It is in process to install the latest version. For now, Modedit can be used to read Radioss file and output Nastran file so that Section D can read it with no material or property lost.

New Developments

1) Component Profile Feature:

- Maximum axial crush strength (Load path design)
- Average crush strength (Energy absorption)
- Bending crush strength (B pillar design for side impact)
- Geometric properties (Bending stiffness, weight…)

2) Combined Axial and Bending loads

- Strength reduction due to offset
- Failure surface

3) Mixed High and Low Strength Materials

  - DP600, DP780, DP980, Martensite, Boron steels
  - Aluminum 5754, 6111…

4) New User Manual 2.0 & Section D Hands on Training.