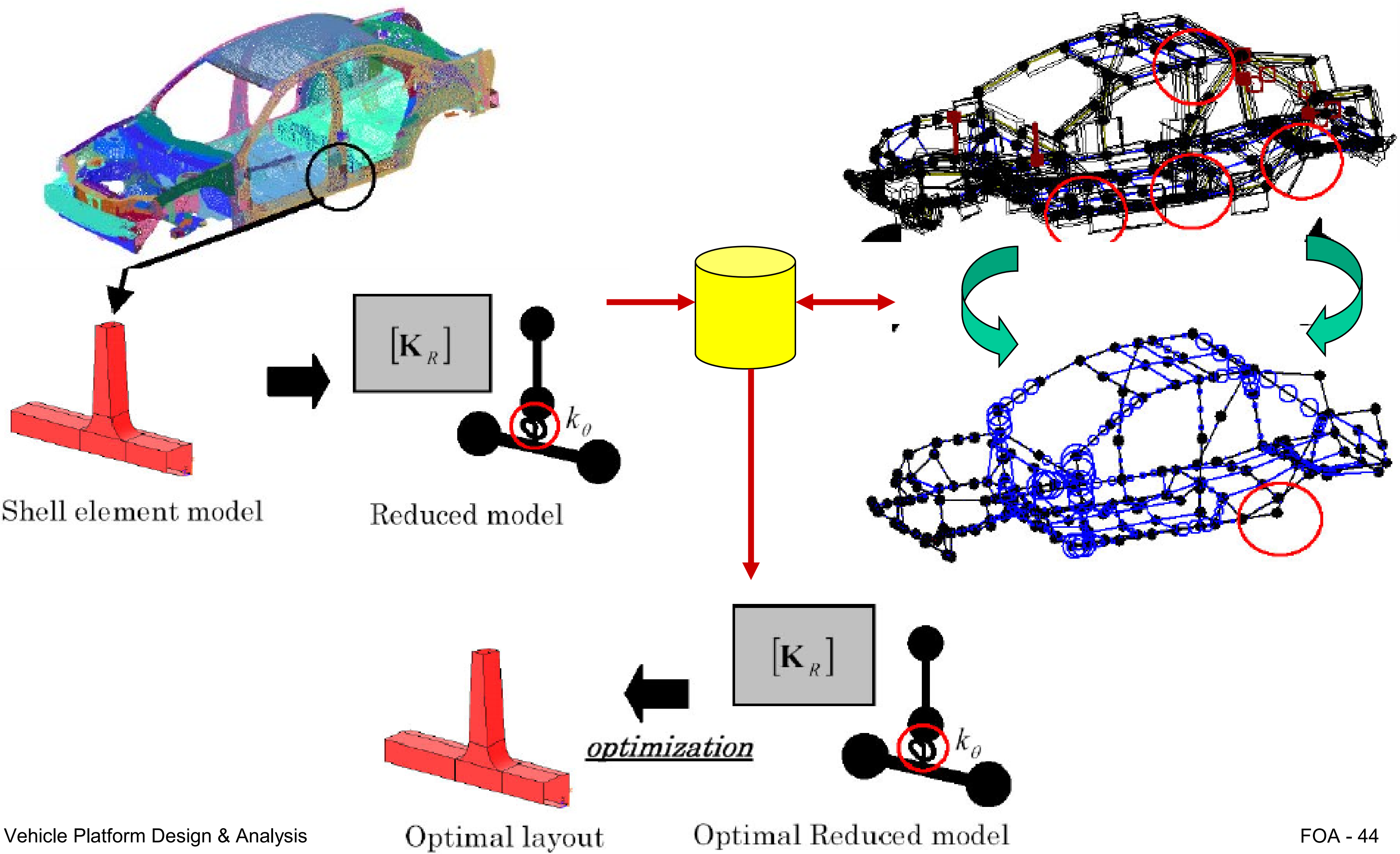
Joint Analysis Considering Nonlinear Behavior

- Simplify the analysis
  - Shell element models of joints → rotational spring element models
  - Rails, pillars and frames → beam elements
- Reasons in difficulty to obtain good accuracy using these spring elements
  - Transformation error from shell element models to spring element models
  - Bad effect of nonlinear behavior due to local elastic buckling

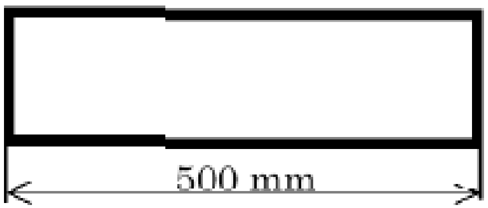
Concept of Global-Local Analysis

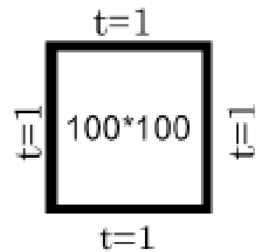


Joint Analysis

- Both a good accuracy and an adequate speed for analyzing in FOA
  - Joint configurations are exactly modeled using shell elements for local analysis. Using this model, necessary performance such as stiffness, vibration and strength is estimated. Nonlinear analysis in addition to linear one is performed
  - A reduced model based on the above results is constructed for global analysis. Databases about typical joint configurations are constructed repeating these procedures.
  - The reduced models of the joints are inserted in a global model and global performance is estimated. This analysis is simple and fast. The joint flexibility of the reduced model is optimized for satisfying a target performance.
  - In the local analysis, the joint configuration (layout) is optimized based on the optimized reduced joint flexibility. In this optimization process, the database is referred and the optimal layout will be found out.

Influence of Local Elastic Buckling: Uniform Beam



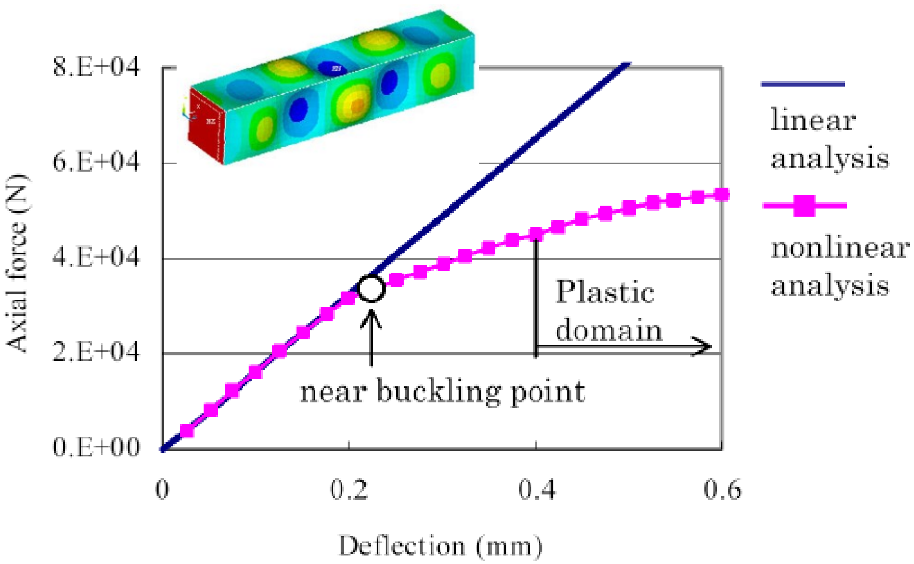


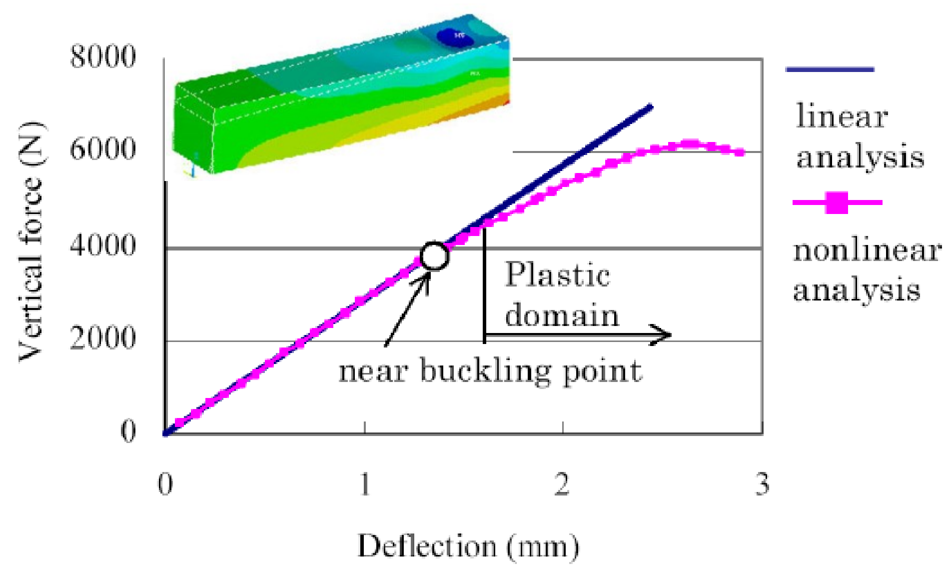
$E\text{(young modulus)} = 203000\left(N/mm^2\right)$

$\upsilon\text{(poisson ratio)} = 0.3$

$\sigma_y\text{(yield stress)} = 269\,(Mpa)$

	Axial compression	Vertical force
Local elastic buckling	3.16E+04	3.82E+03
Yielding	4.52E+04	4.49E+03





Theory of Effective Width

- Estimate the nonlinear behavior (influence of local elastic buckling) without complicated analysis

[axial compression]

$$\text{effective width } b = \begin{cases} w & \text{when } \lambda \le 0.673 \\ \rho w & \text{when } \lambda > 0.673 \end{cases}$$

$$\rho = \frac{1 - \dfrac{0.22}{\lambda}}{\lambda}, \quad \lambda = 1.052 \left(\frac{w}{t} \right) \frac{\sqrt{\sigma / E}}{\sqrt{k}}$$

w: width of the element

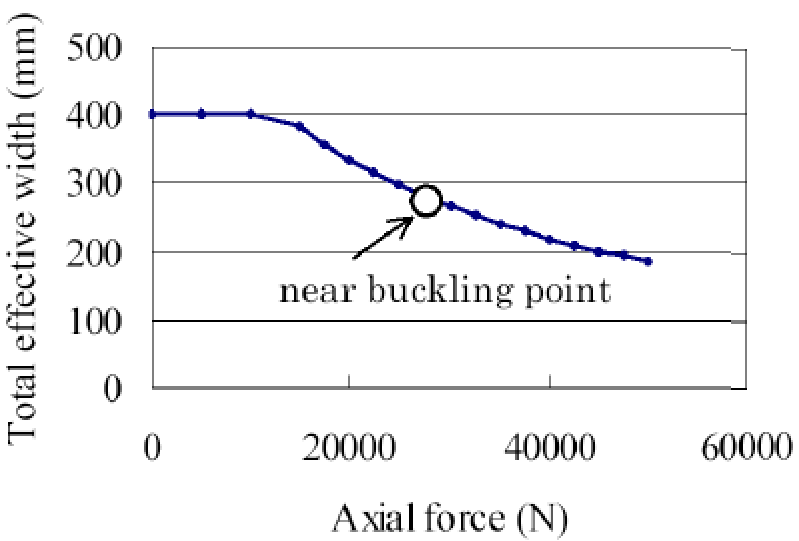
t: thickness of the element

λ: slender factor

σ: stress in the element

k: plate buckling coefficient

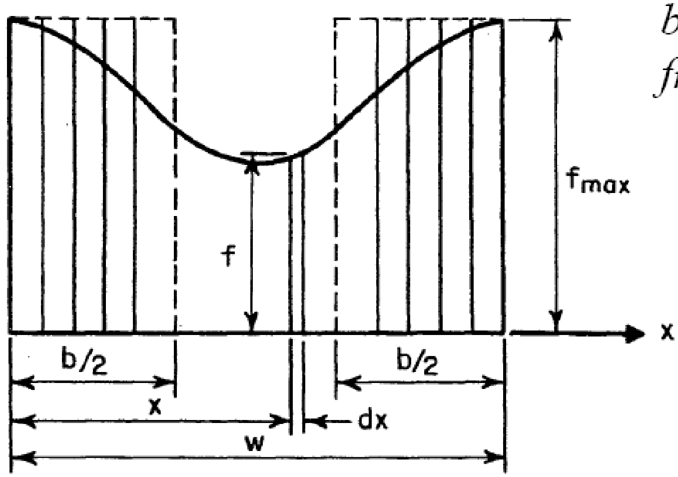
$$b = \left(\frac{1}{\dfrac{B}{w} + \dfrac{0.22}{B}} \right) \quad \text{where } B = 1.052 \left(\frac{w}{t} \right) \sqrt{\frac{f}{4Ekt}}$$



Effective Design Width

- Effective design width is a reduced design width for computing sectional properties when the flat-width-to-thickness ratio of an element exceeds a certain limit.
- It may also be considered that the effective width represents a particular width of the plate which just buckles when the compressive stress reaches the yields point of steel.

- A concept of “effective width” was introduced by von Karman.



b: a fictitious effective width

$fmax$: edge stress

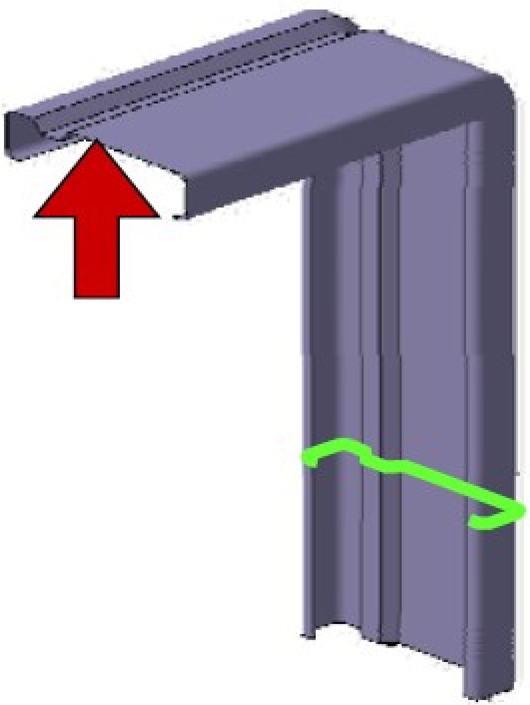
$$\int_0^w f\, dx = b\, f_{max}$$

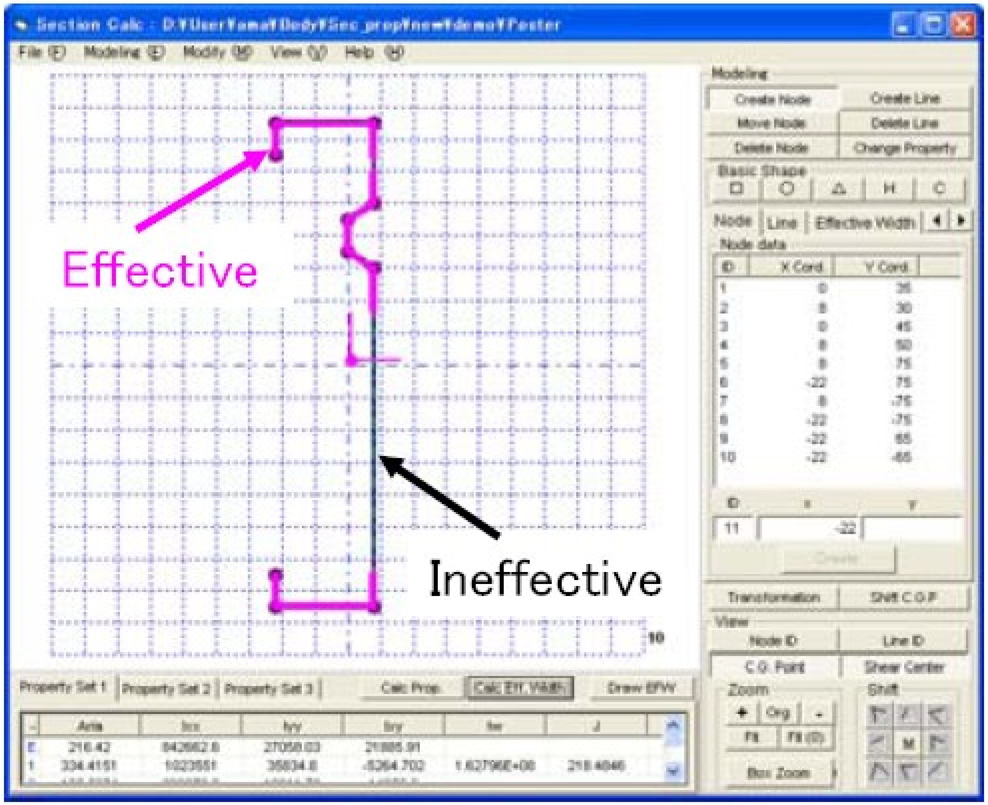
σ_{cr}: critical stress for buckling

σ_y: yield stress

$$\frac{b}{w} = \frac{1}{2}\left(1 + \frac{\sigma_{cr}}{\sigma_y}\right)$$

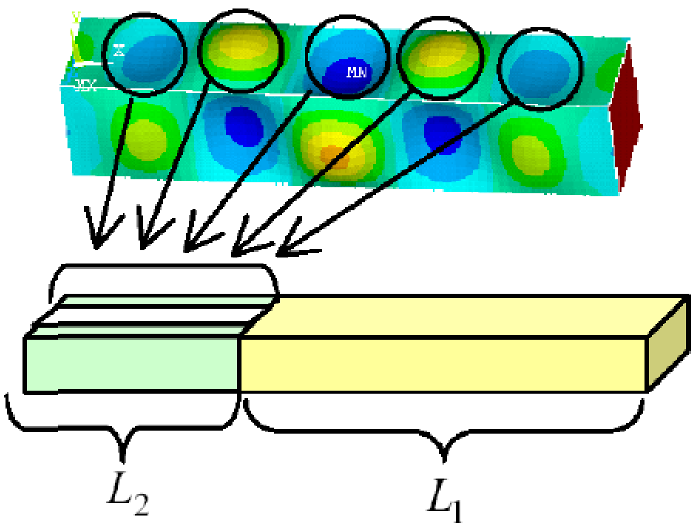
$$\sigma_{cr} = k \frac{E\pi^2}{12\left(1-\mu^2\right)\left(\frac{w}{t}\right)^2}$$

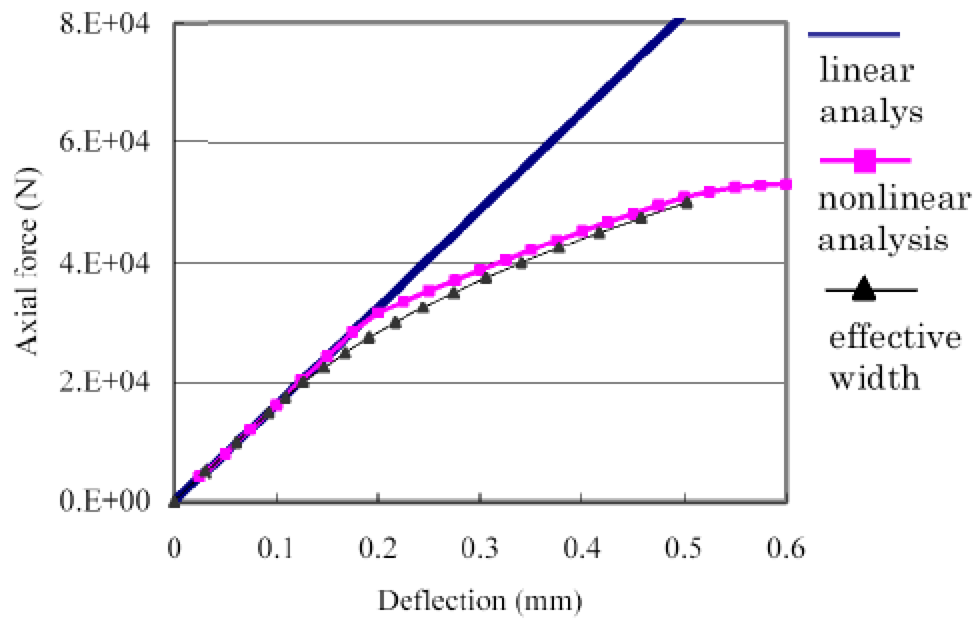



Effective
Ineffective
File
Modeling
Modify
View
Help
Create Node
Create Line
Move Node
Delete Line
Delete Node
Change Property
Basic Shape
Node
Line
Effective Width
Node data
Transformation
Shift C.G.P
Node ID
Line ID
C.G. Point
Shear Center
Zoom
Shift
Box Zoom
Property Set 1
Property Set 2
Property Set 3
Calc Prop.
Calc Eff. Width
Draw EfW

Axial Stiffness

- Linear analysis vs. Nonlinear analysis
- Theory of effective width





$$K = \frac{f}{u} = \frac{EA_1A_2}{L_1A_2 + L_2A_1} \quad \text{where } L_2 = nb$$

$$\begin{cases} K, f, u: \text{ axial stiffness, compression force, deflection} \\ A_1, L_1: \text{ cross section area and length at the fully effective width} \\ A_2, L_2: \text{ cross section area and length at the effective width} \\ b: \text{ effective width} \\ n: \text{ number of mode} \end{cases}$$

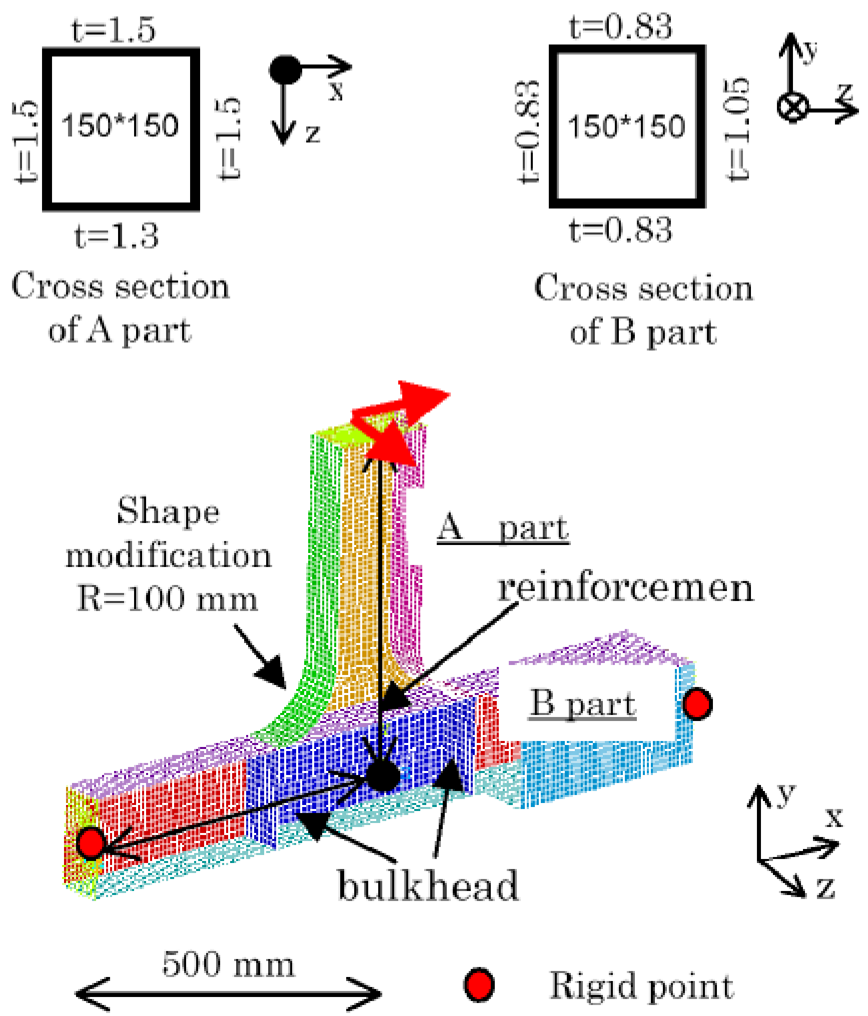
Influence of Local Elastic Buckling: Joint

- Loading conditions
  - In-plane bending
  - Out of plane bending

$$E(\text{young modulus}) = 203000\left(N/mm^2\right)$$

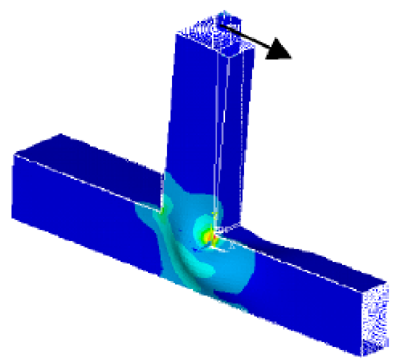
$$\upsilon(\text{poisson ratio}) = 0.3$$

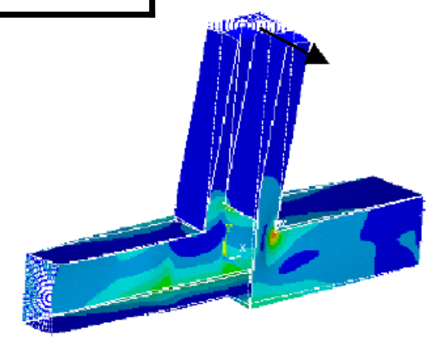
$$\sigma_y(\text{yield stress}) = 400\left(Mpa\right)$$

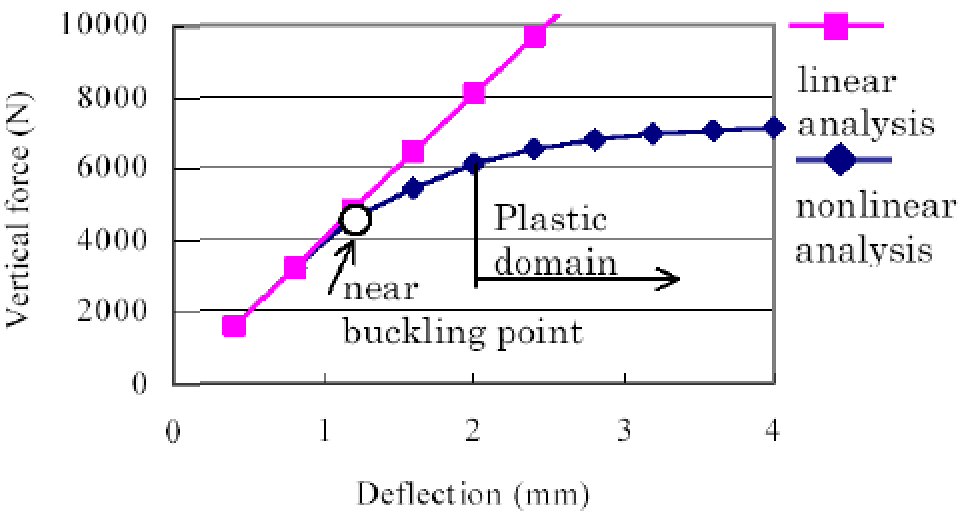


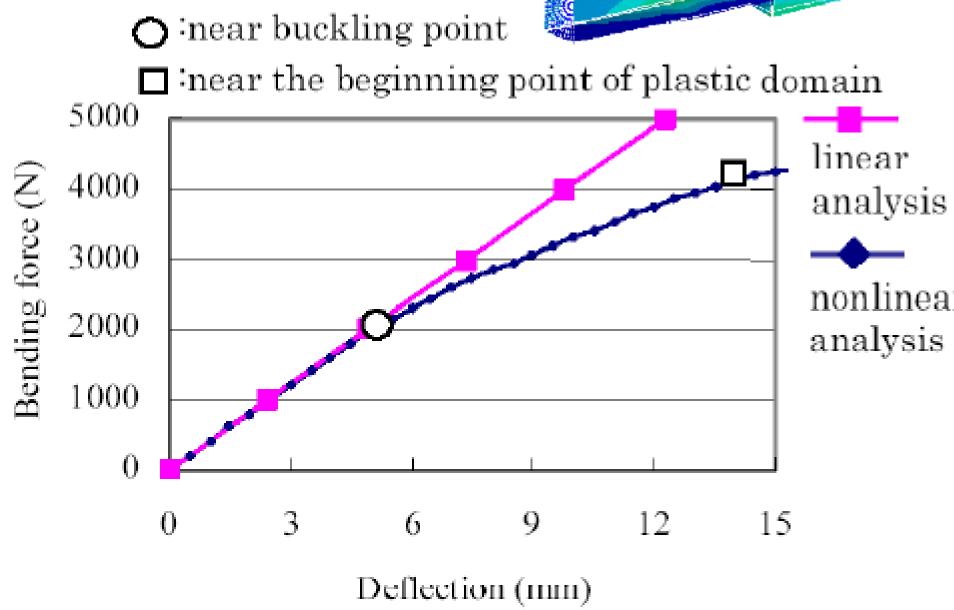
In-plane vs. Out-of-plane Bending

Bending	In-plane	Out-of-plane
Local elastic buckling	4.55E+03	2.54E+03
Yielding	6.07E+03	4.14E+03



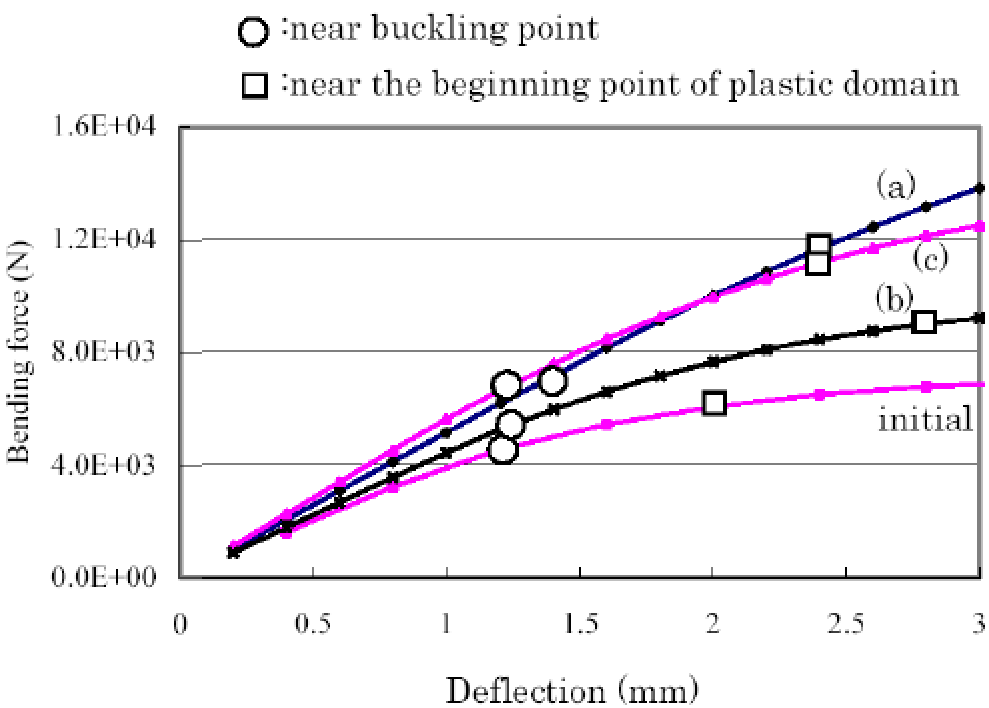




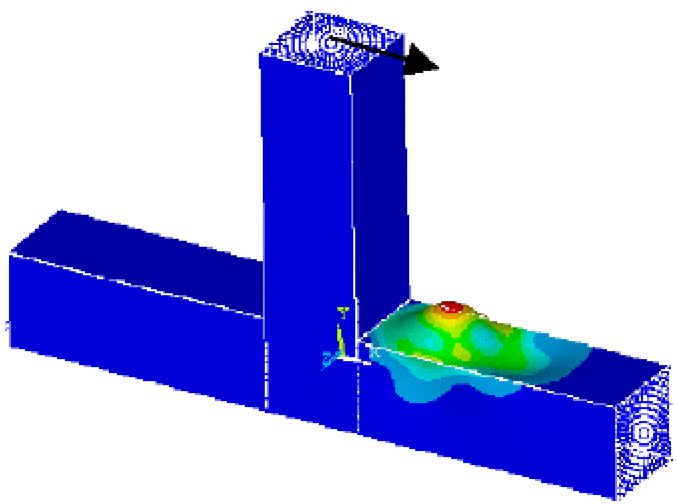


In-Plane Bending

	Initial (N/mm)	Reduced (N/mm)	Reduction rate %
initial	4021	1909	53%
(a) bulkhead	5160	4490	13%
(b) reinforcement	4456	2525	43%
(c)shape modified	5670	3760	34%



- Stiffness decrease of joints due to a local buckling
- Buckling mode
  - Shear
  - Torsional
  - Plate

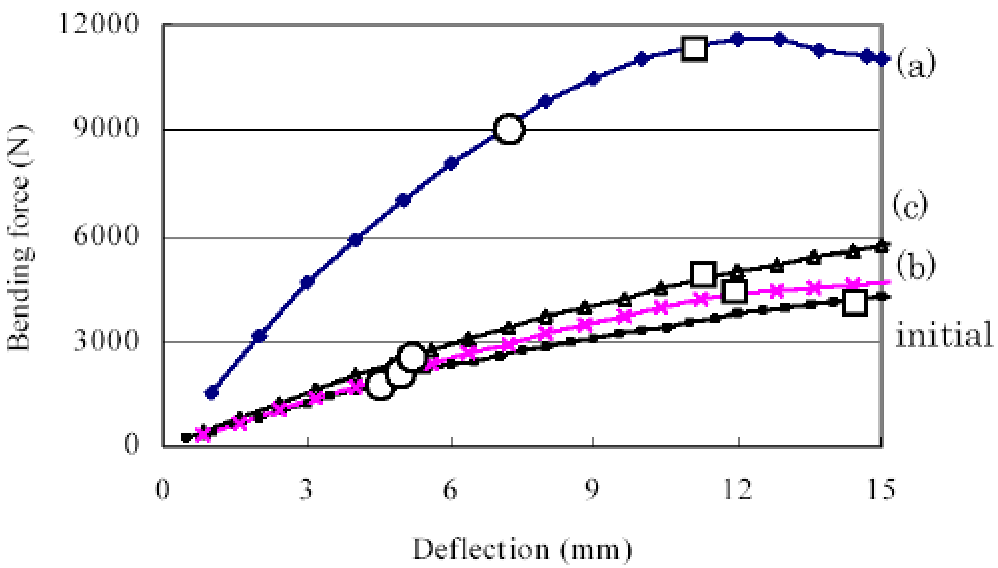


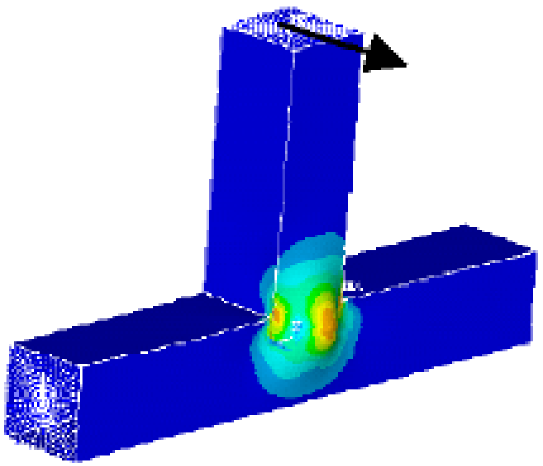
Out-of-Plane Bending

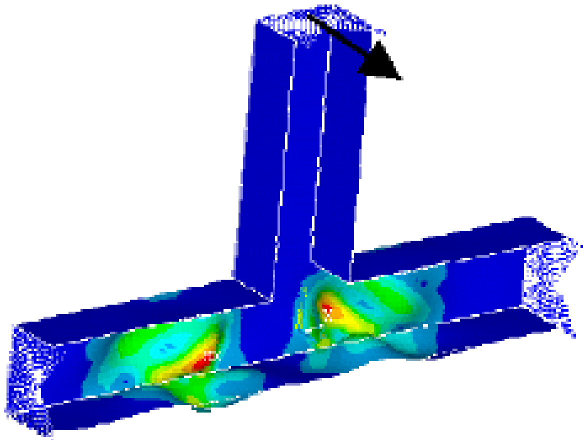
	Initial (N/mm)	Reduced (N/mm)	Reduction rate %
initial	407	232	43%
(a) bulkhead	1560	1080	31%
(b) reinforcement	427	317	26%
(c)shape modified	500	367	27%

○ :near buckling point

□ :near the beginning point of plastic domain

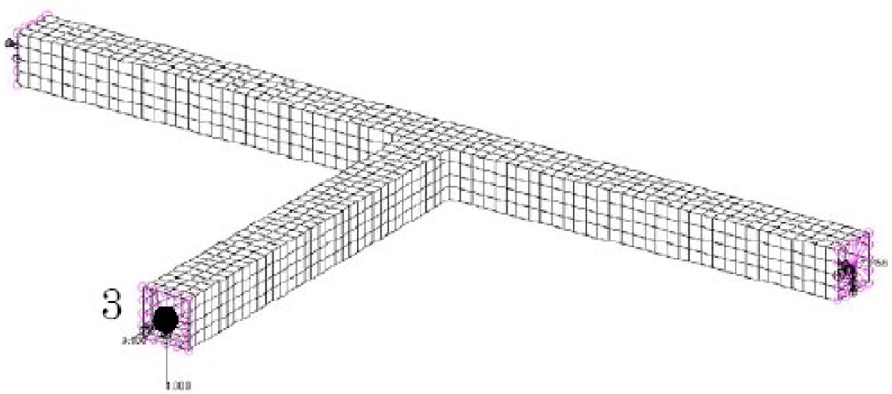






Joint Model

- Shell element: local analysis

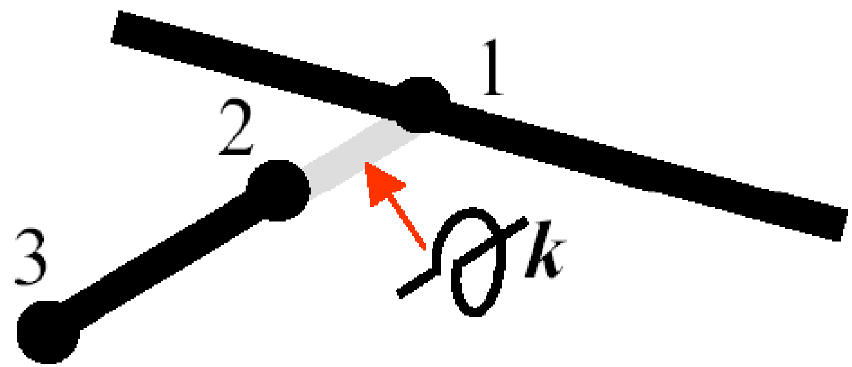


$$\begin{bmatrix} k_{11}+k & k_{12}-k & k_{13} \\ k_{12}-k & k_{22}+k & k_{23} \\ k_{31} & k_{32} & k_{33} \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 1 \end{Bmatrix}$$

$$\begin{cases} k_{ij} : \text{ component of the redued stiffness matrix} \\ k : \text{ rotational spring constant} \\ u_1, u_2 : \text{ rotational displacement} \\ u_3 : \text{ displacement} \end{cases}$$

$\text{if } u_3 = u^* \to k\,?$

- Beam element: global analysis
- reduced model with a nonlinear spring constant

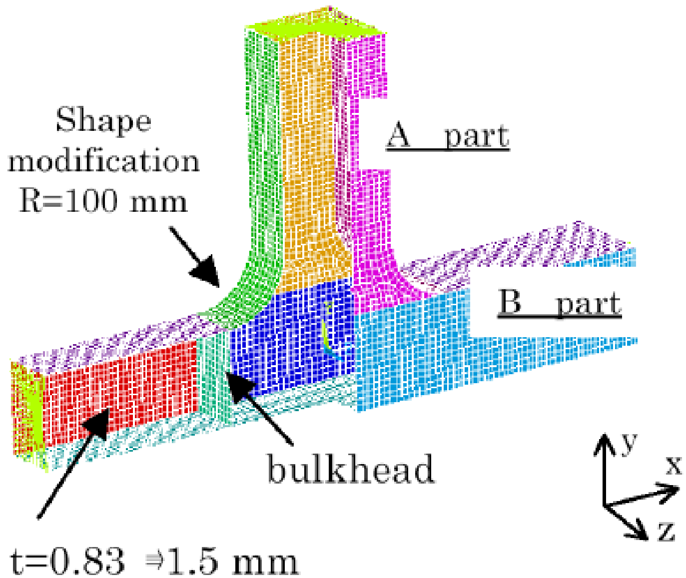


$$k = \frac{\begin{pmatrix} -k_{12}^2 + k_{11}k_{22} + k_{11}k_{23}^2u^* + k_{12}^2k_{33}u^* \\ -k_{11}k_{22}k_{33}u^* + k_{13}^2k_{22}u^* - 2k_{12}k_{13}k_{23}u^* \end{pmatrix}}{\begin{pmatrix} -k_{11} - 2k_{12} - k_{22} - k_{23}^2u^* + k_{11}k_{33}u^* \\ +2k_{12}k_{33}u^* + k_{22}k_{33}u^* - k_{13}^2u^* - 2k_{13}k_{23}u^* \end{pmatrix}}$$

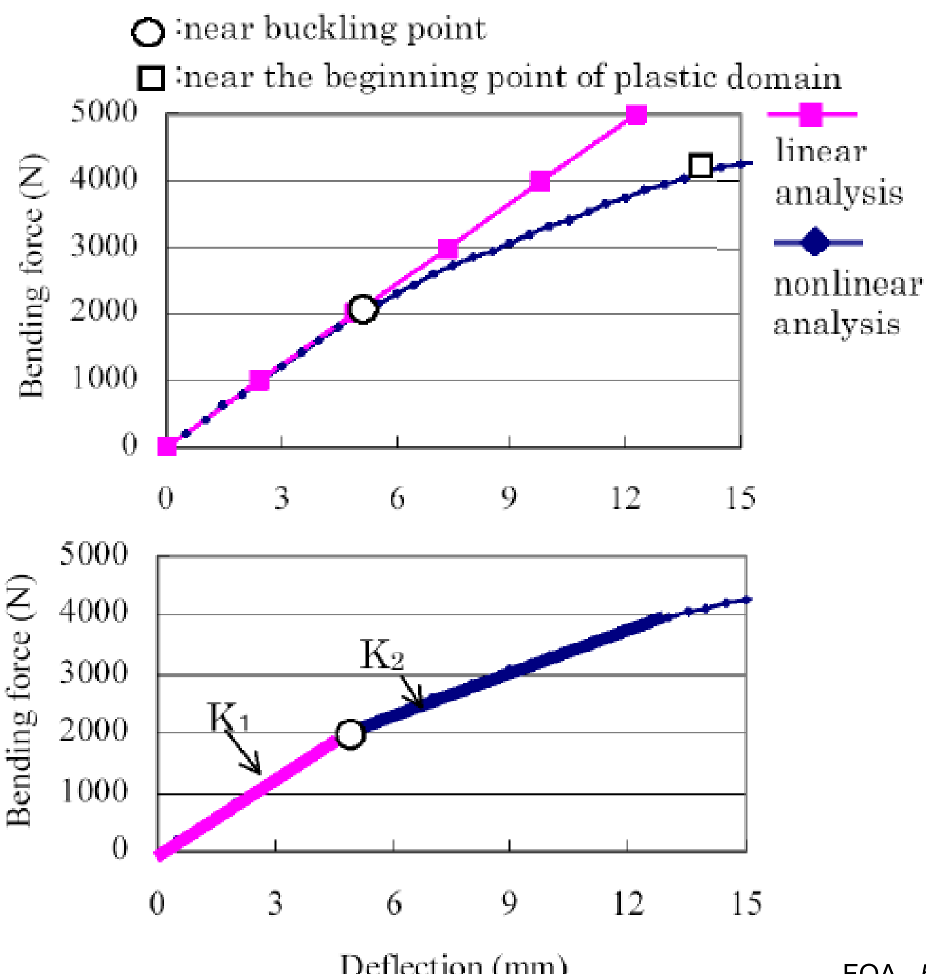
$\text{if} \quad u_3 = u^*$

Typical Modifications for Increasing Stiffness

- Bulkhead
- Shape modification
- Thickness increase



- Nonlinear stiffness

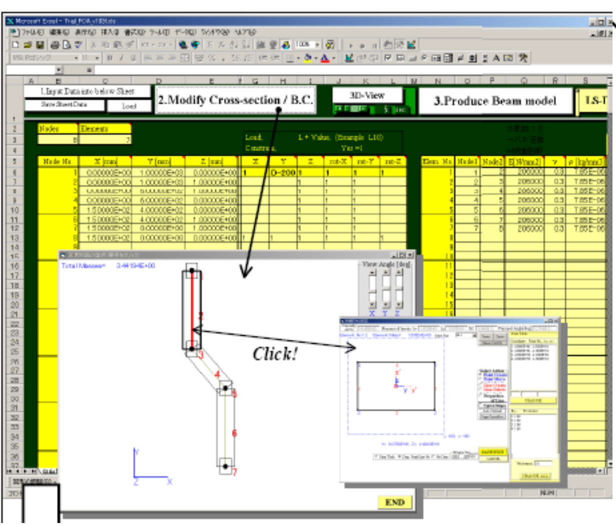


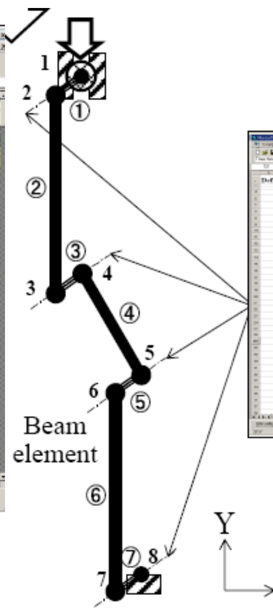
Crashworthiness Analysis Using Beam Elements

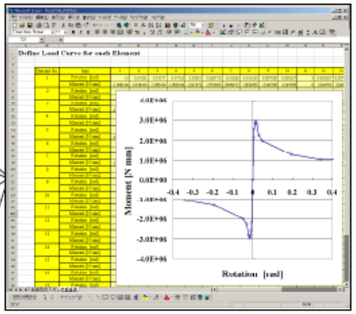
- Predict the collapse behavior of the frame member
  - Collapse analysis under loading conditions of combined axial force and bending moment to the cantilever
  - Previously obtained moment – rotation angle relationship using the beam element
- Theory of mechanics of materials and the simple analysis using beam element
  - Unsuitable for quantitative examination
  - Effective in an understanding of a phenomenon by the reason for simplifying an object based on designer's know-how
- thin-walled members subject to large deformation
  - High demand for weight efficient and crashworthy design of automobile bodies

FOA for Crashworthiness Analysis

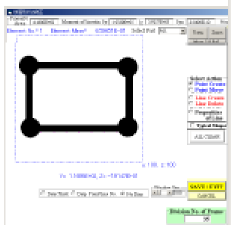
- In-house finite element analysis (FEA) software
  - Beam element with nonlinear stiffness
  - Large deformation and vibration of structure
  - Beam theory, which updates the coordinates of structure for every time step
  - Calculate the dynamic response of structure by direct numerical integration



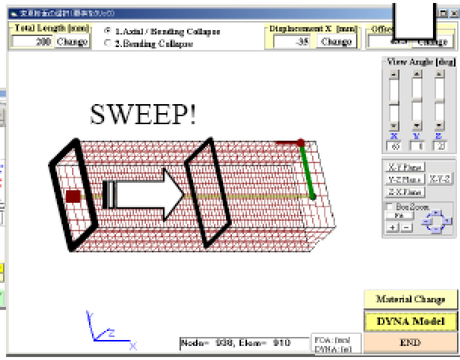




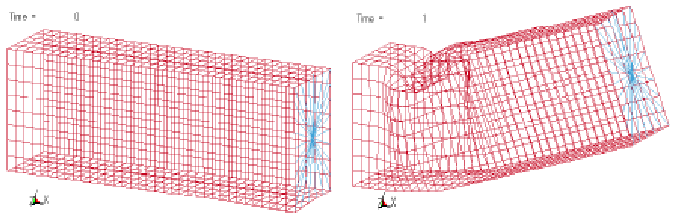
Moment – rotation angle relationship for nonlinear torsion stiffness



Cross-section

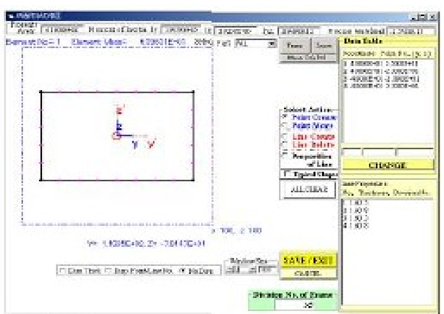


Assistant tool to make FEA model

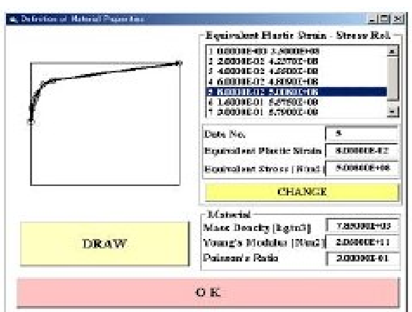


Collapse Characteristic of Bending Part

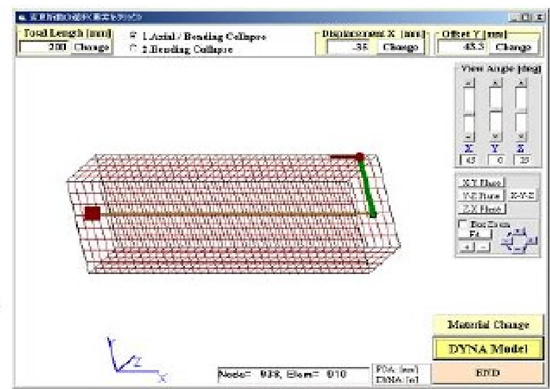
– Design of cross-sectional shape
– Modification of the material characteristics
– Construction of extended FEA model using shell elements
– Collapse analysis using LS-DYNA
– Post-process of moment-rotation angle relationship



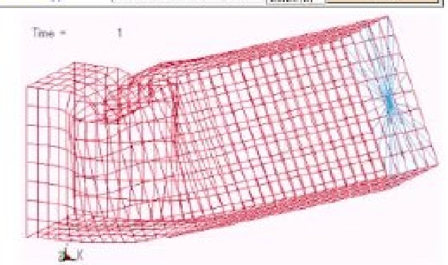
(a) Cross-sectional shape



(b) Material characteristic

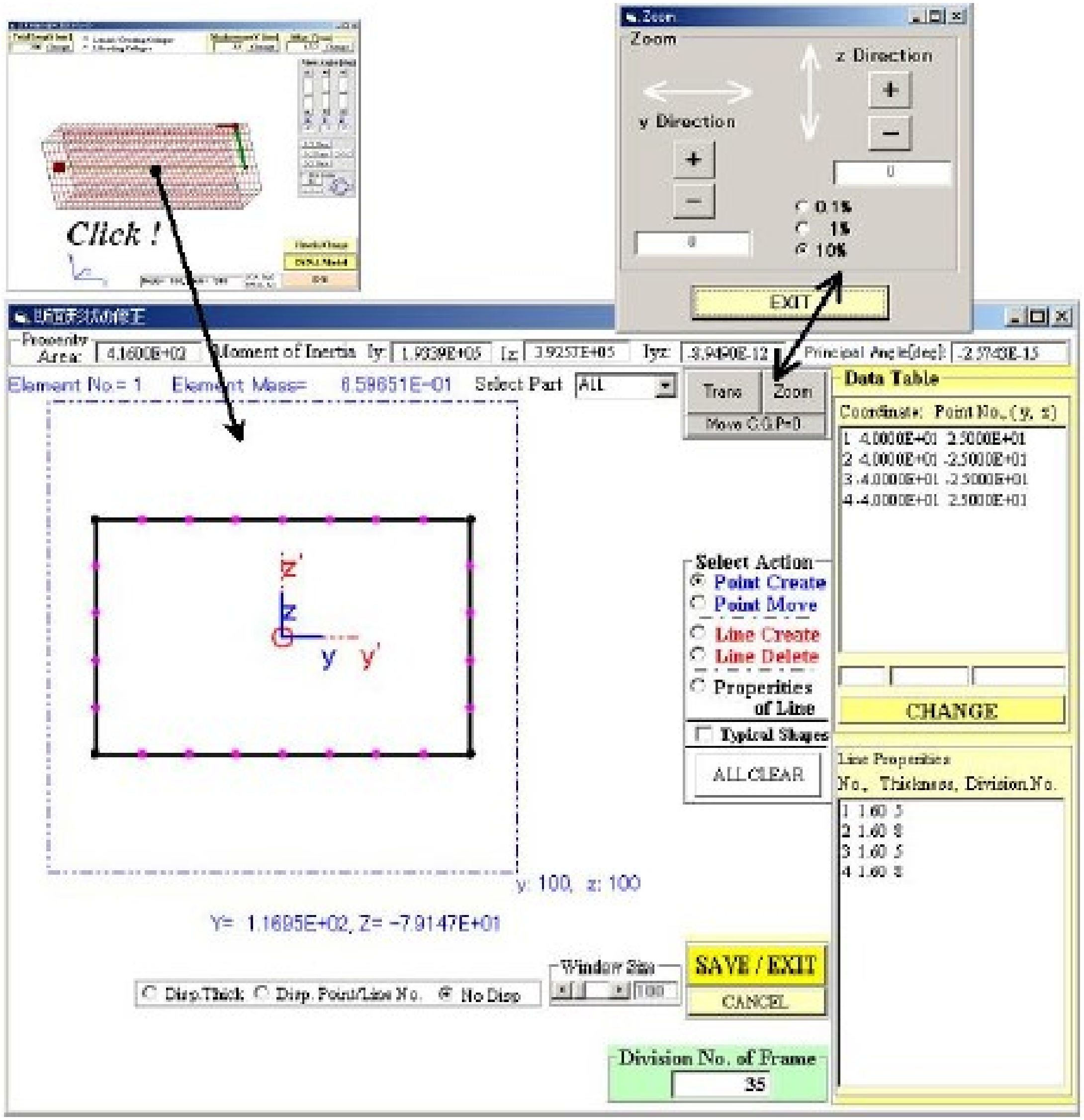


(c) Extended FEA model using shell element

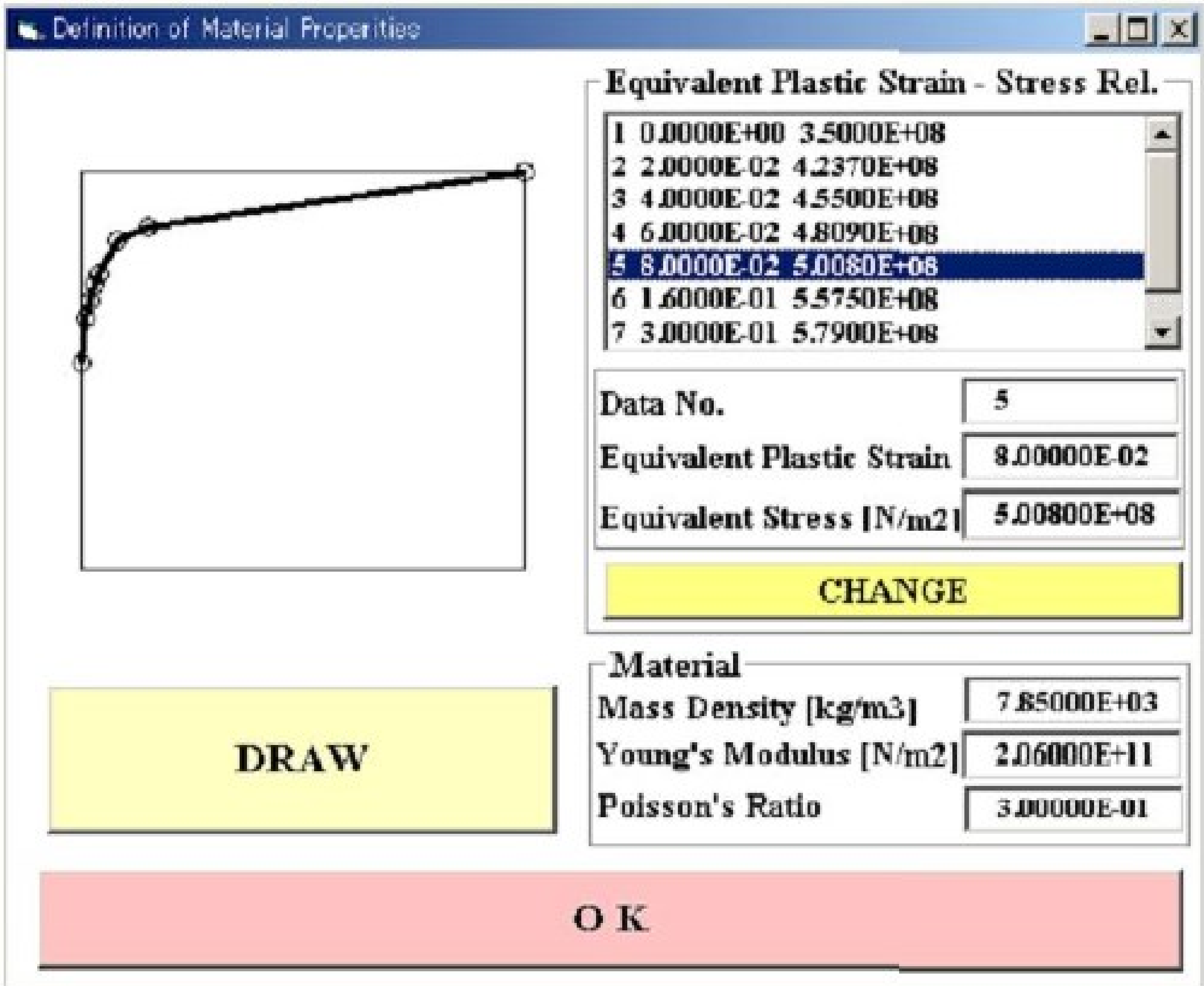

(d) Collapse analysis using LS-DYNA

(e) Moment – rotation angle relationship

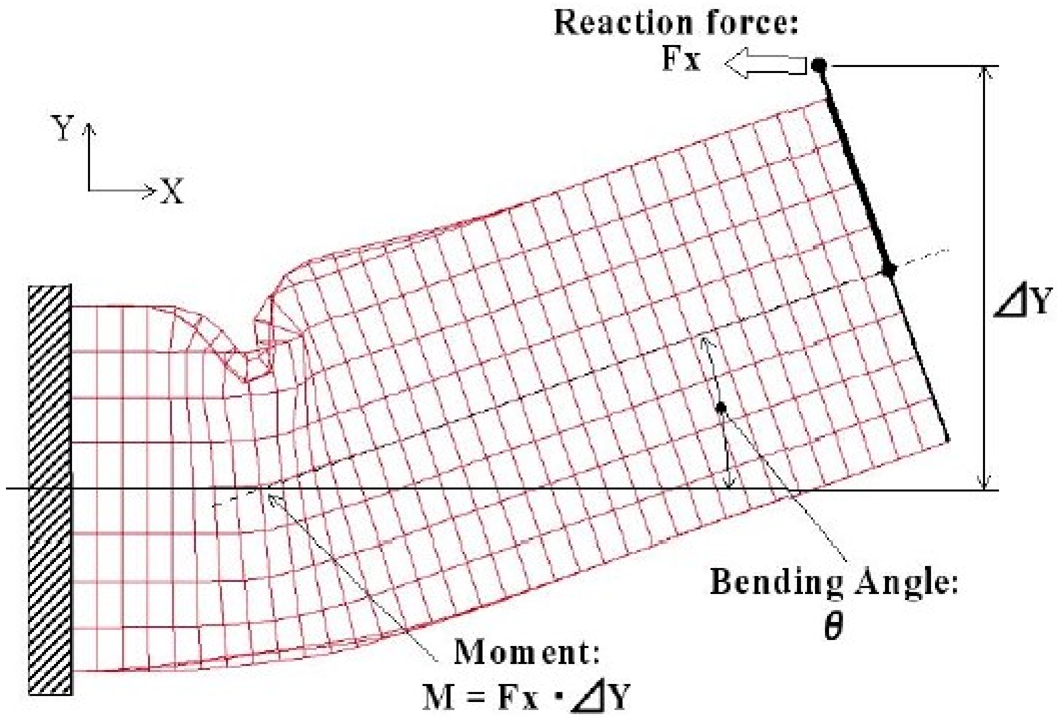
Cross-sectional Shape



Material Characteristics

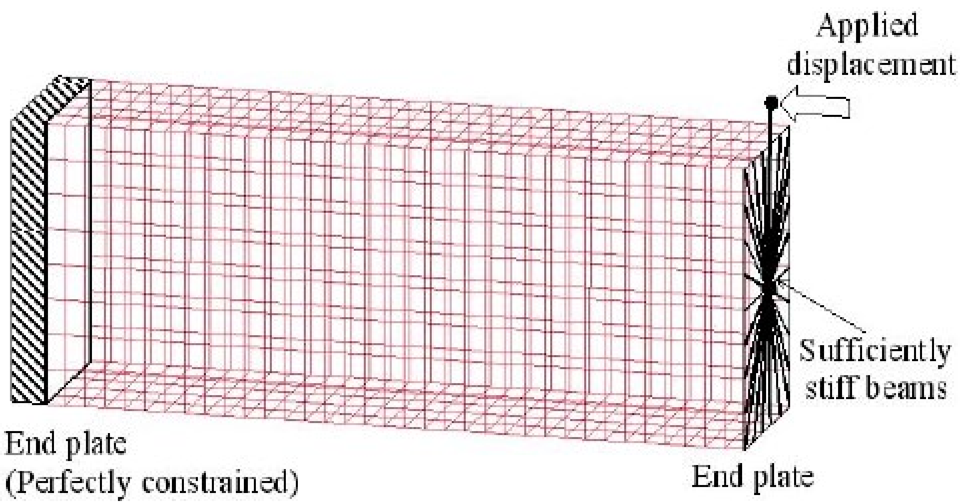


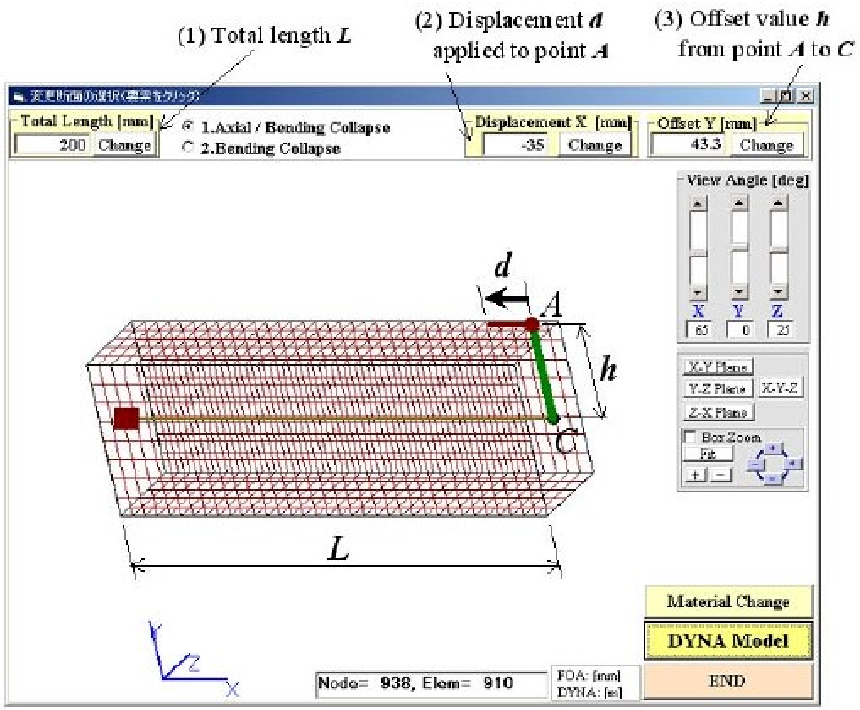
Applied Moment M



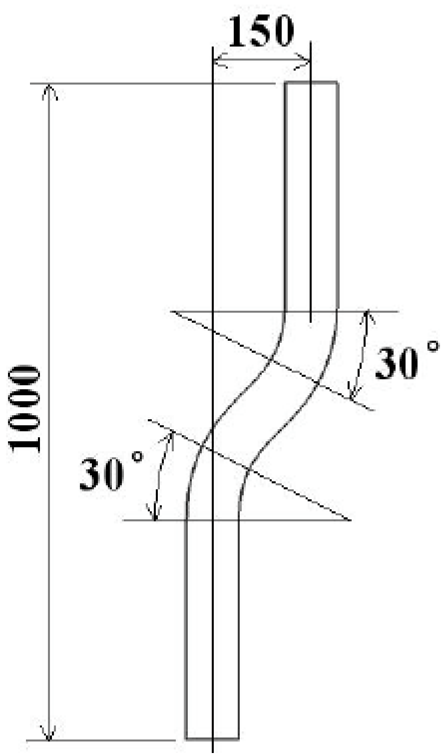
Collapse Analysis

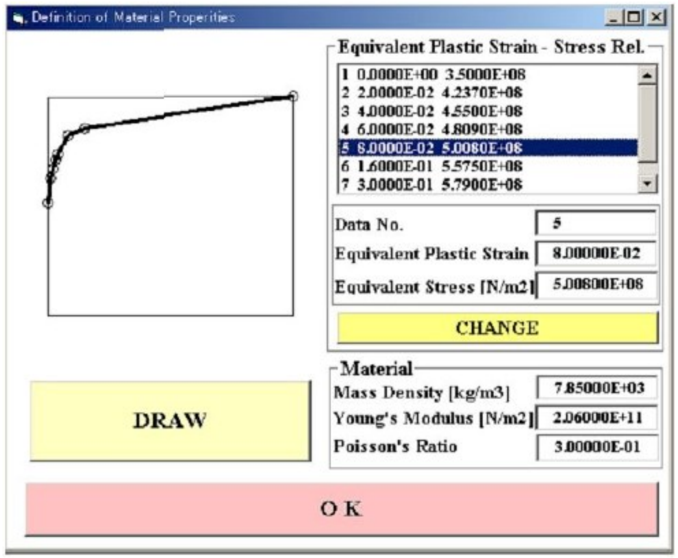
- Analyze the large deformation of a structure
  - Incremental finite element method
  - Step by step time integration method

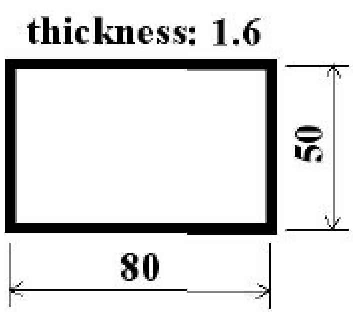




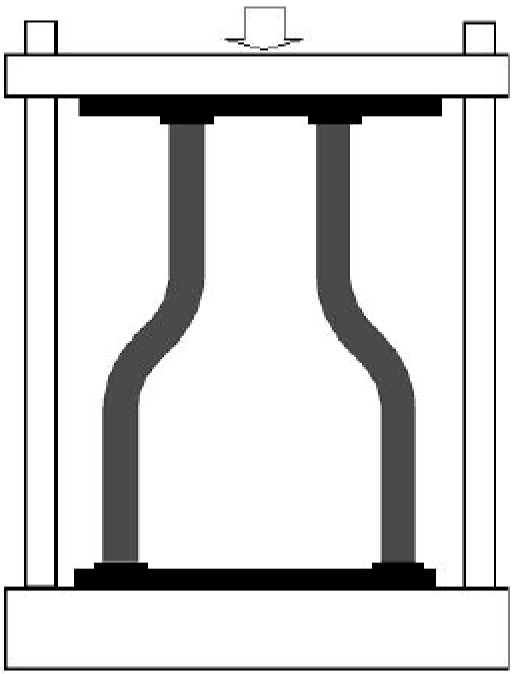
Example: S member



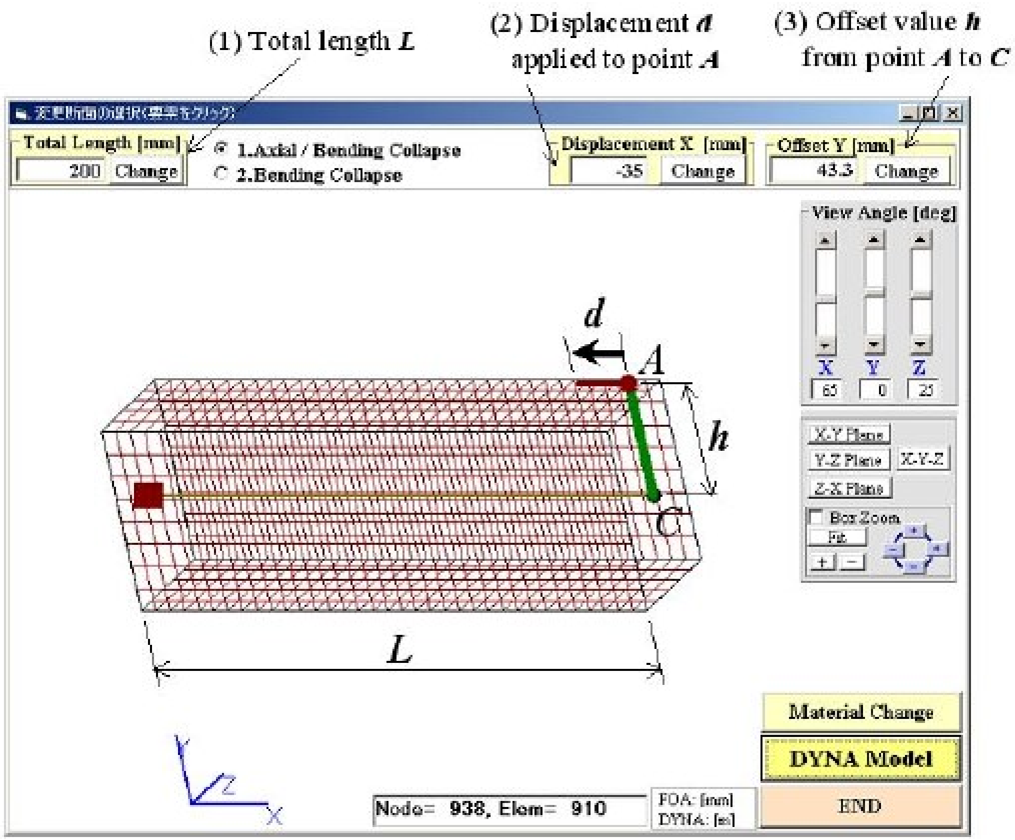




Cross-section

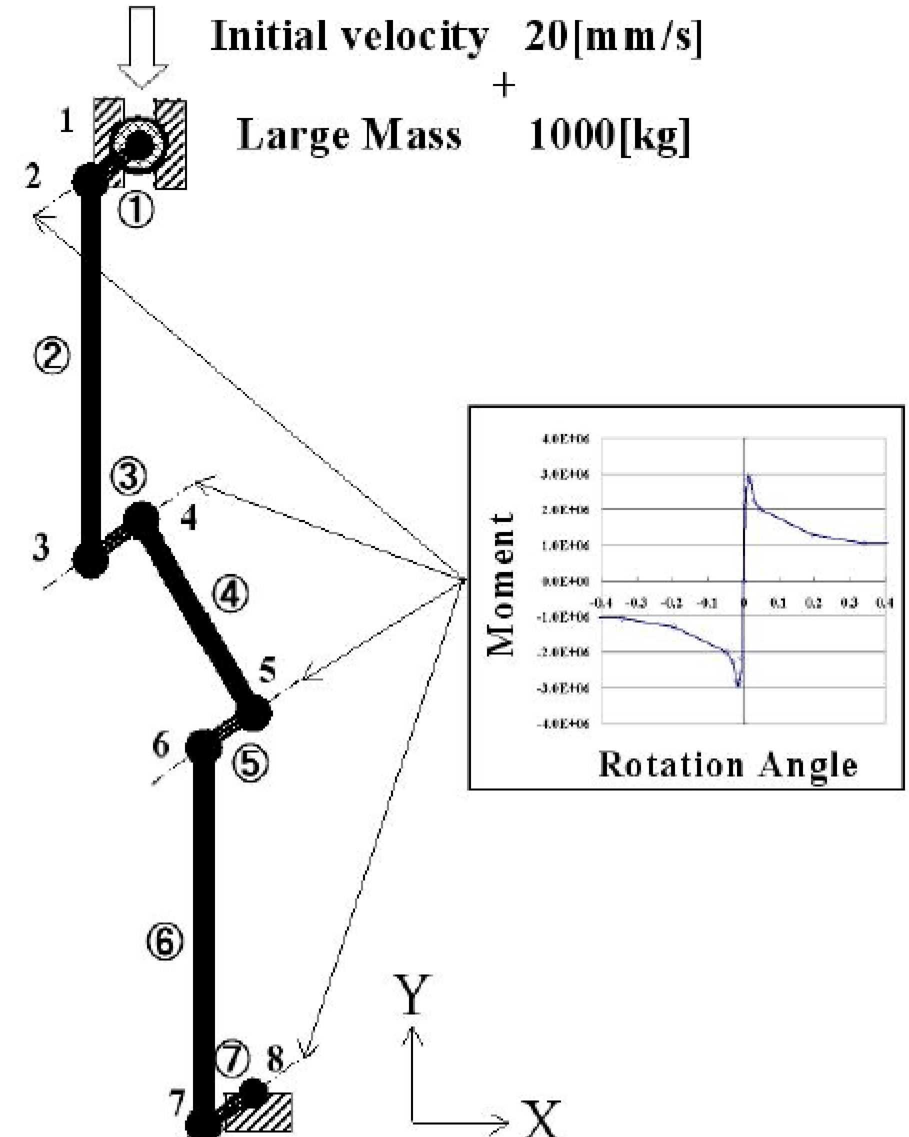


– h = 43.3mm (ratio of the moment and load of curved part using preliminary linear analysis)
– L = 200mm, d = 35mm



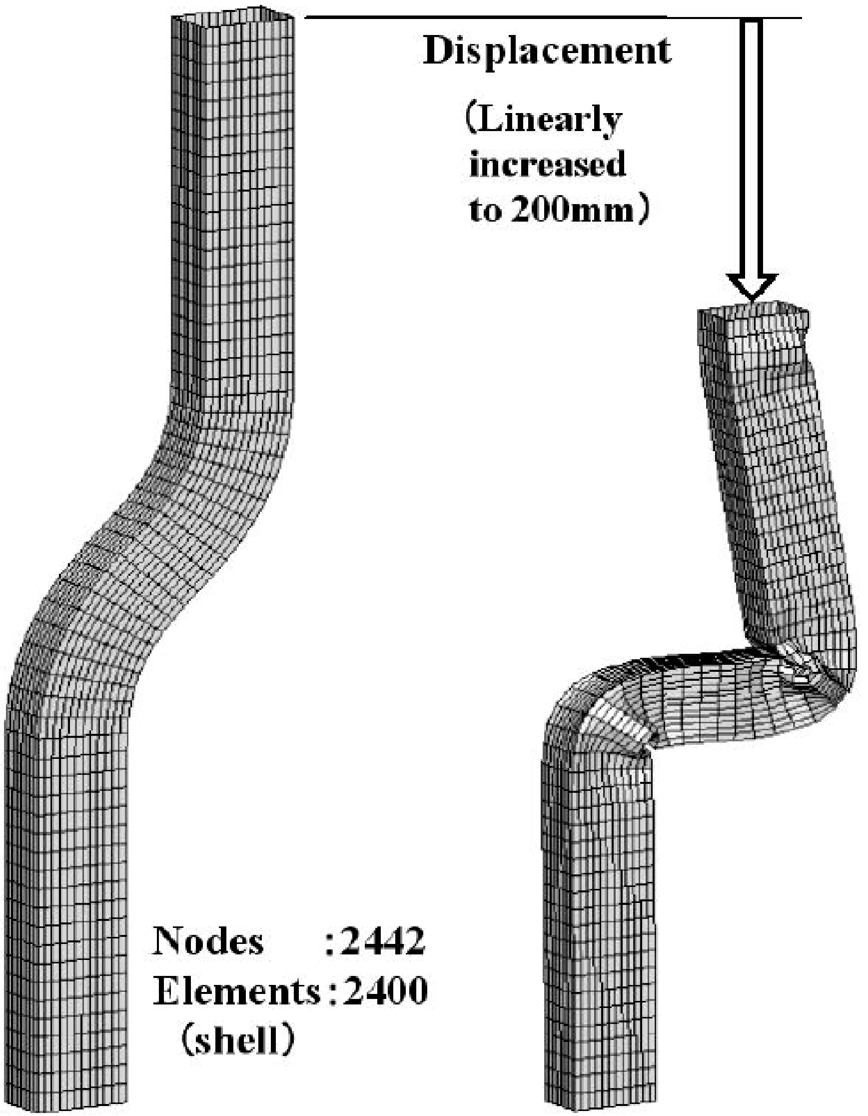
Beam Model

- ①③⑤⑦
  - beam element which has the nonlinear torsion characteristic with a length of 1mm
- ②④⑥
  - Usual beam element
- Perfectly constrained at node 8
- Constant speed at node 1
- 10 sec, final displacement: 200 mm linearly

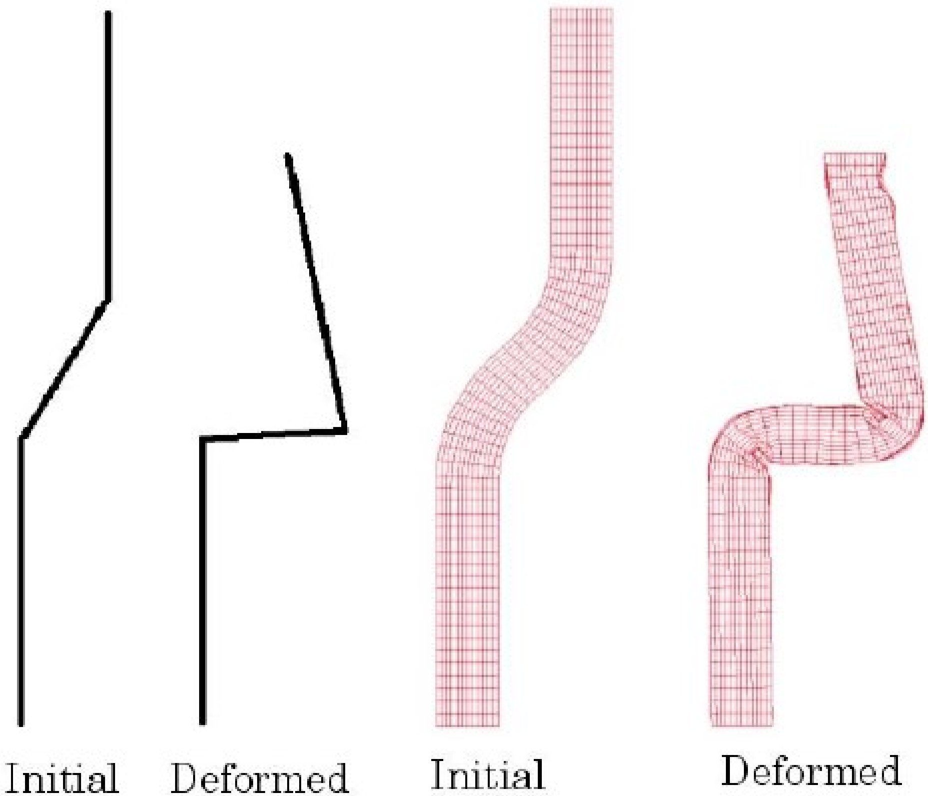


LS-DYNA

- Shell element
  - fully integrated formulation: type 16
  - Number of through thickness integration points: 5
- Material type
  - elasto-plastic material with an arbitrary stress versus strain curve: type 25



Verifications



(a) FOA (b) Detailed FEA for verification