An explicit ductile fracture model based on SMCS criterion for large-scale FE-analysis of steel structures under cyclic loading

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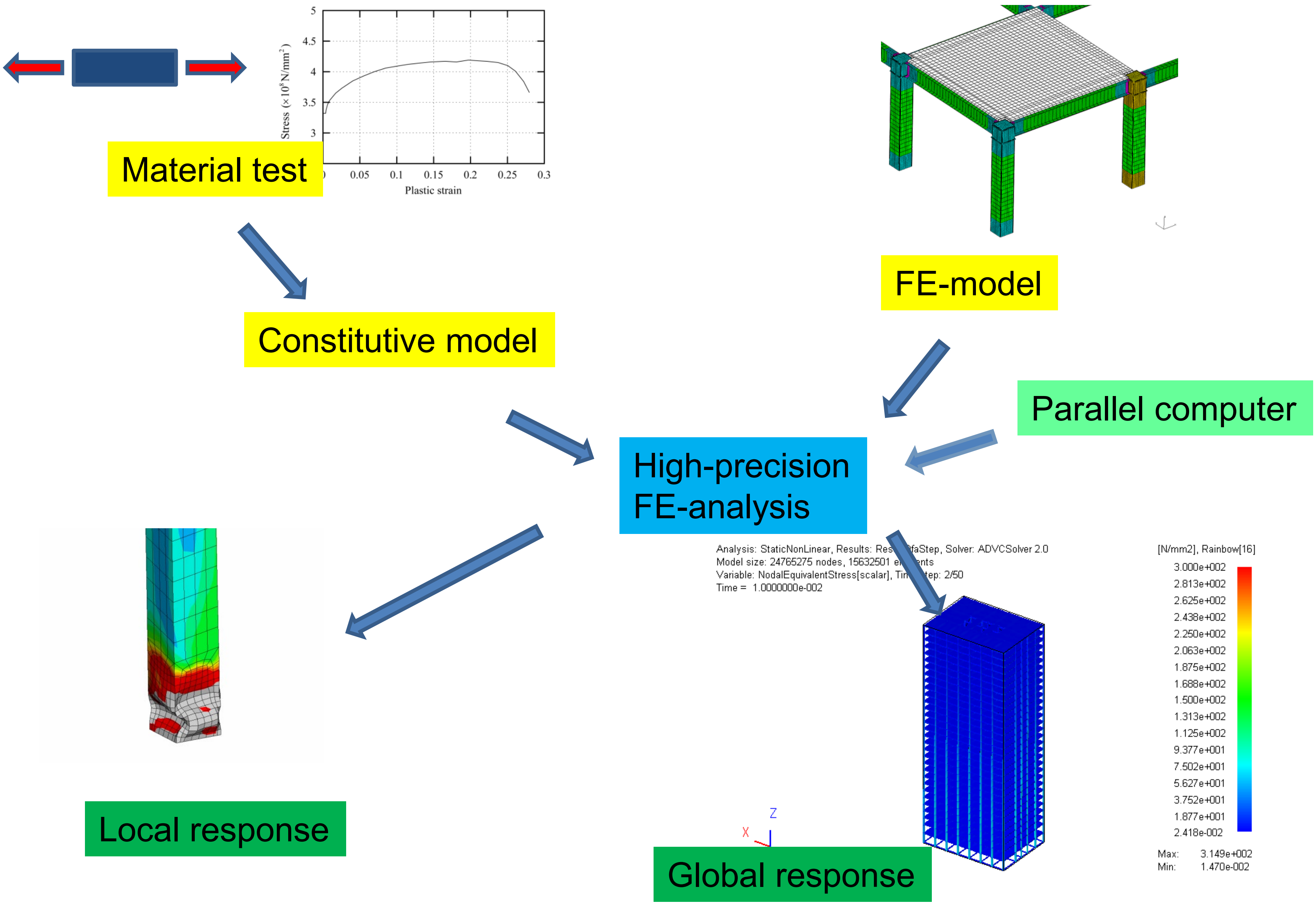
Purpose

- Develop a method for analysis of steel structures considering ductile fracture
- Applicable to large-scale FE-analysis of long-period motion (quasi-static cyclic deformation)
- Implicit integration and simple evaluation of stiffness degradation
  – Do not use small mesh
  – Do not allow explicit integration method with small time increment

E-Simulator Project

- Hyogo Earthquake Engineering Research Center (E-Defense) of National Research Institute for Earth Science and Disaster Resilience (NIED), Japan
- WG of Building Frame
- Platform for High-precision FE-analysis of steel frame
  - Do not use macro model
    (plastic hinge, composite beam, column base, etc.)
  - Utilize only material model and FE-mesh.
  - Simulate global and local responses simultaneously
- Investigation of collapse behavior of members and connections
  - Develop new devices for seismic control

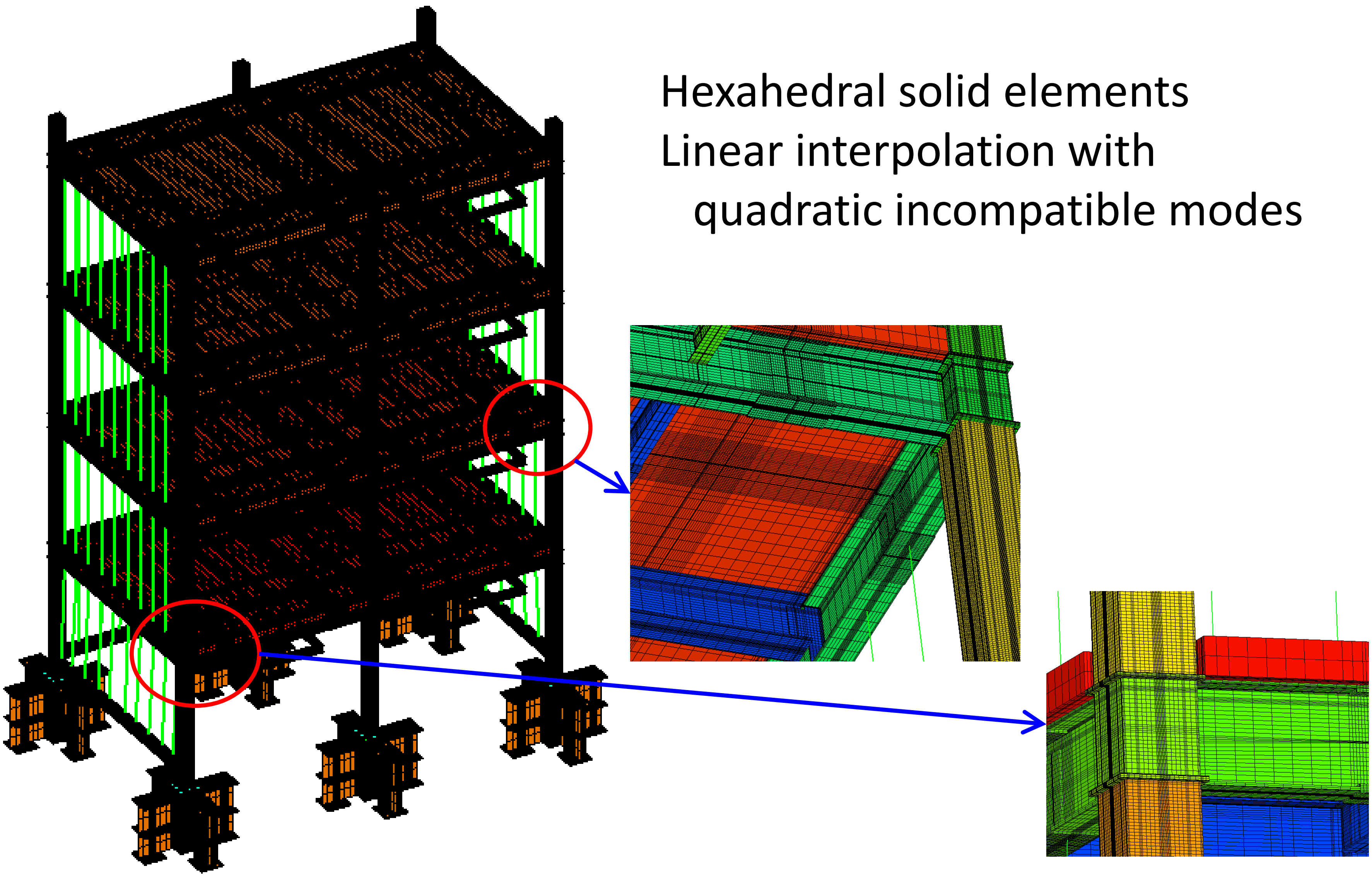


Material test
Stress (×10^8 N/mm^2)
Plastic strain
Constitutive model
FE-model
Parallel computer
High-precision FE-analysis
Local response
Global response
Time = 1.0000000e-002
[N/mm2], Rainbow[16]
3.000e+002
2.813e+002
2.625e+002
2.438e+002
2.250e+002
2.063e+002
1.875e+002
1.688e+002
1.500e+002
1.313e+002
1.125e+002
9.377e+001
7.502e+001
5.627e+001
3.752e+001
1.877e+001
2.418e-002
Max: 3.149e+002
Min: 1.470e-002

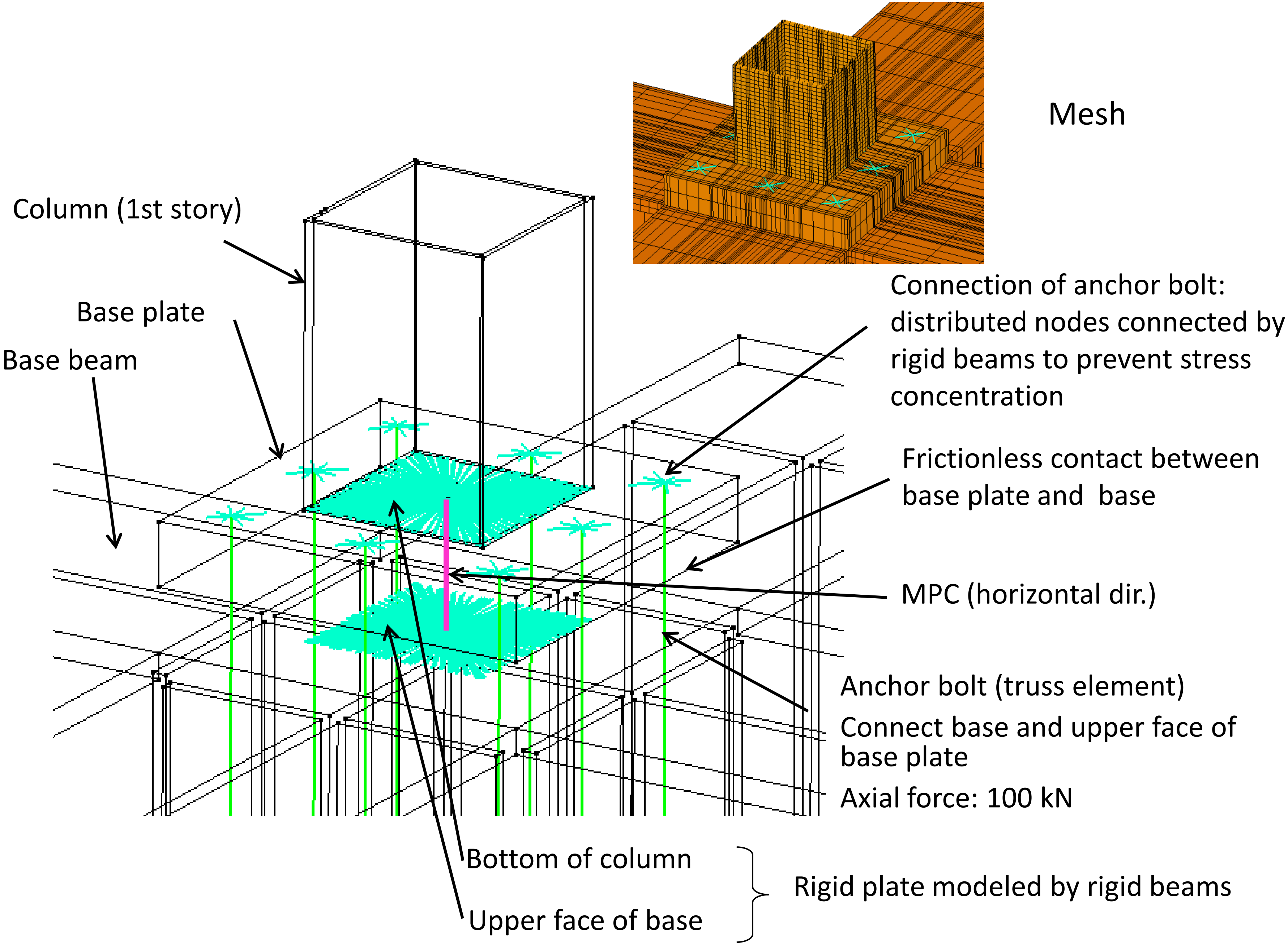
Total-Collapse Shaking-Table Test of 4-Story Steel Frame at E-Defense

Details of FE-Mesh

Hexahedral solid elements
Linear interpolation with
quadratic incompatible modes

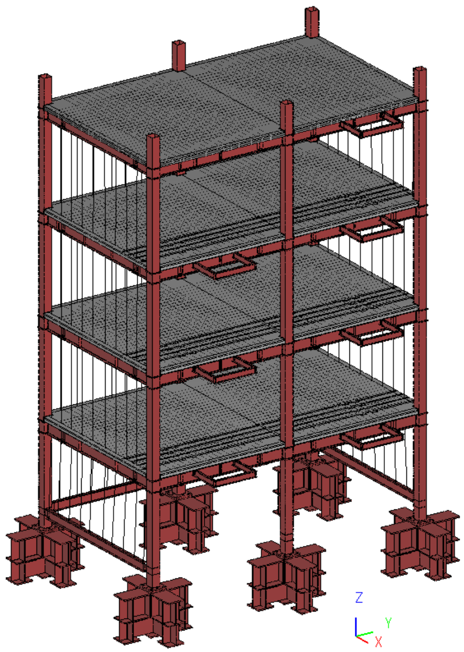


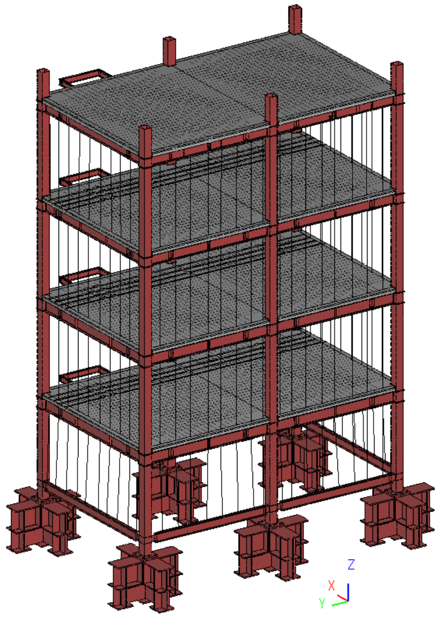
FE-Model of Column Base



FE-Models

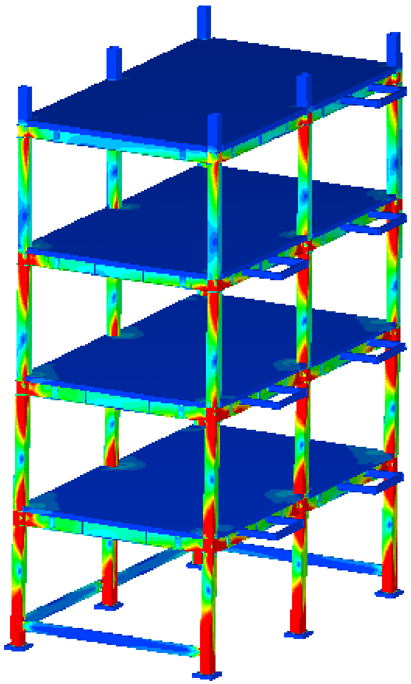
- **Spring model for exterior wall**



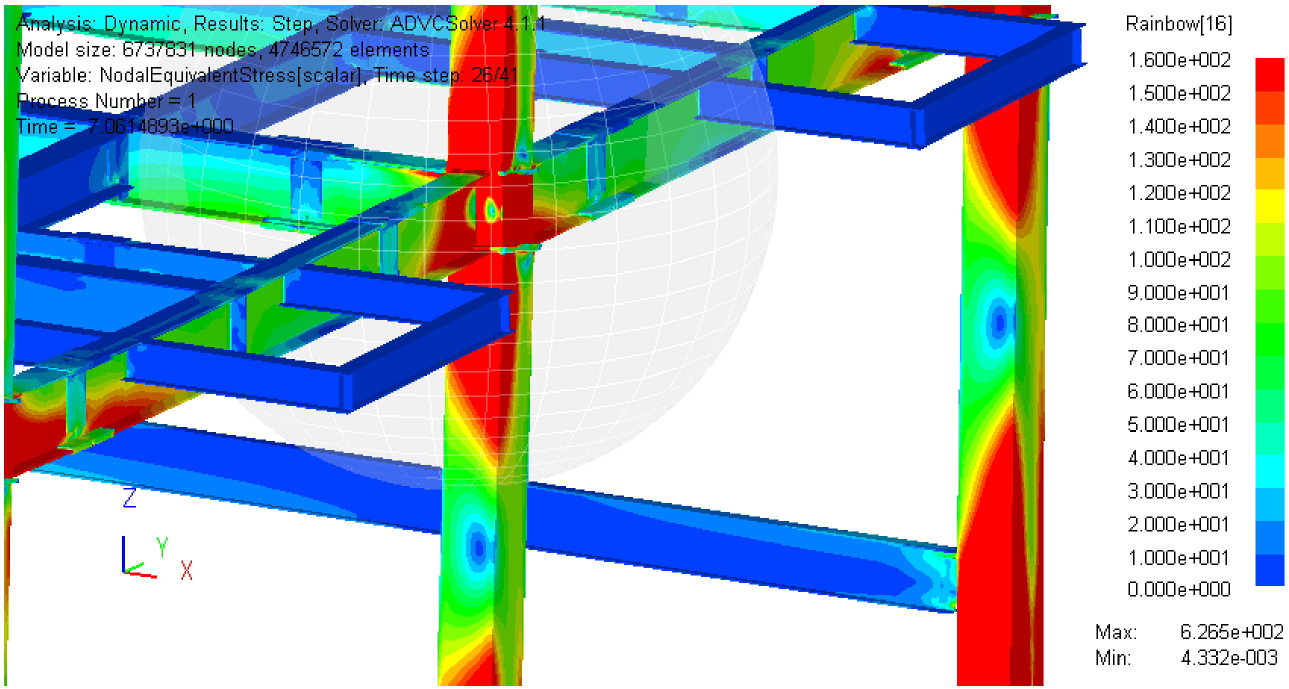


Number of elements	Number of nodes	Number of DOF	Column base	Exterior wall
4,532,742	6,330,752	18,992,256	FE-model	Spring

Equivalent Stress at the Maximum Deformation under Takatori wave



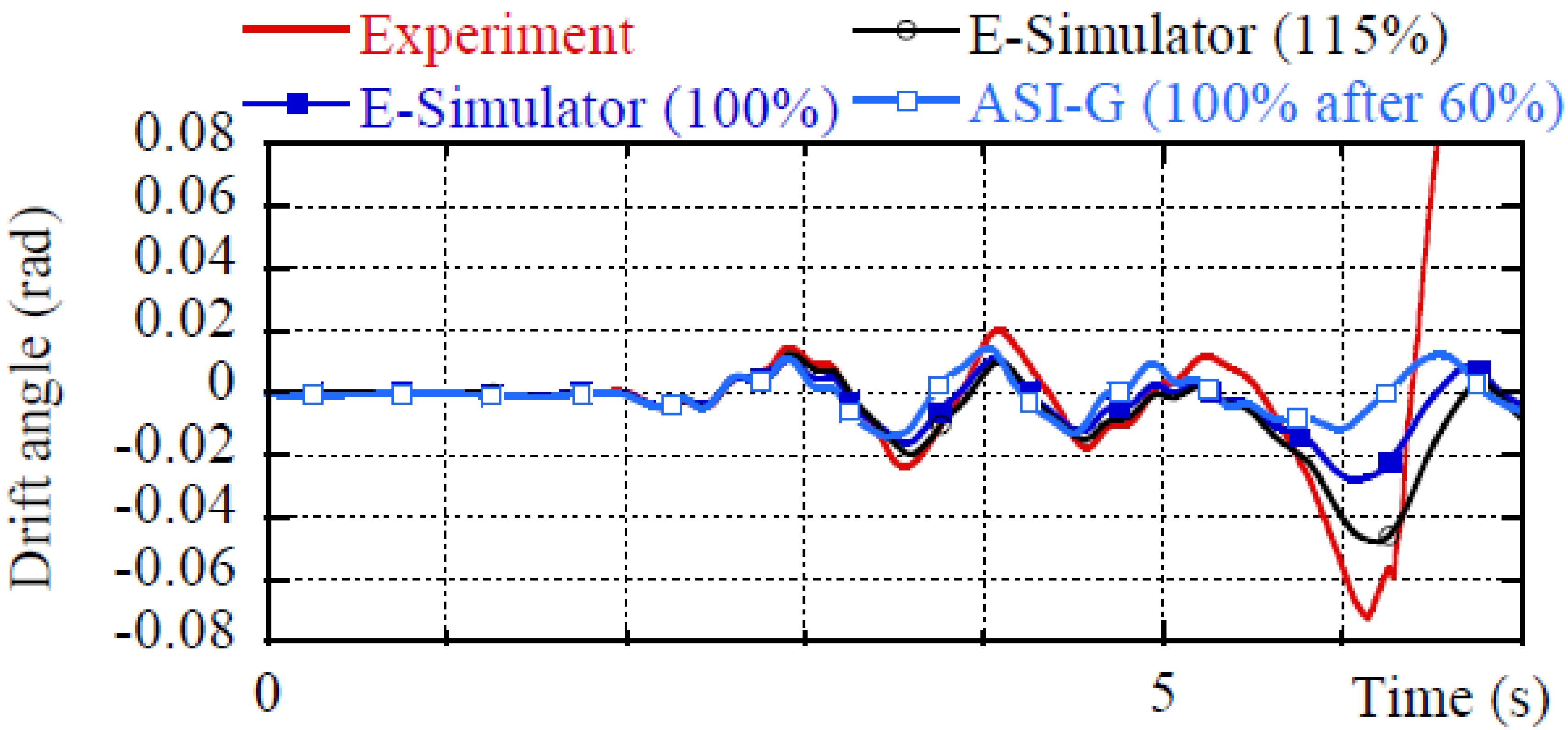
Whole frame



Close view around the 2nd floor and the 1st story

Large stress is observed around the column base and beam-to-column connections.

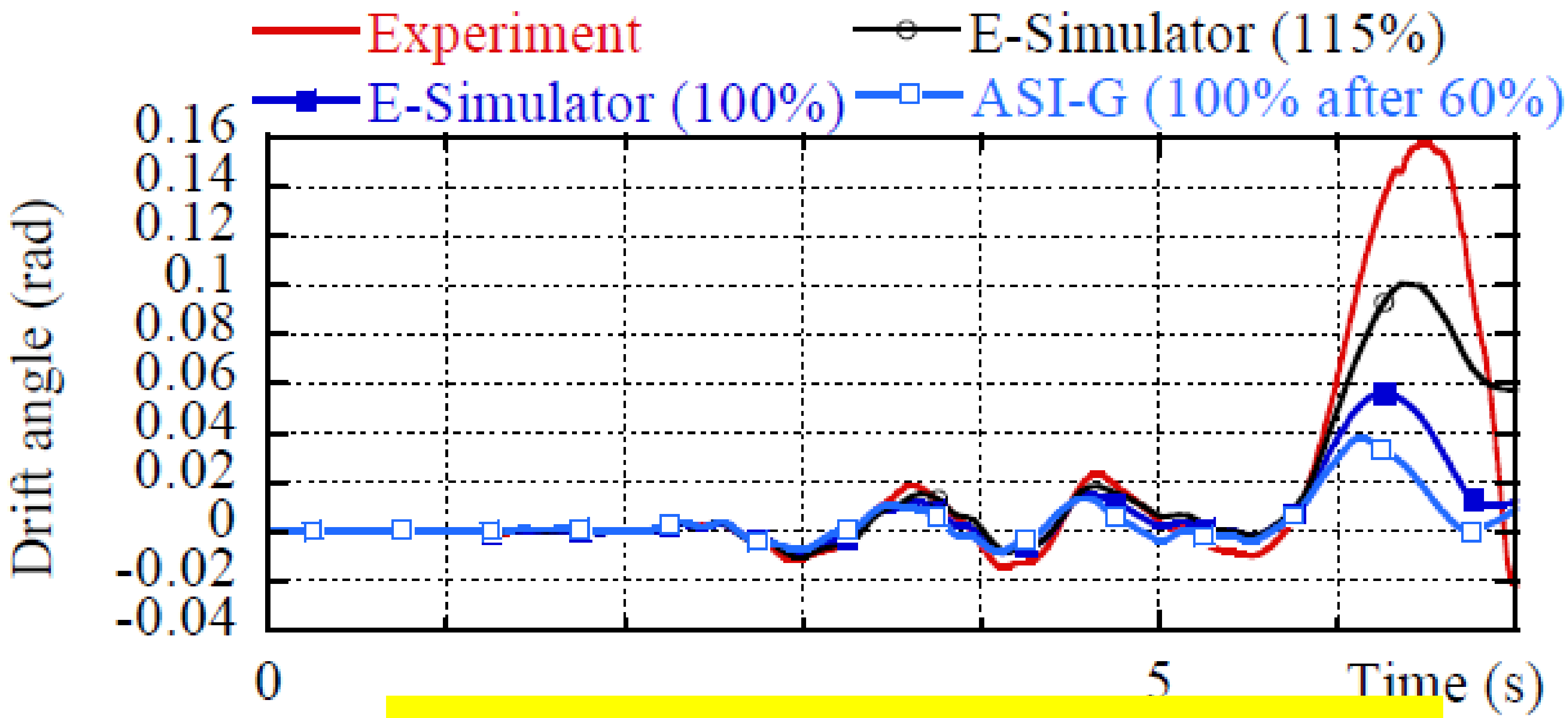
Analysis against 100% and 115% Takatori wave



Interstory drift angle of 1st story

X-direction

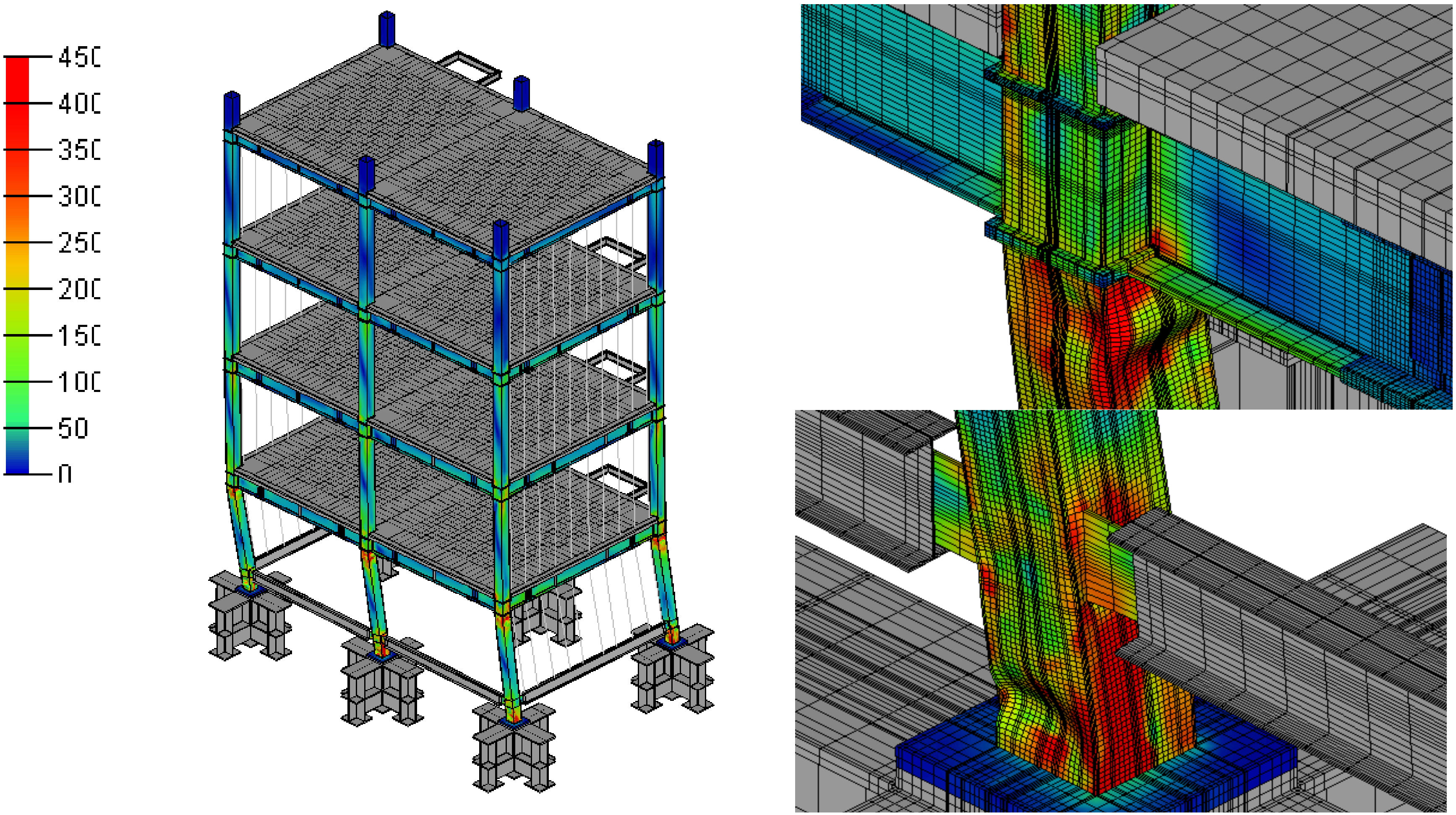
Analysis against 100% and 115% Takatori wave



Interstory drift angle of 1st story

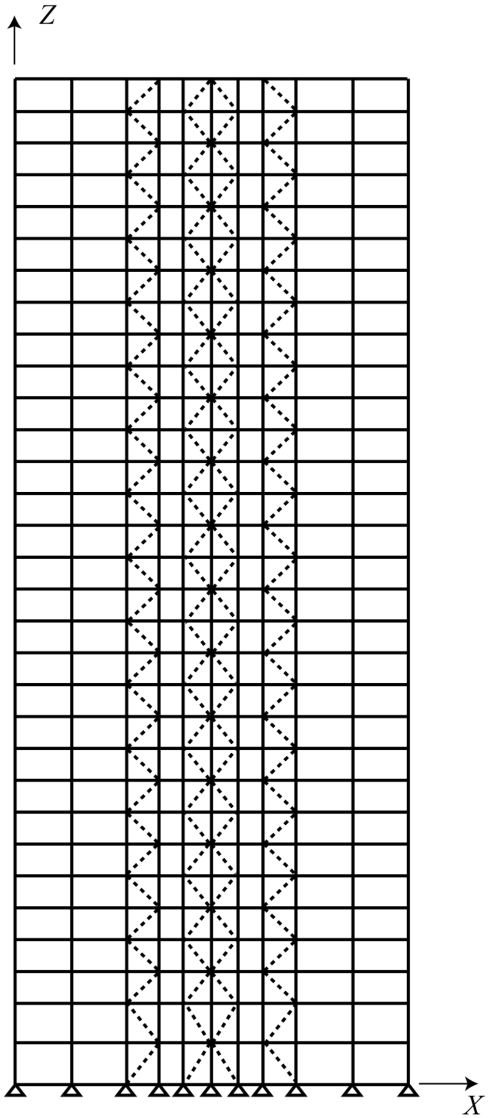
Y-direction

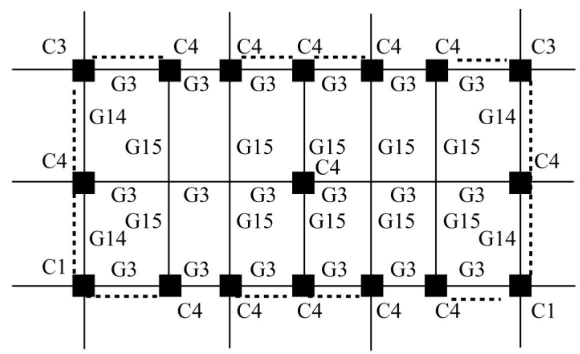
Equivalent stress (115%)



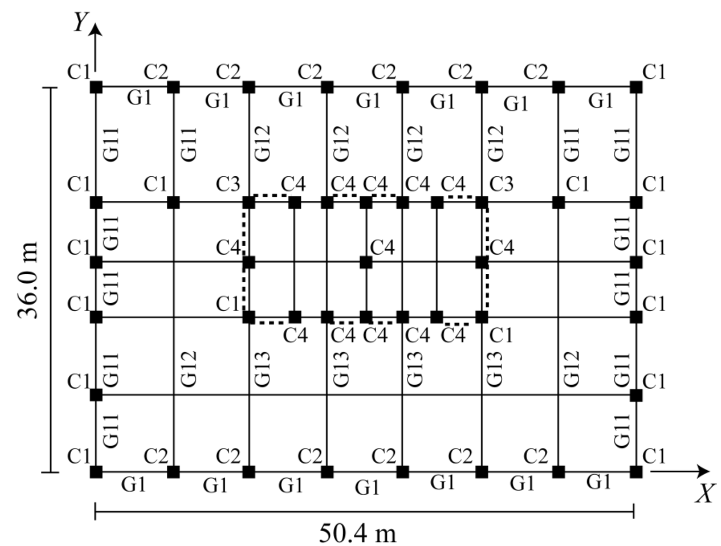
Ductile fracture is not considered

Seismic response analysis of 31-story steel building

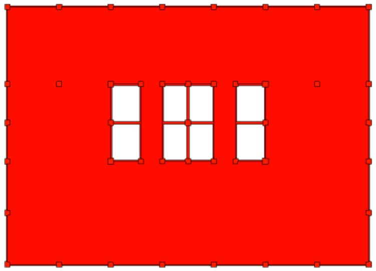


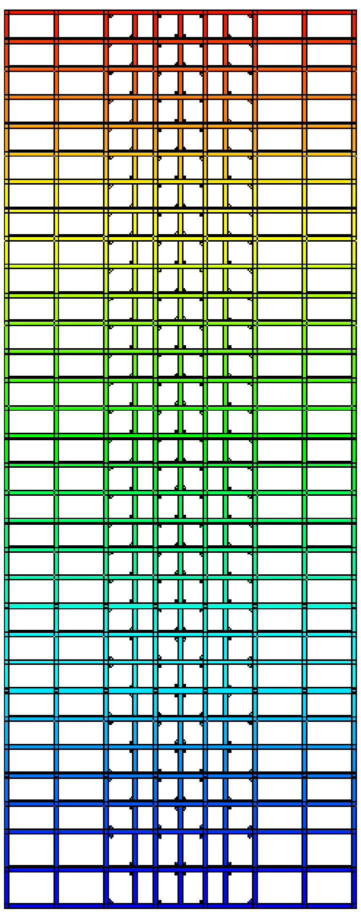


Close view of the core

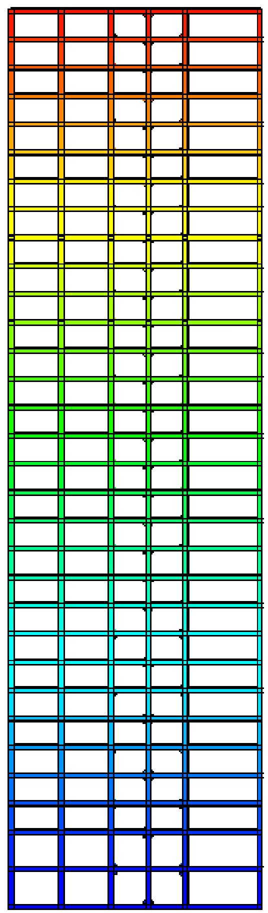


CAD Model

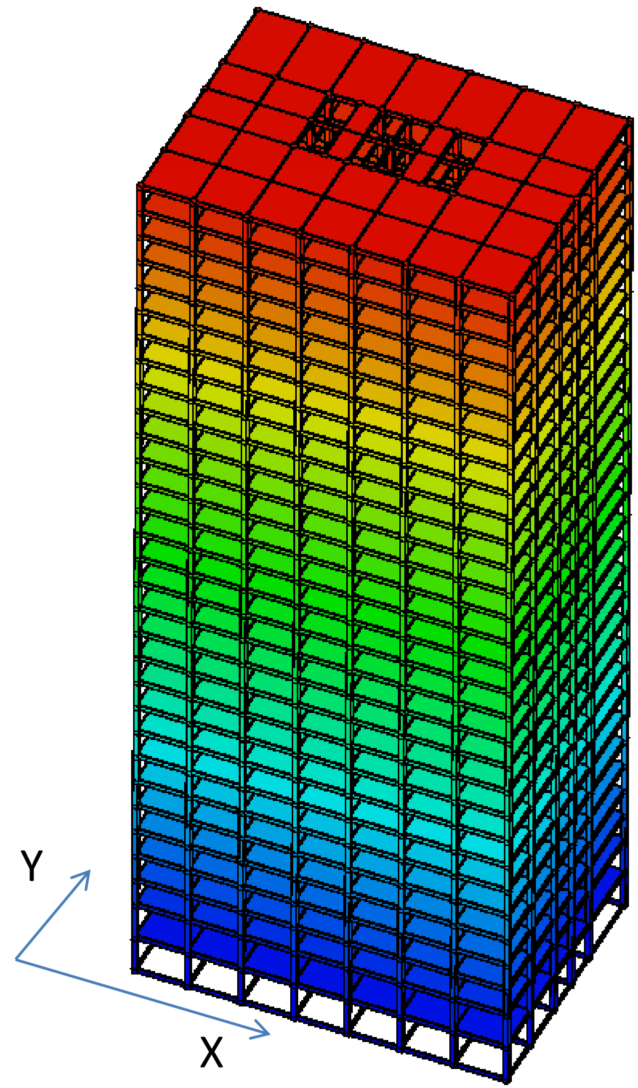


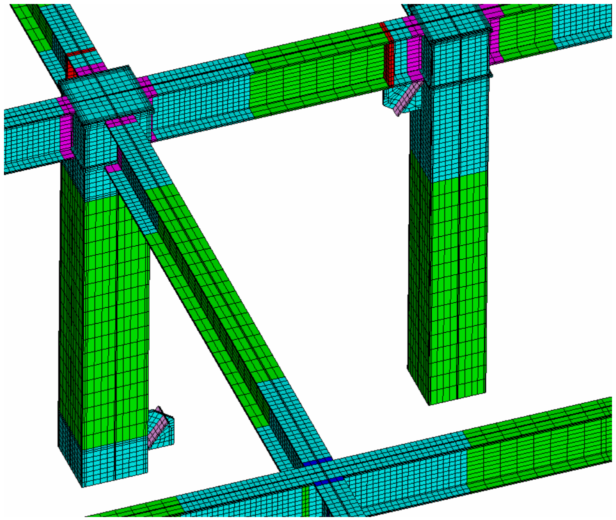


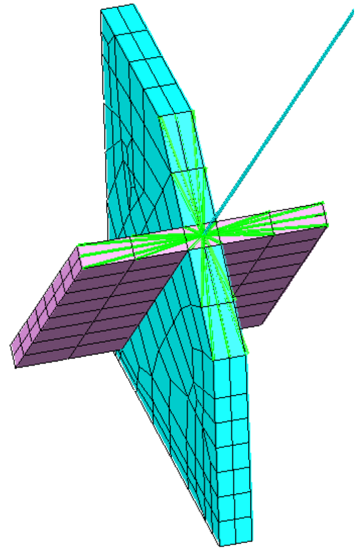
X-Dir

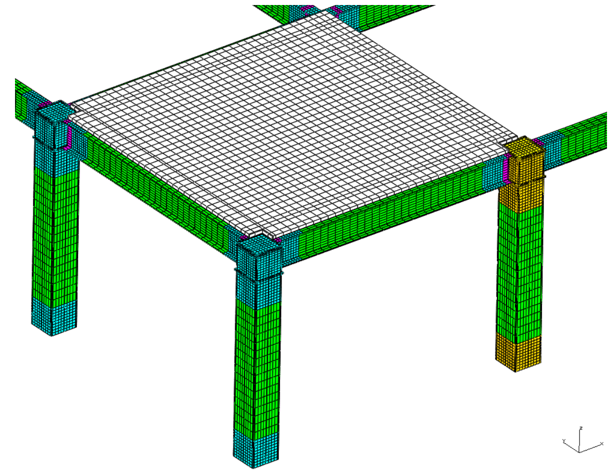


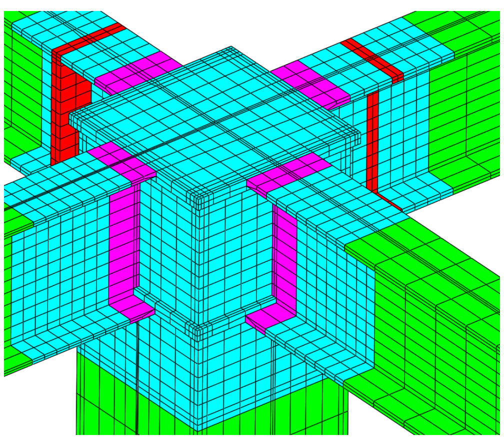
Y-Dir.

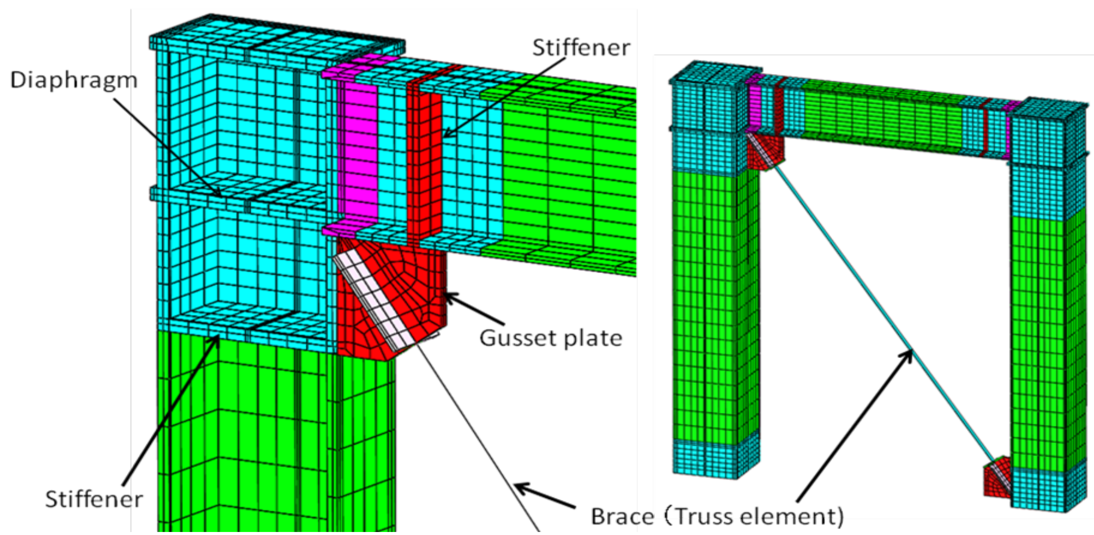




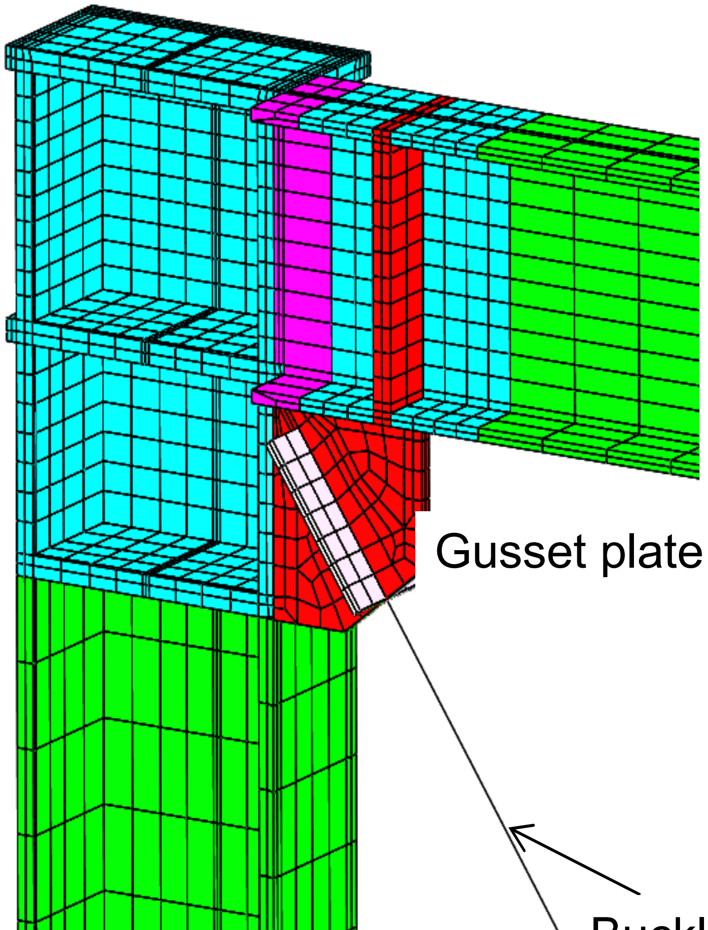


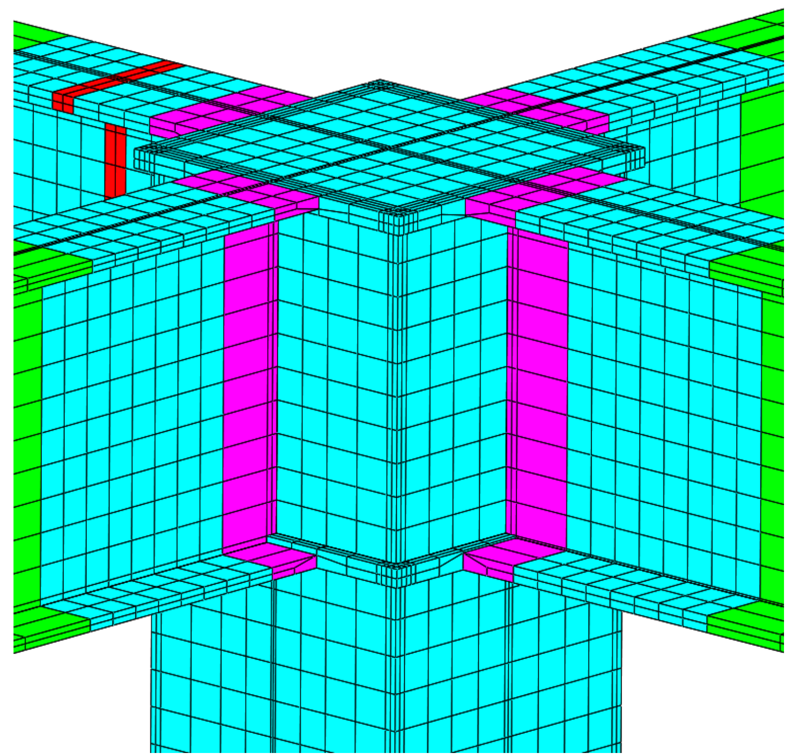




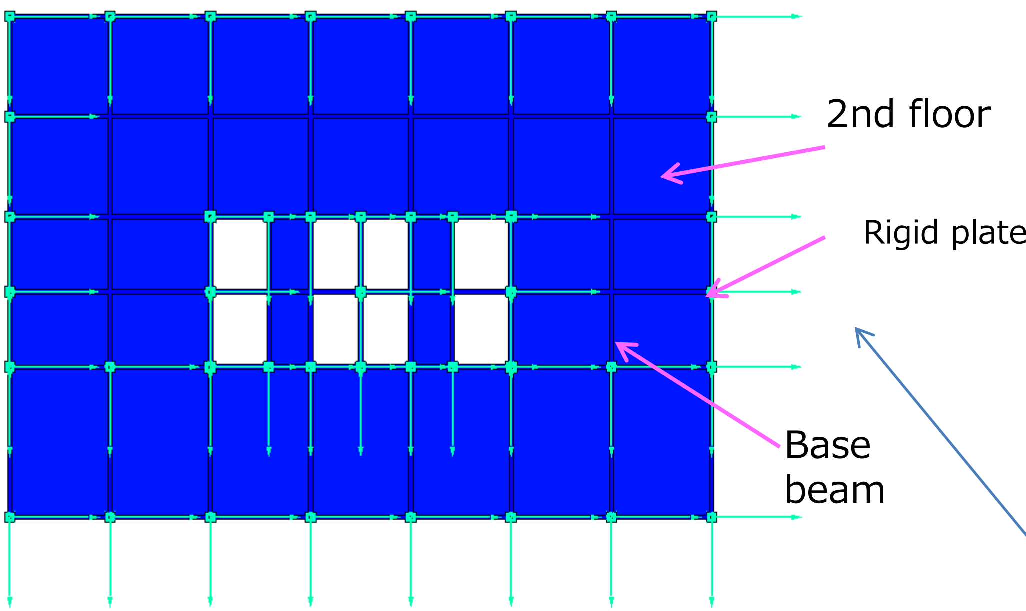

Diaphragm
Stiffener
Gusset plate
Stiffener
Brace（Truss element）

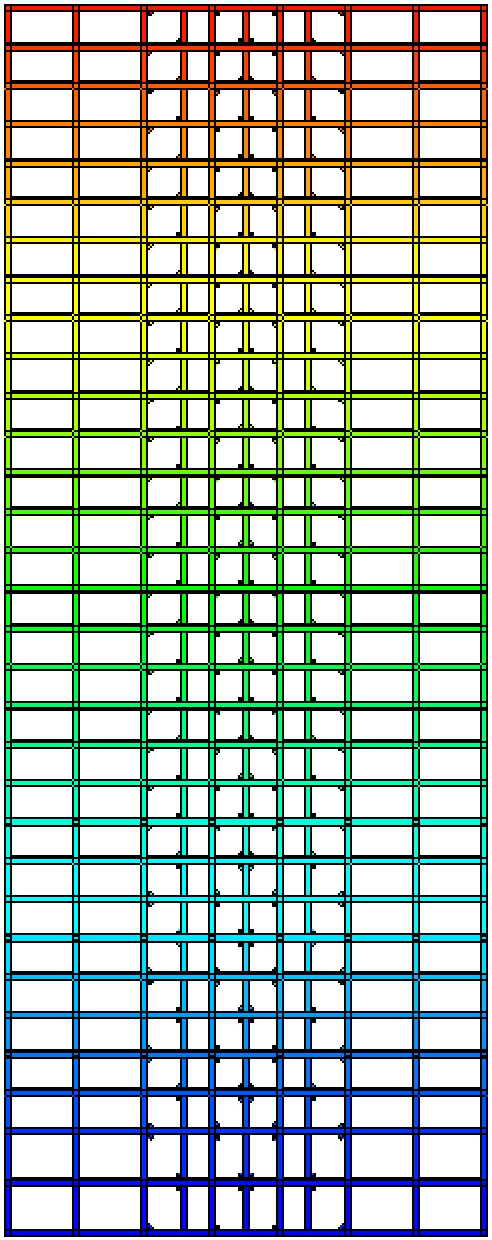
FE-mesh





Node	24,765,275
Hex. Element	15,592,786
Rigid beam	78,686
Truss	372
Slave node	1,503,130
DOFs	74 million





JR-Takatori wave of Kobe Earthquake, 1995.

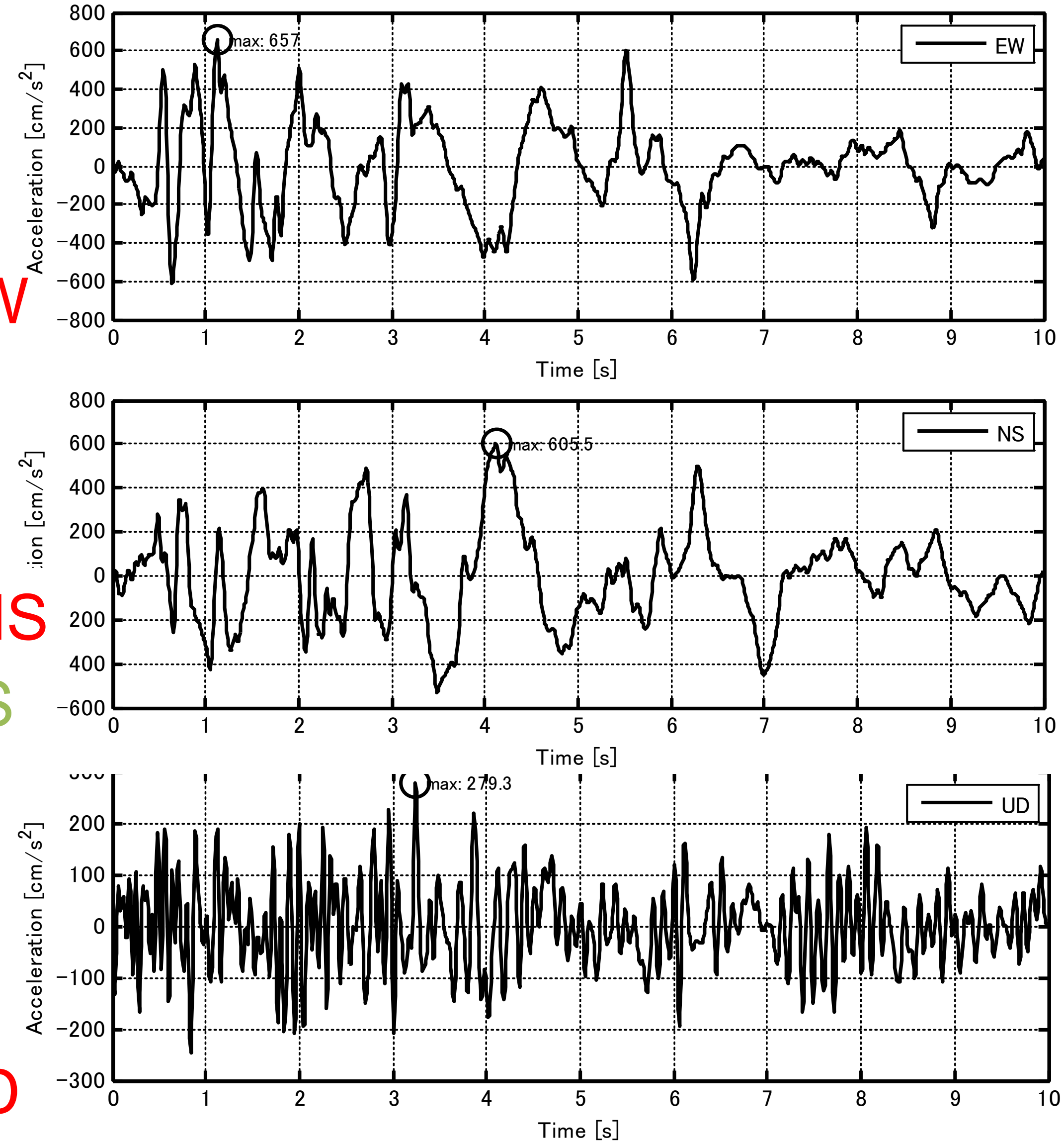
EW

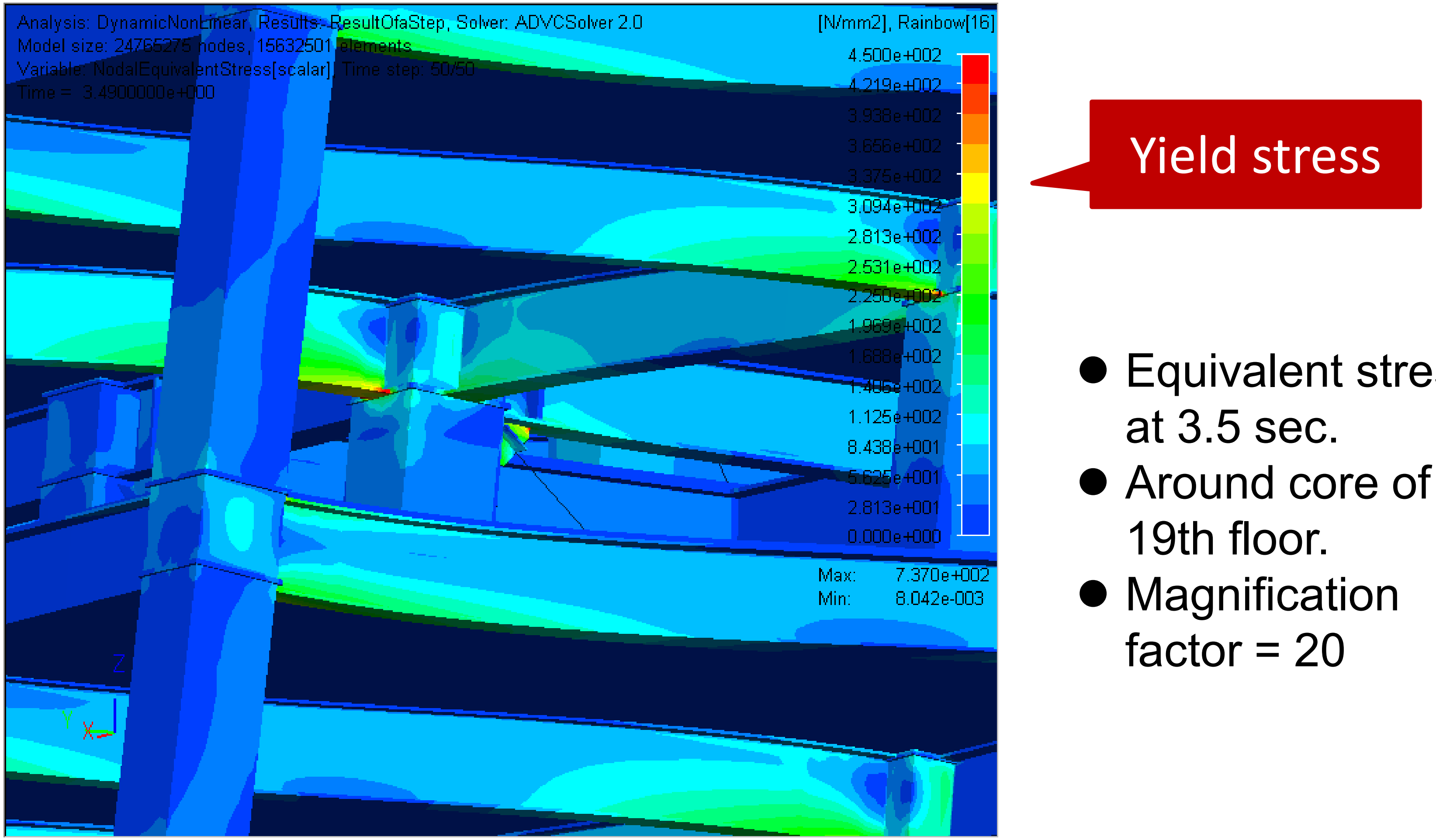
NS

NS

Y

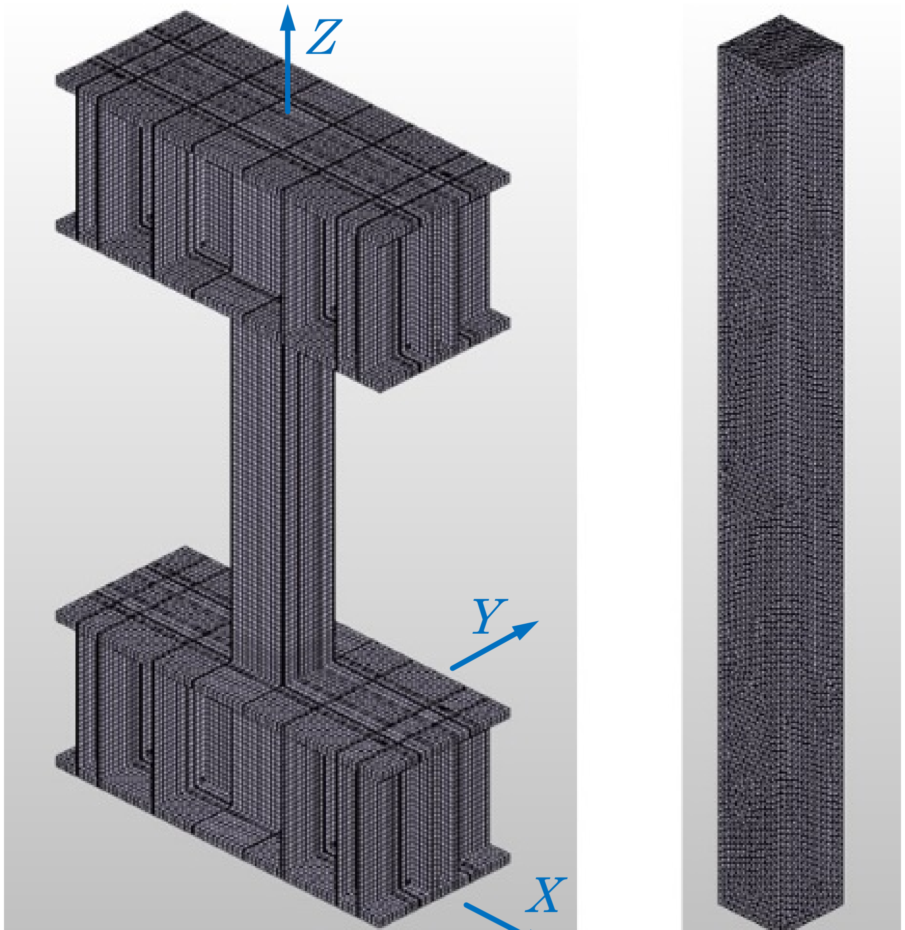
UD





- Equivalent stress at 3.5 sec.
- Around core of 19th floor.
- Magnification factor = 20

CFT (Concrete-Filled Tube) column



Steel tube　　Filled concrete

Finite Element Mesh Model

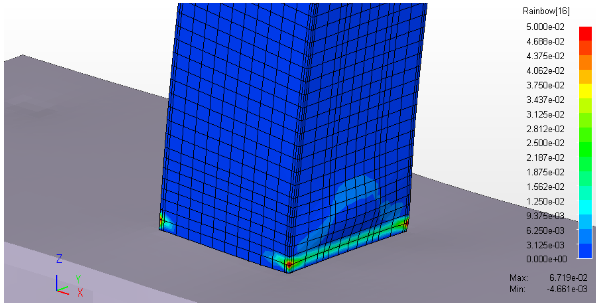
Steel:
- Linear hexahedron
- Incompatible mode

Filled Concrete:
- Linear tetrahedron

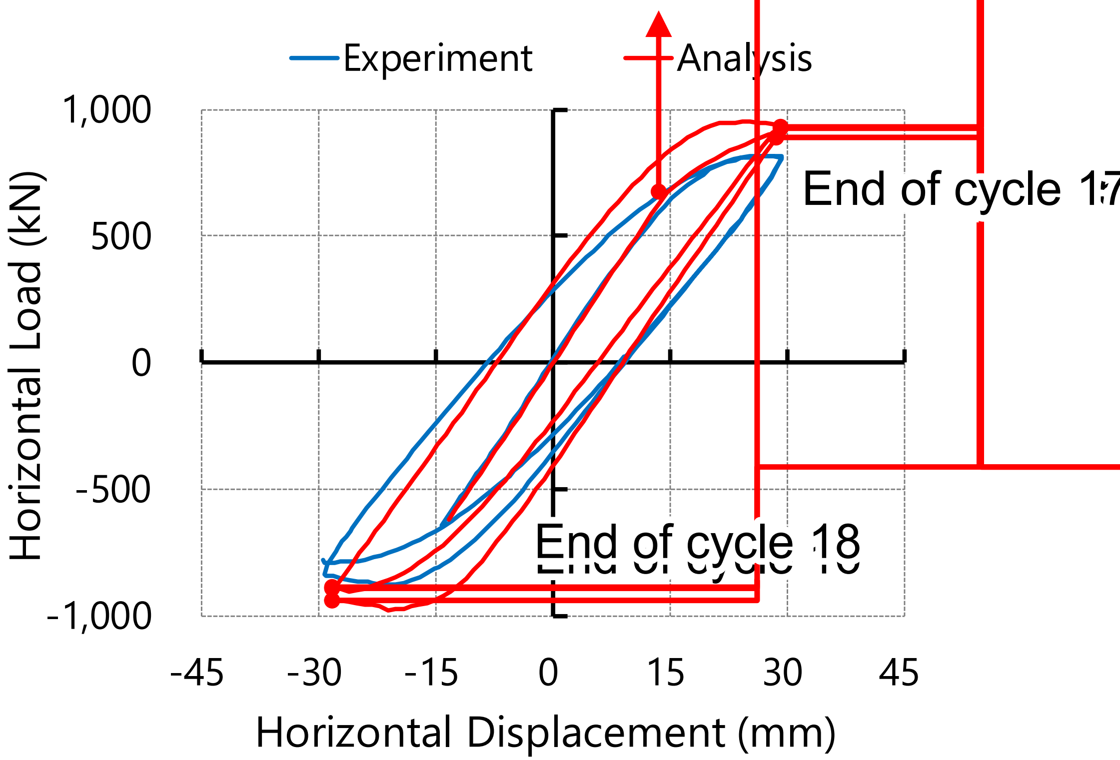
Size of Elements:
- 15-20 mm

Size of Mesh Model:
- 122,320 nodes
- 165,131 elements

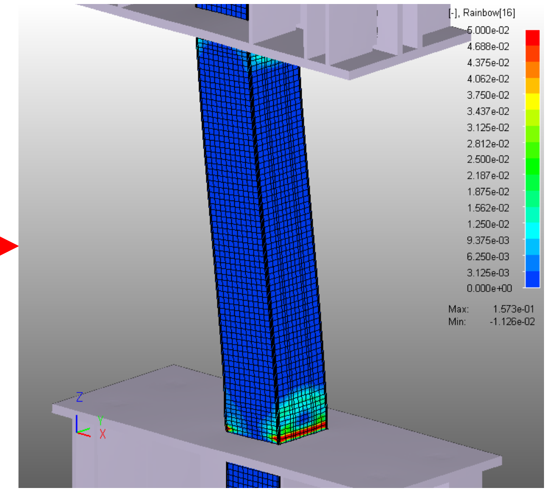
Contact btw concrete and steel tube:
- Out-of-plane: contact
- In-plane: slip



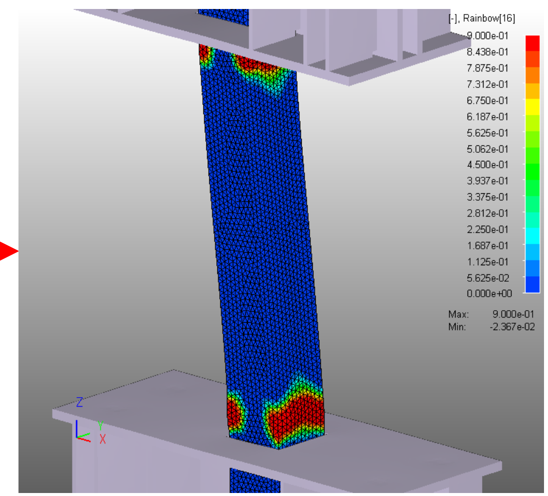
Local buckling of steel tube
(Also in exp. Observed in cycle 15)



Cycles 15-18



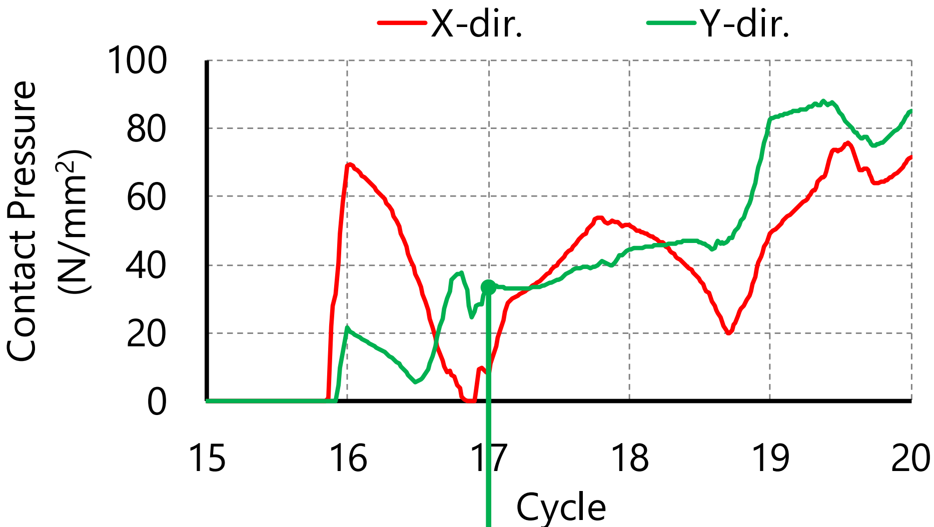
Eq. plastic strain of steel tube



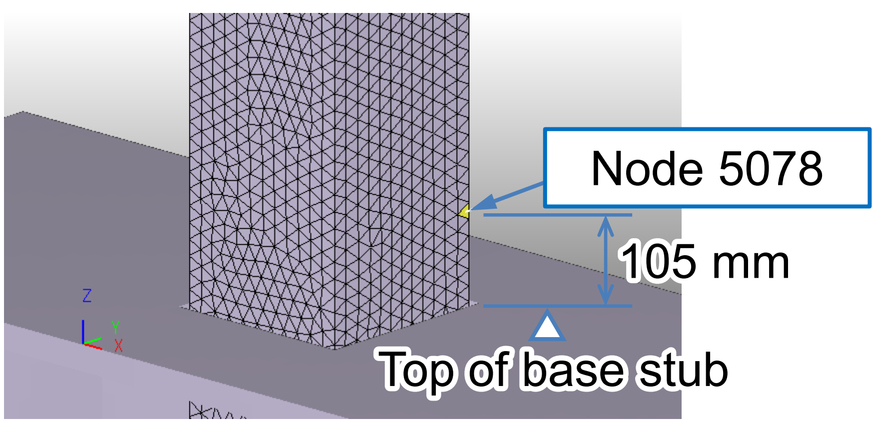
f_{cave} of filled concrete

Interaction between Steel Tube and Filled Concrete:

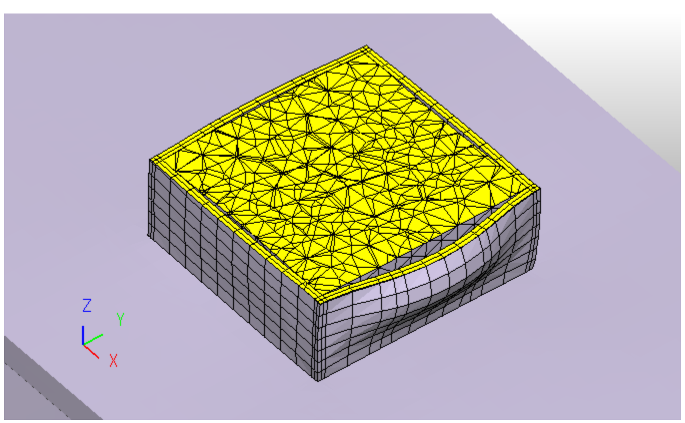
- X-dir.: Due to bending
- Y-dir.: Due to plastic deformation of concrete



Contact Pressure at node 5078



Position of node 5078



Section at node 5078 (End of Cycle 17)

Ductile fracture model for steel

- Linear cumulative damage rule
  - S-N curve, Minor's rule, modified Minor's rule
  - Not applicable to low-cycle fatigue (damage)
- Computational damage model
  - Gurson model: Damage due to void growth
- Mason-Coffin rule
  - Relation between strain amplitude and number of cycles
- Damage plasticity model
  - Mainly for concrete
- Fracture index
  - SMCS (stress modified critical strain) rule
- Two types of damage ductile damage/fracture model
  - Degradation before fracture / No degradation before fracture

Fracture without degradation

D : Damage parameter

$$\Delta D = \begin{cases} (Y / S)^t \Delta\varepsilon^p & \text{for} \quad \sigma_m / \sigma_e > -1/3 \\ 0 & \text{for} \quad \sigma_m / \sigma_e \le -1/3 \end{cases}$$

Y : twice of elastic strain energy

σ_e : equivalent stress, σ_m : mean stress

$\Delta\varepsilon^p$: plastic strain increment, S, t : parameter

Fracture occurs if D exceeds the specified value

D can be integrated explicitly

σ_m / σ_e=1/3 for uniaxial, 2/3 for biaxal tension

- Lemaitre, J. : A Course on Damage Mechanics, Springer-Verlag, pp.95-151, 1992
- Dufalilly, J. and Lemaitre, J. : Modeling Very Low Cycle Fatigue, International, Journal of Damage Mechanics, Vol.4, pp.153-170, 1995
- Huang, Y. and Mahin, S. : Evaluation of Steel Structure Deterioration with Cyclic Damaged Plasticity, Proceedings of 14WCEE, 2008

Gurson model

$$\phi = \left(\frac{\sigma_e}{\sigma_Y}\right)^2 + 2fq\cosh\left(\frac{3\sigma_m}{\sigma_Y}\right) - [1 + (qf)^2] = 0$$

ϕ : yield function, σ_Y : yield stress without damage

σ_e : equivalent stress, σ_m : mean stress

f : volume ration of void, q : parameter $(= 1.5)$

Stiffness degradation due to void growth

- A. Needleman and V. Tvergaard, Numerical modeling of the ductile-brittle transition, Int. J. Fracture, Vol. 101, pp. 73-97, 2000.
- A. L. Gurson, Continuum theory of ductile rupture by void nucleation and growth: Part I, Tield criteria and flow rules for porus ductile media, J. Eng. Material and Tech., ASME, Vol. 99, pp. 2-15, 1977.

Damage plasticity for concrete

D : Isotropic damage degradarion parameter

$\boldsymbol{\sigma}$: Stress tensor, $\tilde{\boldsymbol{\sigma}}$: Effective stress tensor

$$\tilde{\boldsymbol{\sigma}} = [1/(1-D)]\,\boldsymbol{\sigma}$$

$\mathbf{E}_0$: Initial elastic stiffness tensor

$\mathbf{E} = (1-D)\mathbf{E}_0$: Effective elastic stiffness tensor

$\boldsymbol{\varepsilon}^e$: Elastic strain tensor

$$\tilde{\boldsymbol{\sigma}} = \mathbf{E}_0\boldsymbol{\varepsilon}^e, \quad \boldsymbol{\sigma} = \mathbf{E}\boldsymbol{\varepsilon}^e = (1-D)\mathbf{E}_0\boldsymbol{\varepsilon}^e$$

- J. Lee and G. Fenves, Plastic-damage model for cyclic loading of concrete structures, J. Struct. Eng., Vol. 124(8), pp. 892-900, 1998.

Damage plasticity for concrete

Yield condition

$$F(\tilde{\boldsymbol{\sigma}}, \boldsymbol{\alpha}, \kappa) = 0$$

$\boldsymbol{\alpha}$: Back stress tensor, κ : Size of yield surface

↓

$$\tilde{F}(\boldsymbol{\sigma}, \hat{\boldsymbol{\alpha}}, \hat{\kappa}) = 0$$

$$\hat{\boldsymbol{\alpha}} = (1 - D)\,\boldsymbol{\alpha}, \quad \hat{\kappa} = (1 - D)\,\kappa$$

Evolution rule for *D* based on principal stresses

Fracture index

σ_m : Mean stress, σ_e : Equivalent stress (von Mises stress)

$T = \dfrac{\sigma_m}{\sigma_e}$: Stress triaxiality

(1/3 for uniaxial stress, 2/3 for uniform biaxial stress)

$\varepsilon^c = \beta \exp(-1.5T)$: fracture strain

$\hat{\varepsilon}^p$: accumlated plastic stress for tension state $\sigma_m > 0$

$$\text{Fracture index} = \frac{\hat{\varepsilon}^p}{\varepsilon^c}$$

- J. W. Hancock and A. C. Mackenzie, On the mechanism of ductile failure in high-strength steels subjected to multi-axial stress-states, J. Mech. Phys. Solids, Vol. 24, pp. 147-169, 1976.

Fracture index

Fracture condition

$$\hat{\varepsilon}^p \geq \varepsilon^c = \beta \exp(-1.5T)$$

$$\Rightarrow \quad \alpha > \beta \quad (\alpha = \hat{\varepsilon}^p \exp(1.5T): \quad \text{deformation parameter})$$

$$\text{Uniaxial tension:} \;\; T = 1/3 \;\; \Rightarrow \;\; \alpha = e^{0.5}\hat{\varepsilon}^p = 1.649\hat{\varepsilon}^p$$

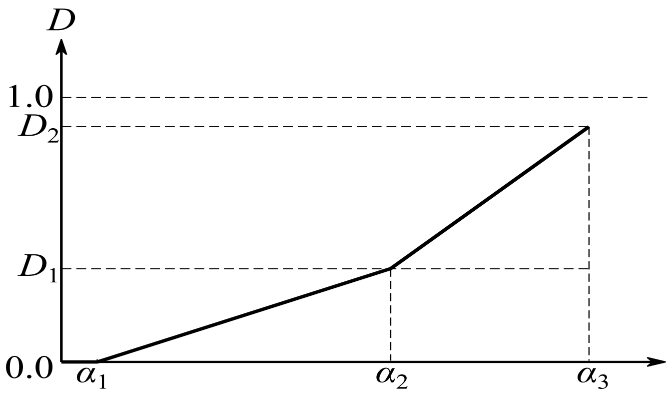
A. M. Kanvinde and G. G. Deierline, Void growth model and stress modified critical strain model to predict ductile fracture in structural steels, J. Struct. Eng., ASCE, Vol. 132(12), pp. 1907-1918, 2006.
S. El-Tawil, E. Vidarsson, T. Mikesell and S. K. Kunnath, Inelastic behavior and design of steel panel zones, J. Struct. Eng, ASCE, Vol. 125, No. 2, pp. 183-193, 1999.

Damage model using fracture index

Bilinear relation

D : damage parameter (fracture ratio)

$$D = \begin{cases} 0 & (\alpha \le \alpha_1) \\ \dfrac{D_1}{\alpha_2 - \alpha_1}(\alpha - \alpha_1), & (\alpha_1 \le \alpha \le \alpha_2) \\ \alpha_2 + \dfrac{D_2 - D_1}{\alpha_3 - \alpha_2}(\alpha - \alpha_2) & (\alpha_2 \le \alpha \le \alpha_3) \\ D_2 & (\alpha_3 \le \alpha) \end{cases}$$

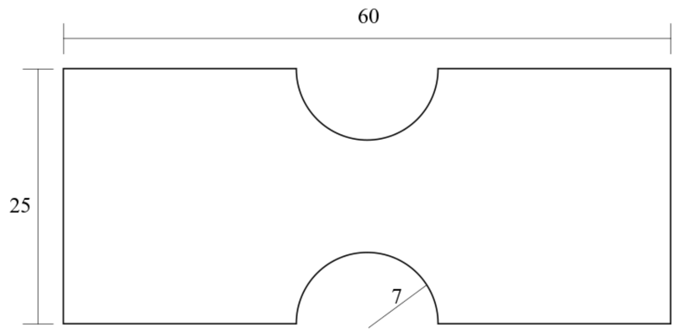


Piecewise linear relation

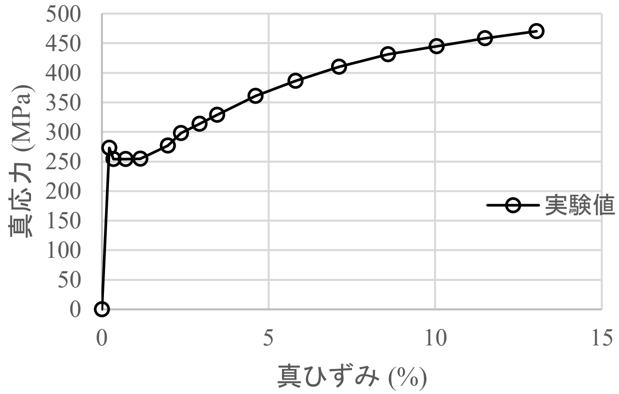
Finite element analysis

- E-Simulator based on ADVENTURECluster
- Linear hexahedral element with selective reduced integration of volumetric strain
- Implicit integration using updated Lagrangian formulation
- Cancellation of unbalanced force at next step

Analysis of notched rod model



Notched rod model

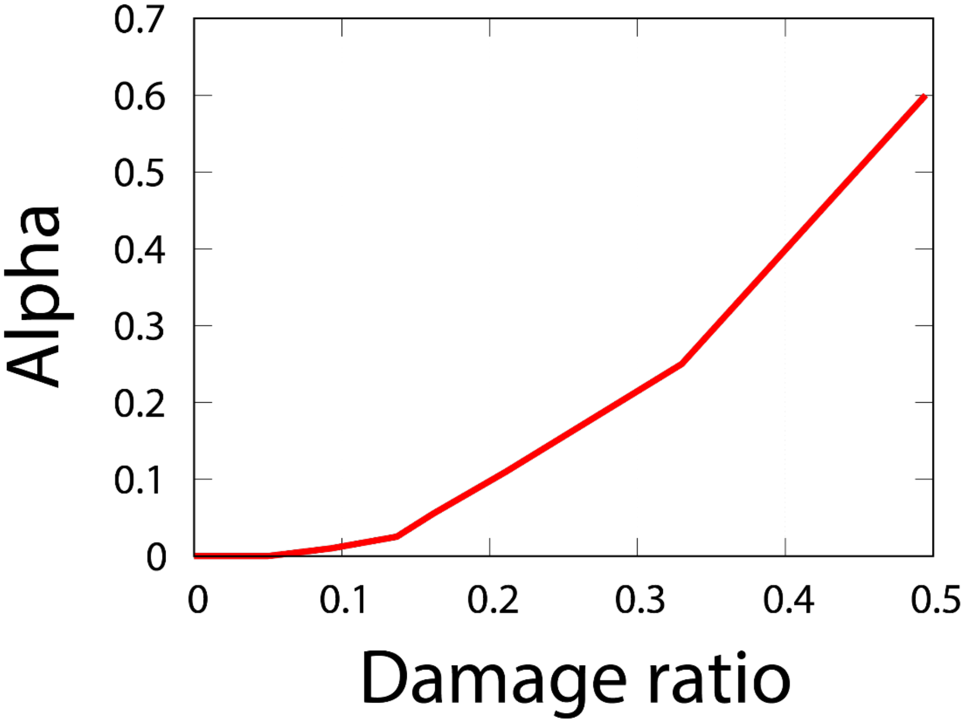


Stress-strain relation
(rod without notch)

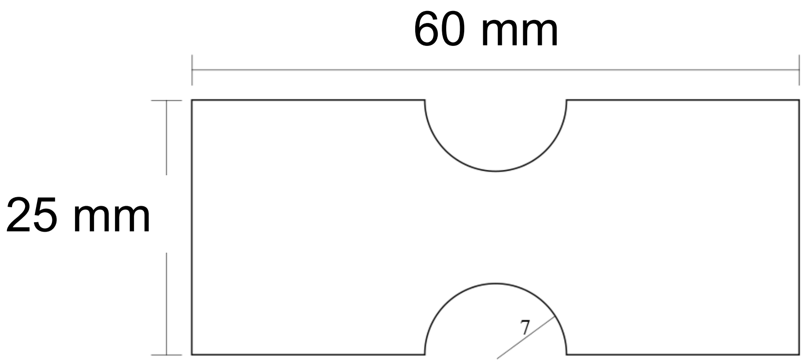
- M. Obata, A. Mizutani and Y. Goto, The verification of plastic constitutive relation and its application to FEM analysis of plastic fracture of steel members, J. JSCE, No. 626/I-48, pp. 185-195, 1999. (in Japanese)

Parameter for fracture

	α	*D*
1	0	0
2	0.0500	0
3	0.9250	0.010
4	0.1370	0.025
5	0.1672	0.055
6	0.2110	0.110
7	0.3298	0.250
8	0.4947	0.600



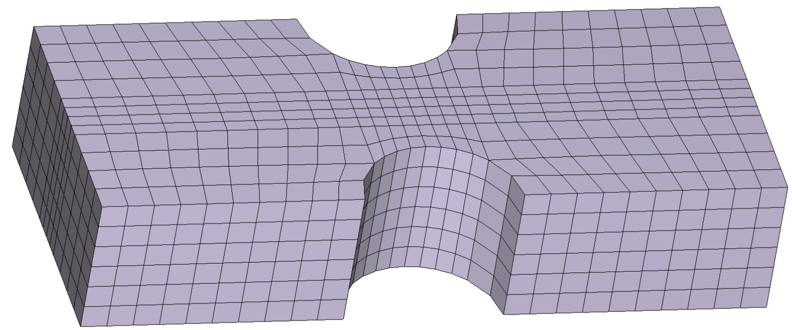
Analysis of rod model

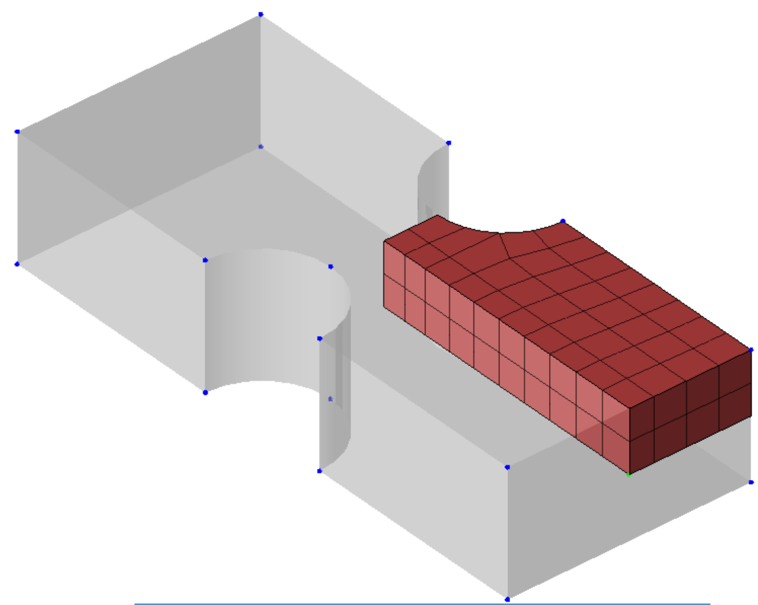


Thickness = 12.7 mm

Notched rod model

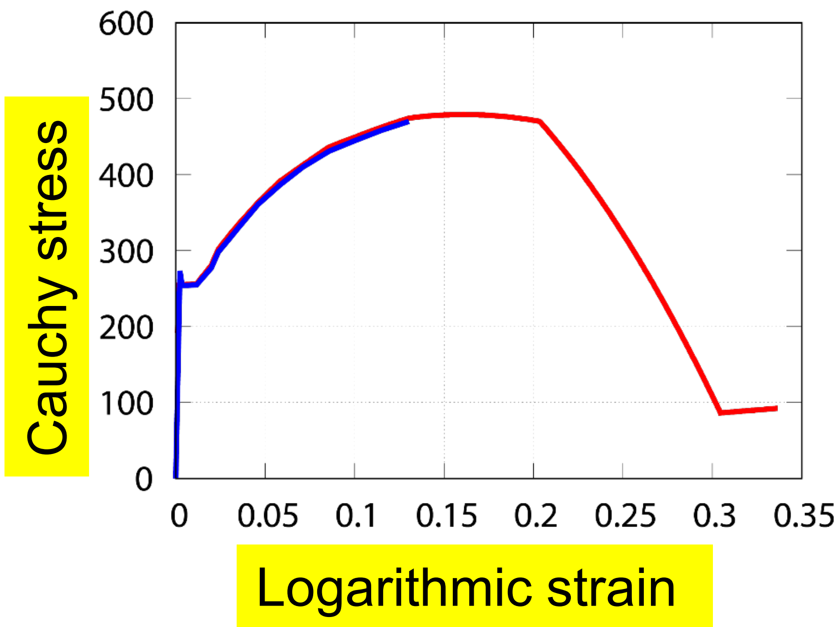
No. Elements: 1824
No. Nodes: 2443
NDOF: 7329

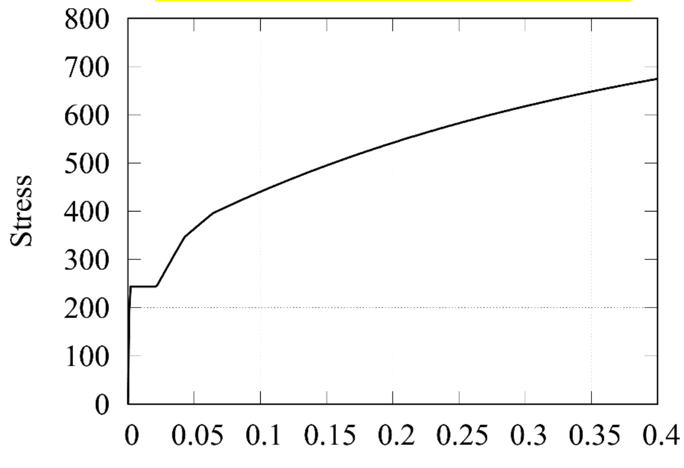




Unit size = 2.0 mm

Identification of material property





Relation without damage

$$\sigma_t = (1+\varepsilon_e)\sigma_e$$

$$\varepsilon_t = \begin{cases} \log(1+\varepsilon_e): & \text{before necking} \\ \log(A_0 / A): & \text{after necking} \end{cases}$$

σ_t : Cauchy stress

σ_e : engineering stress

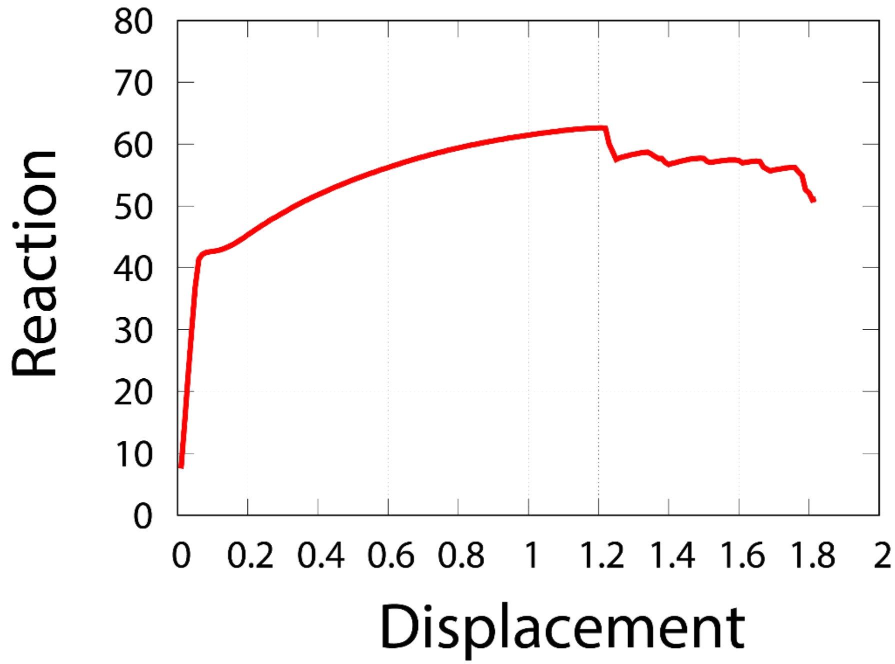
ε_t : true strain

ε_e : engineering strain

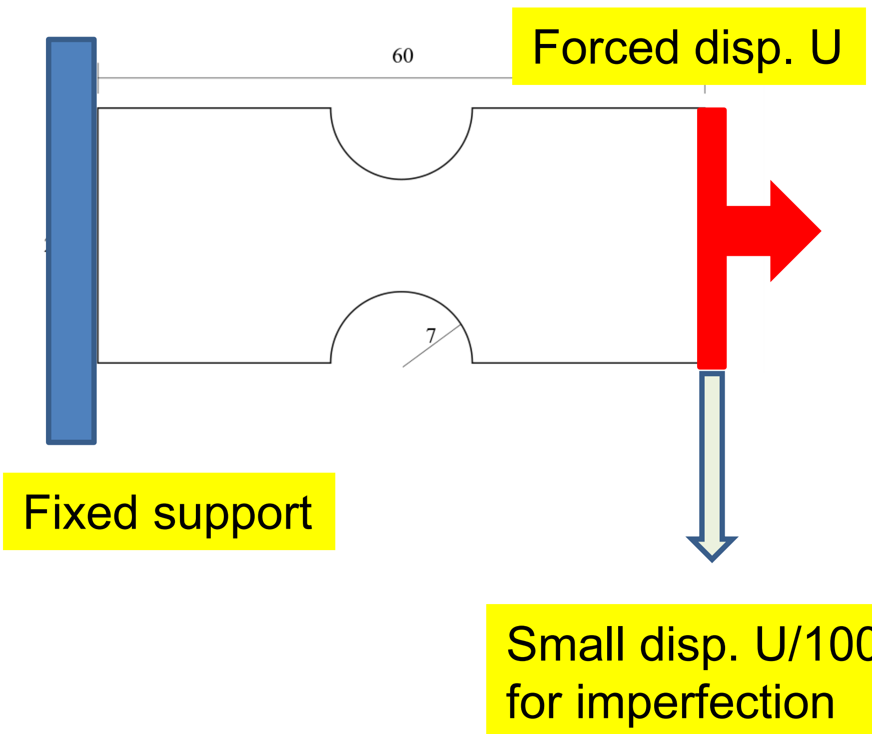
A : deformed area

A_0 : undeformed area

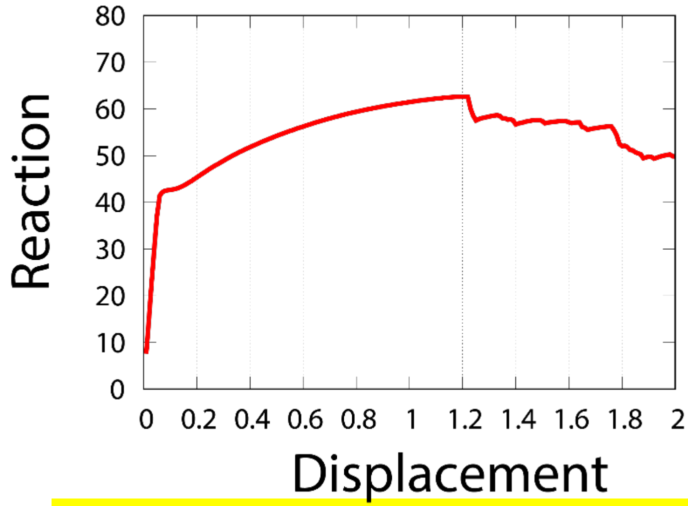
Force-displacement relation



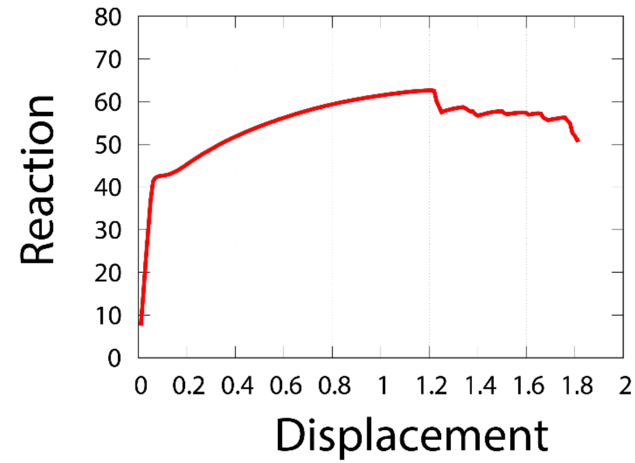
$\Delta = 0.001$, $\zeta = 10^{-8}$,



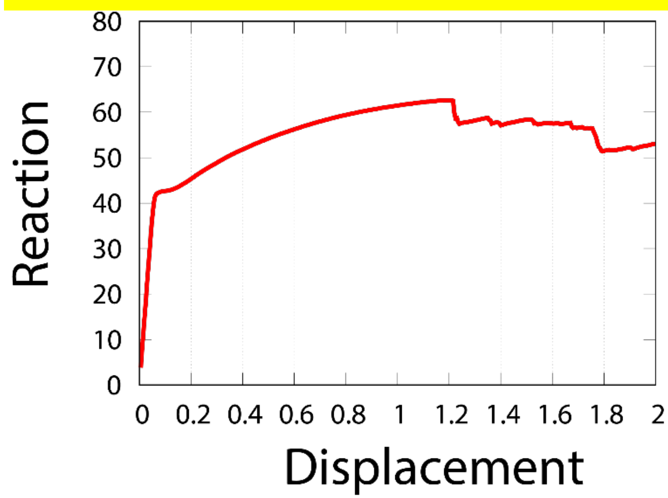
Force-displacement relation



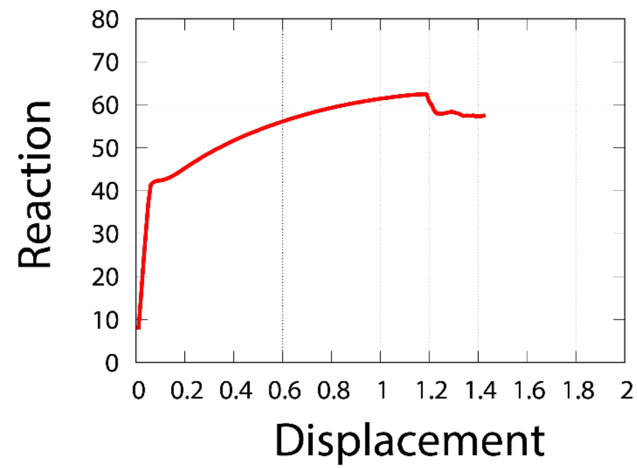
Δ = 0.001, ζ = 10^{-8}, imperfection



Δ = 0.001, ζ = 10^{-5},



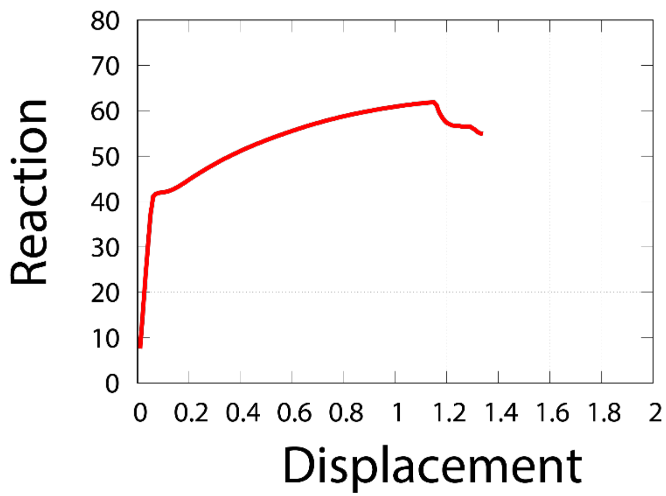
Δ = 0.0005, ζ = 10^{-3}, imperfection



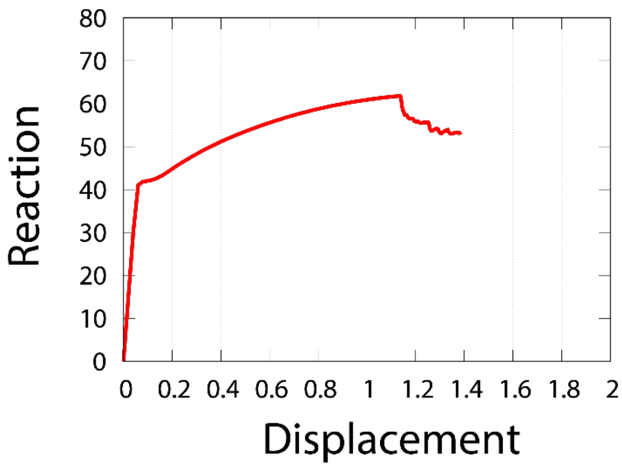
Incompatible mode, Δ = 0.001, ζ = 10^{-5},

Force-displacement relation

Unit size = 0.15625 mm,

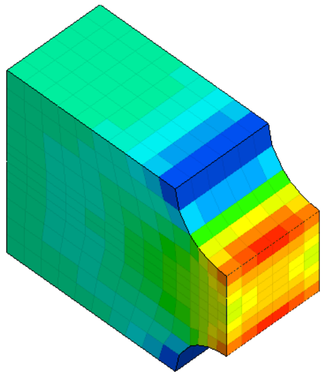


$\Delta = 0.001$, $\zeta = 10^{-8}$

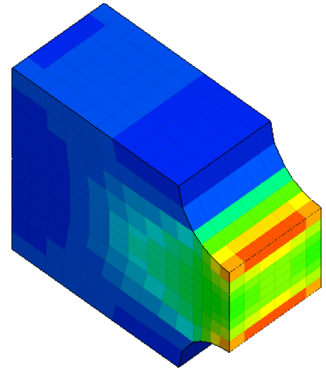


$\Delta = 0.0001$, $\zeta = 10^{-5}$

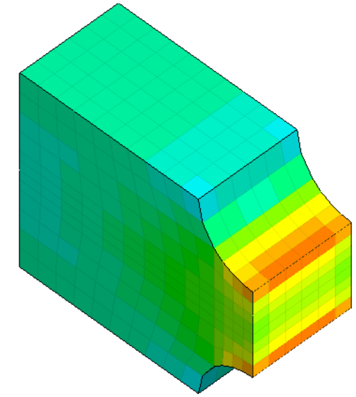
Fracture at U = 1.2
→ No significant mesh dependence
→ No stress concentration



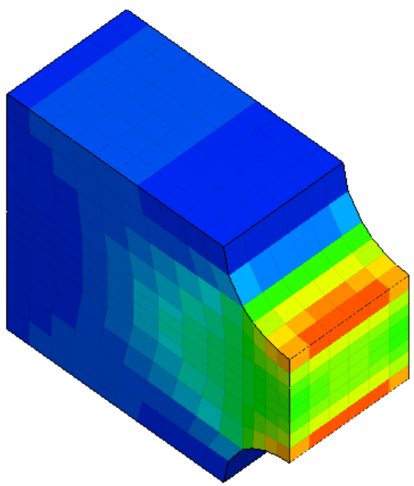
X-directional stress



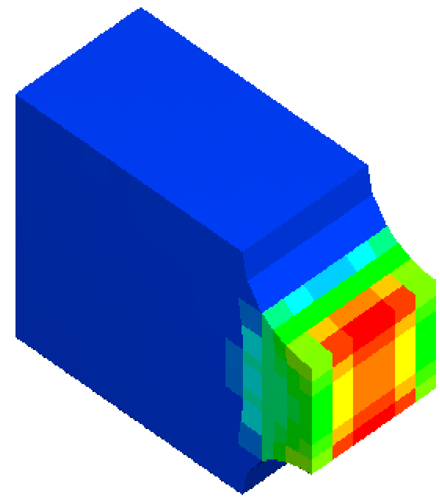
X-directional strain



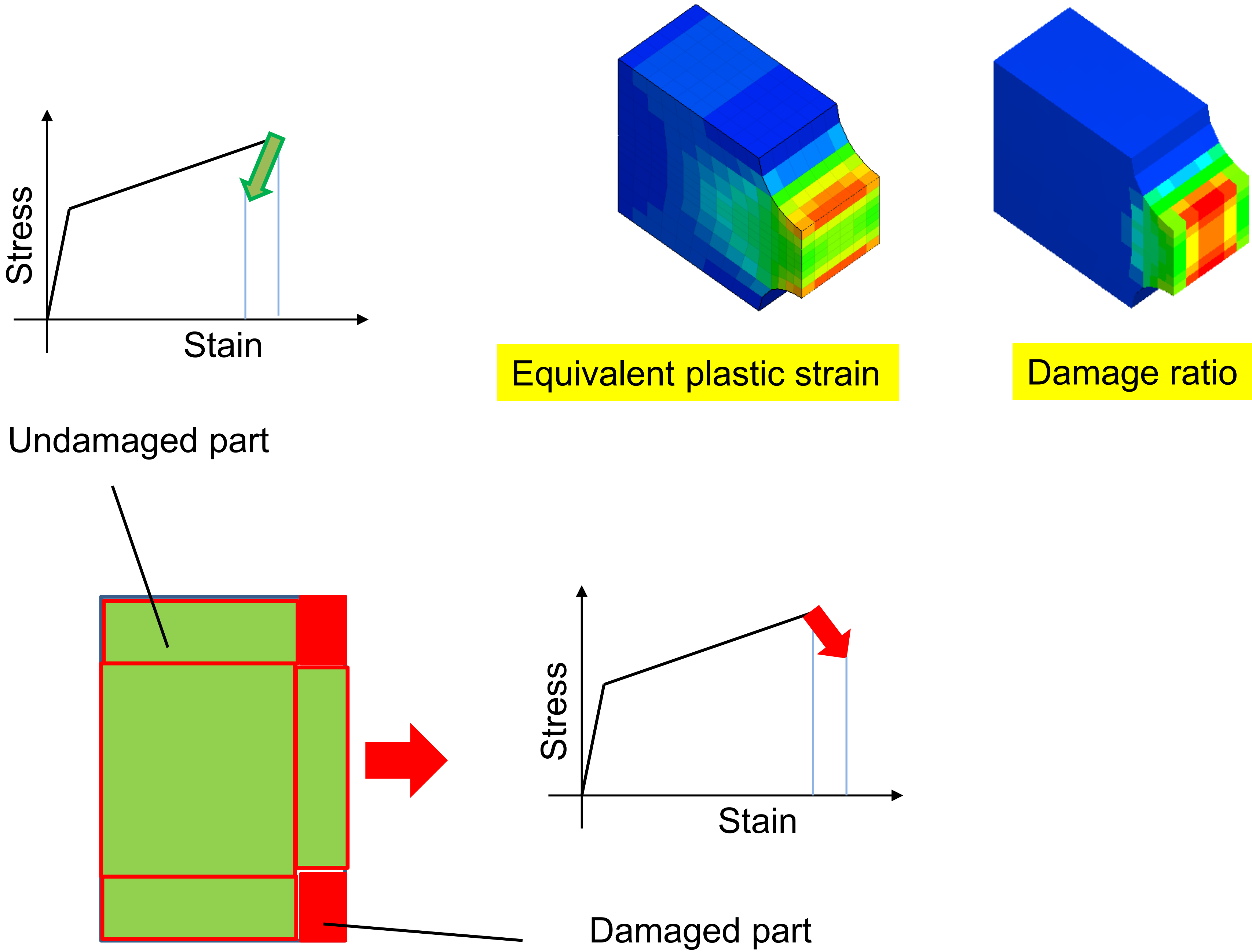
Equivalent stress



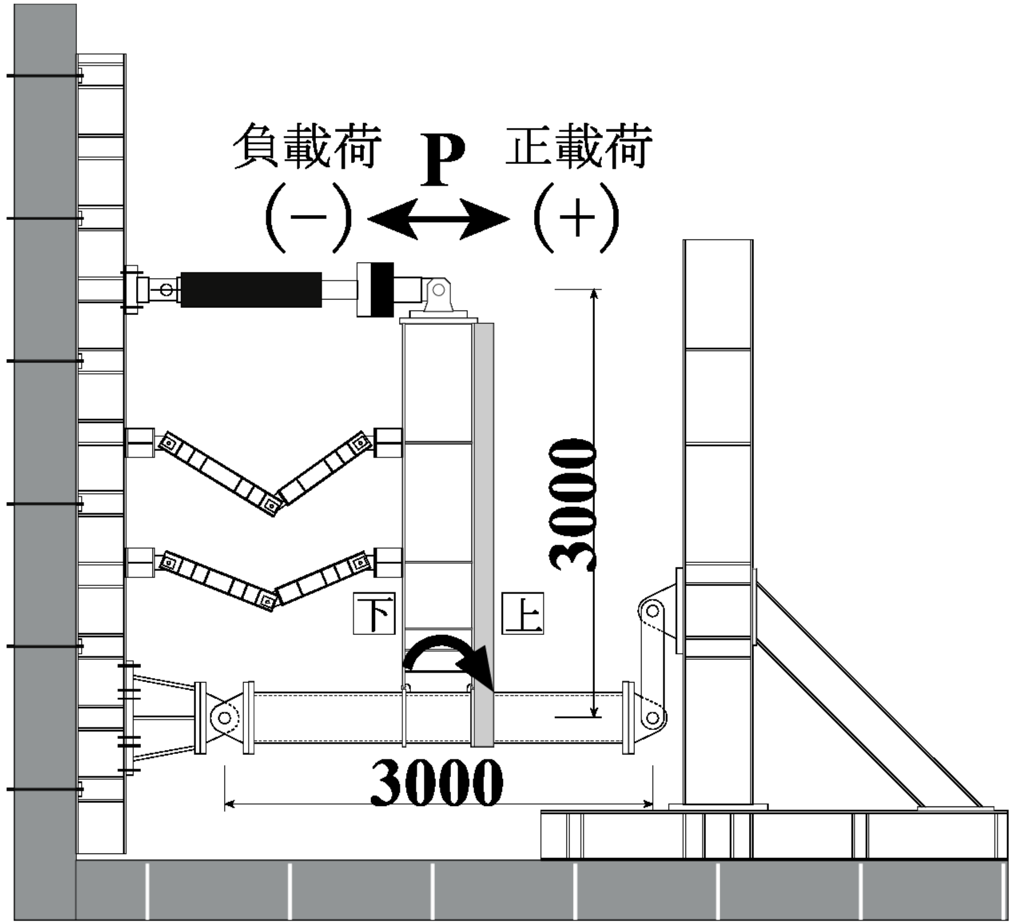
Equivalent plastic strain



Damage ratio

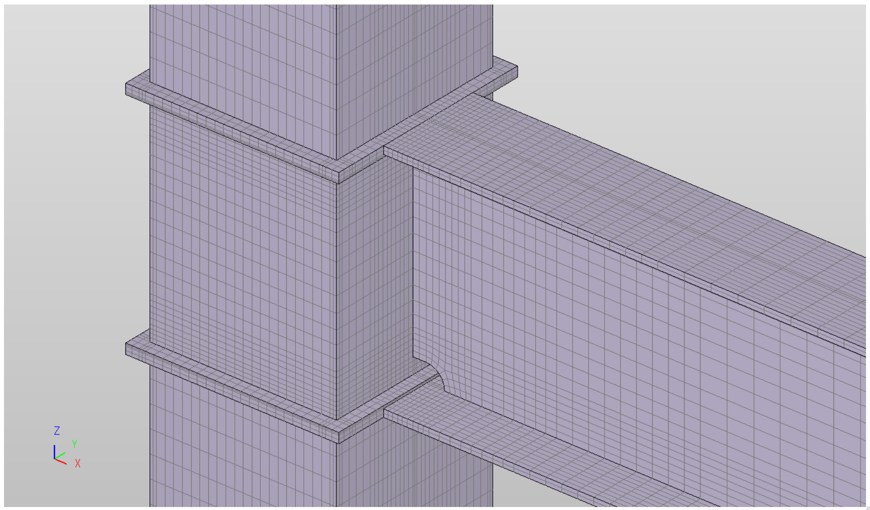

Stress
Stain
Equivalent plastic strain
Damage ratio
Undamaged part
Stress
Stain
Damaged part

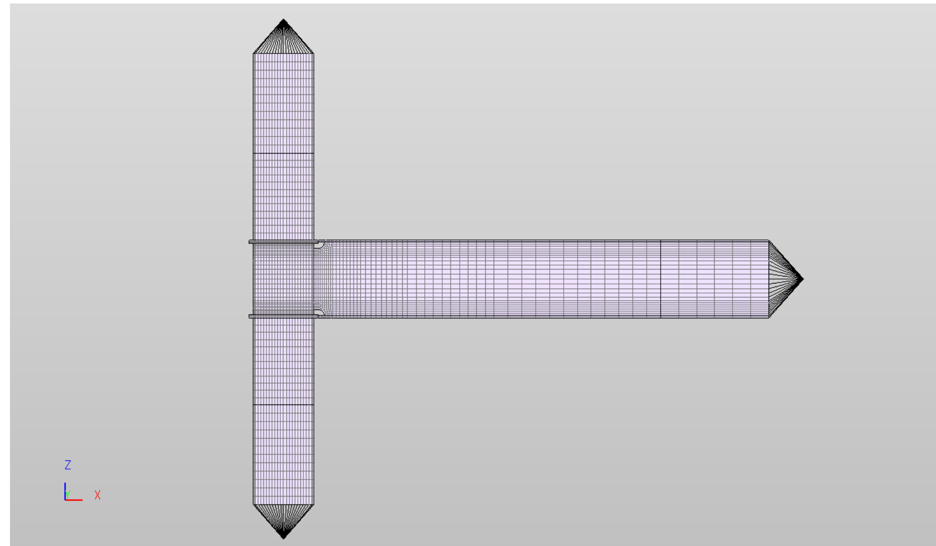
Analysis of beam-column model

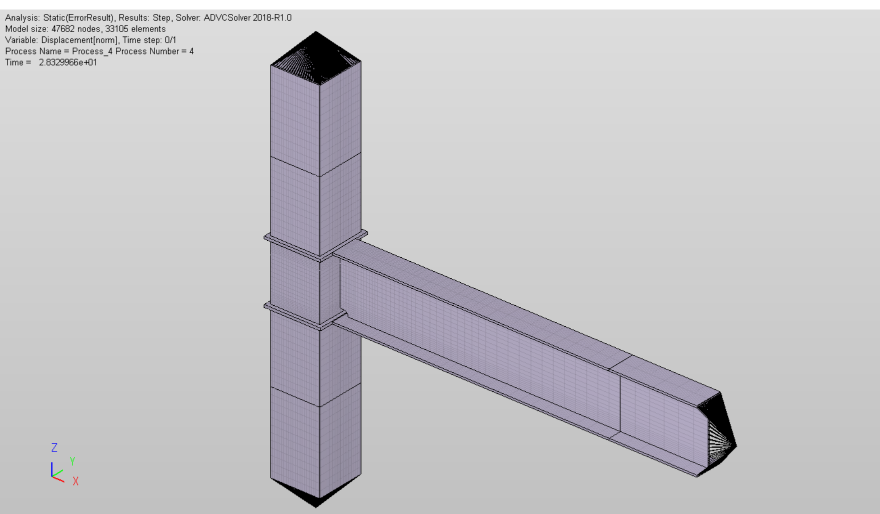


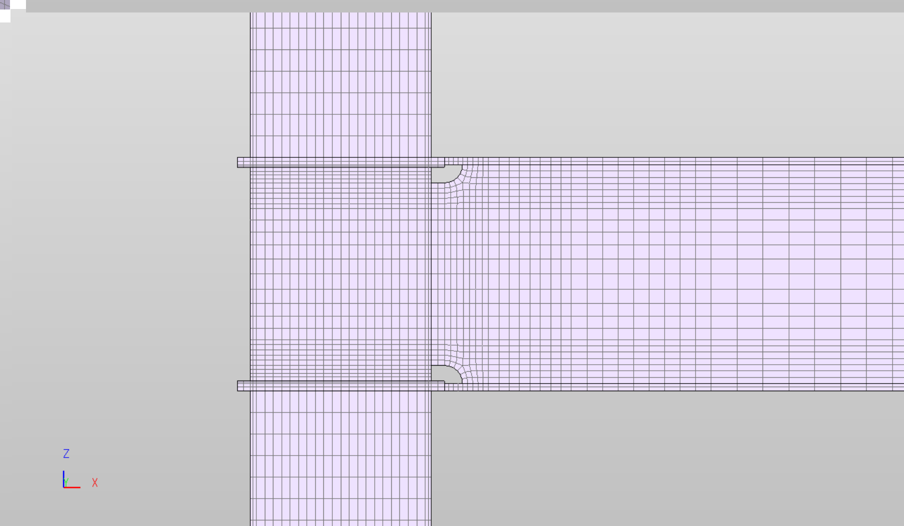
- D. Fukuoka, H. Namba and S. Morikawa, E-defense shaking table test for full scale steel building on cumulative damage by sequential strong ground motion (Part 2 Subassemblage Tests), Proc. Annual Symp. AIJ, Paper No. 22489, 2014.

Analysis of beam-column model

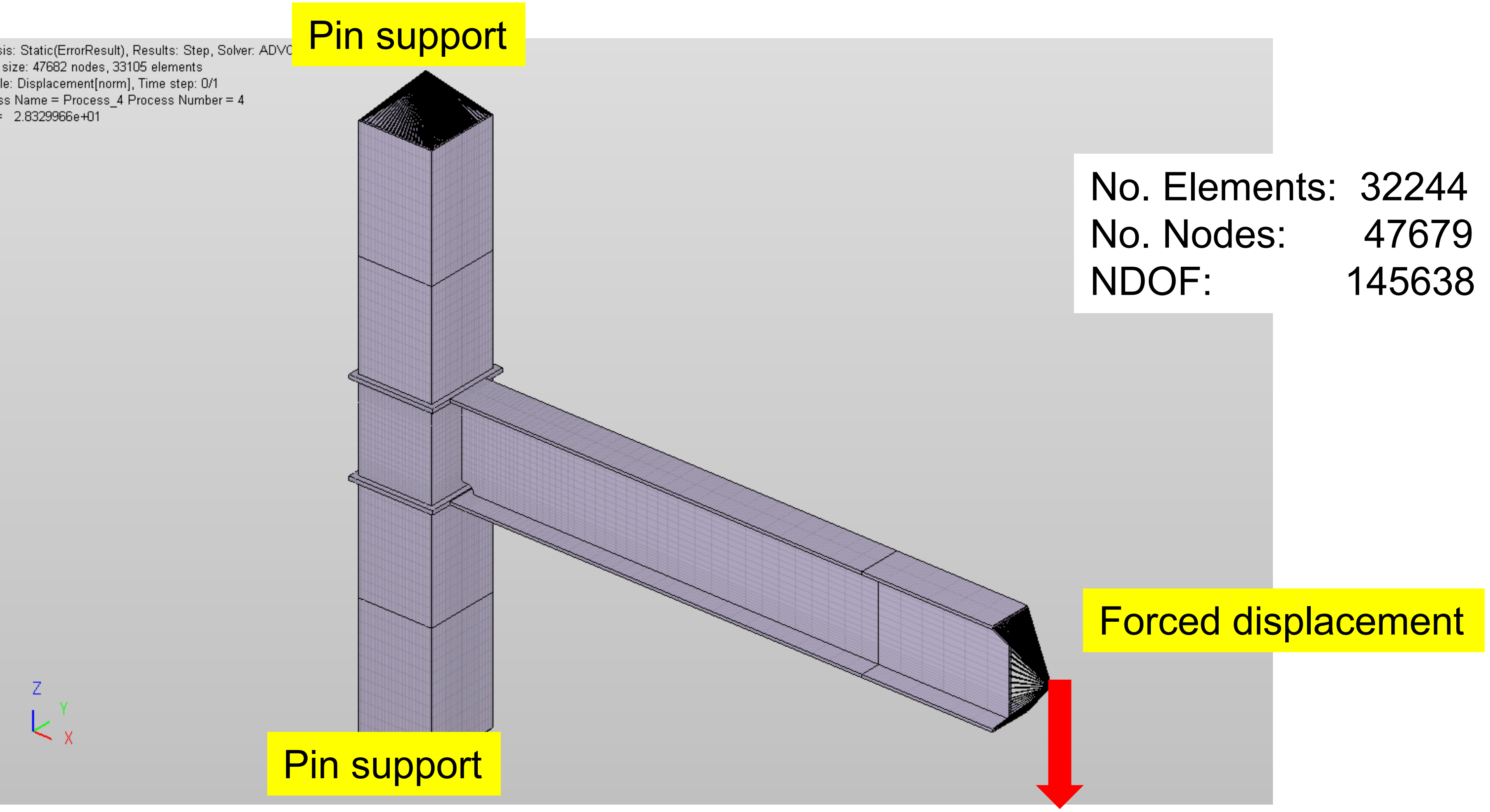




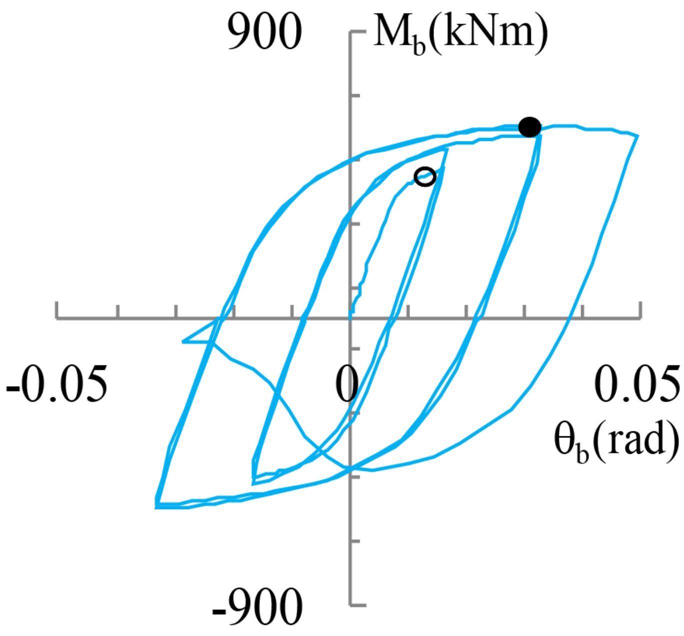


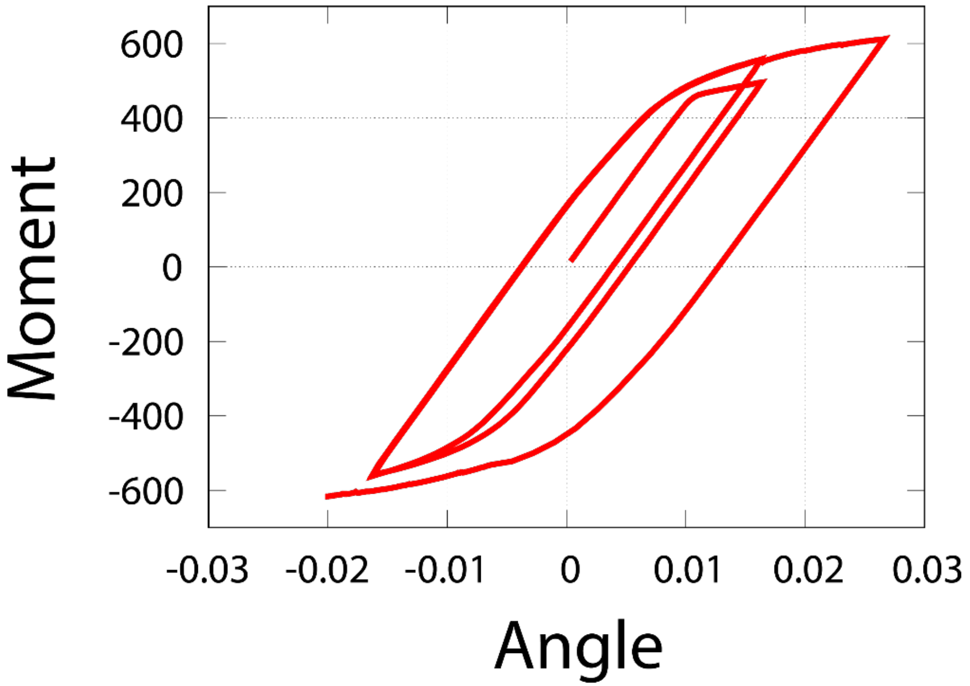


Analysis of beam-column model



Moment-angle relation





Conclusion of first part

- A method for analysis of steel structures considering ductile fracture
- Implicit integration and simple evaluation of stiffness degradation
- Cancellation of unbalanced force at next step
- Application to notched beam and beam-column joint

- Analysis sometimes stops after fracture
  →
  Necessary to convert the total formulation to incremental form

Optimization approaches

- Mathematical programming
- Population-based heuristic approach

Geometrical/material nonlinearity → Poor convergence

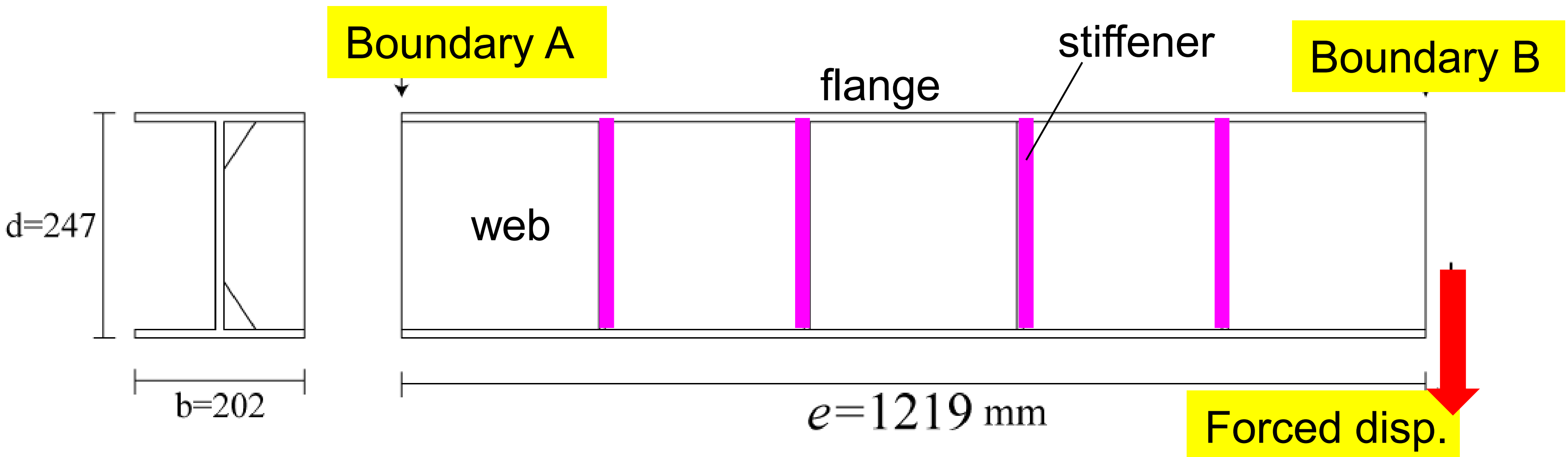
High computational cost → Evaluate response many times

Tabu search:

- ◆ single-point search heuristics based on local search
- ◆ solution is always improved

Outline of optimization

- Optimize location and thickness of stiffeners
- Increase plastic energy dissipation property
- Prevent buckling and collapse near connections
- FEM code: ABAQUS
- Shell element: Thick shell with reduced integration (S4R)
- Forced vertical displacements



Ductile failure criteria

- SMCS (stress modified critical strain)
  (Chi, Kanvinde and Deierline, J. Struct Eng, ASCE, 2006)
- Index for low cycle fatigue
- Defined by stress triaxiality（σ_m / σ_e）

$$\mathrm{FI} = \frac{\varepsilon_{\mathrm{p}}}{\varepsilon_{\mathrm{p,critical}}}$$

ε_{p} Equivalent plastic strain

σ_{e} von Mises equivalent stress

σ_{m} Mean stress
(sum of principal stresses / 3)

Critical plastic strain: $\varepsilon_{\mathrm{p,critical}} = \alpha \exp\left(-1.5 \frac{\sigma_{\mathrm{m}}}{\sigma_{\mathrm{e}}}\right)$

- Decreasing function of triaxiality（σ_m / σ_e）
- Fracture occurs if FI=1.0

- Compute FI of all elements and find the max. value I_{f}

Optimization problem

Objective function

Plastic dissipated energy

Constraint

Max. value I_f of FI is less than 1.0

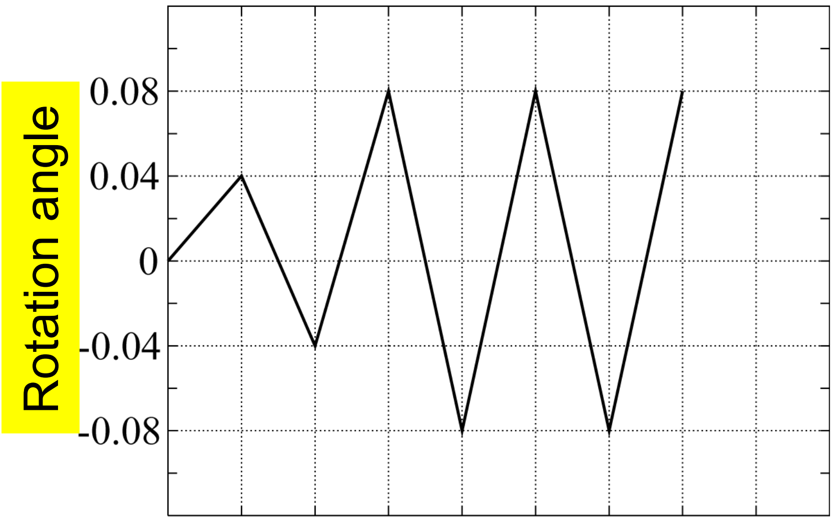
Design variables

– Location, thickness, and angle of stiffeners
– Discretize real variables x_i to integer variables J_i
– $x_i = x_i^0 + (J_i - 1) \times \Delta x_i$
$(i = 1, \cdots, m)$

$$\text{maximize} \quad F(\boldsymbol{J}) = E_{\mathrm{p}}(\boldsymbol{J})$$

$$\text{subject to} \quad I_{\mathrm{f}}(\boldsymbol{J}) \leq 1.0$$

$$J_i \in \{1, \cdots, s\}$$



Optimization using ABAQUS

TS Algorithm

Generate coordinates, thickness, length

Preprocessing (Python Script)

(1) Flange, web, plate parts

(2) Material and section

(3) Assemble beam part

(4) Boundary and load

(5) FE-mesh

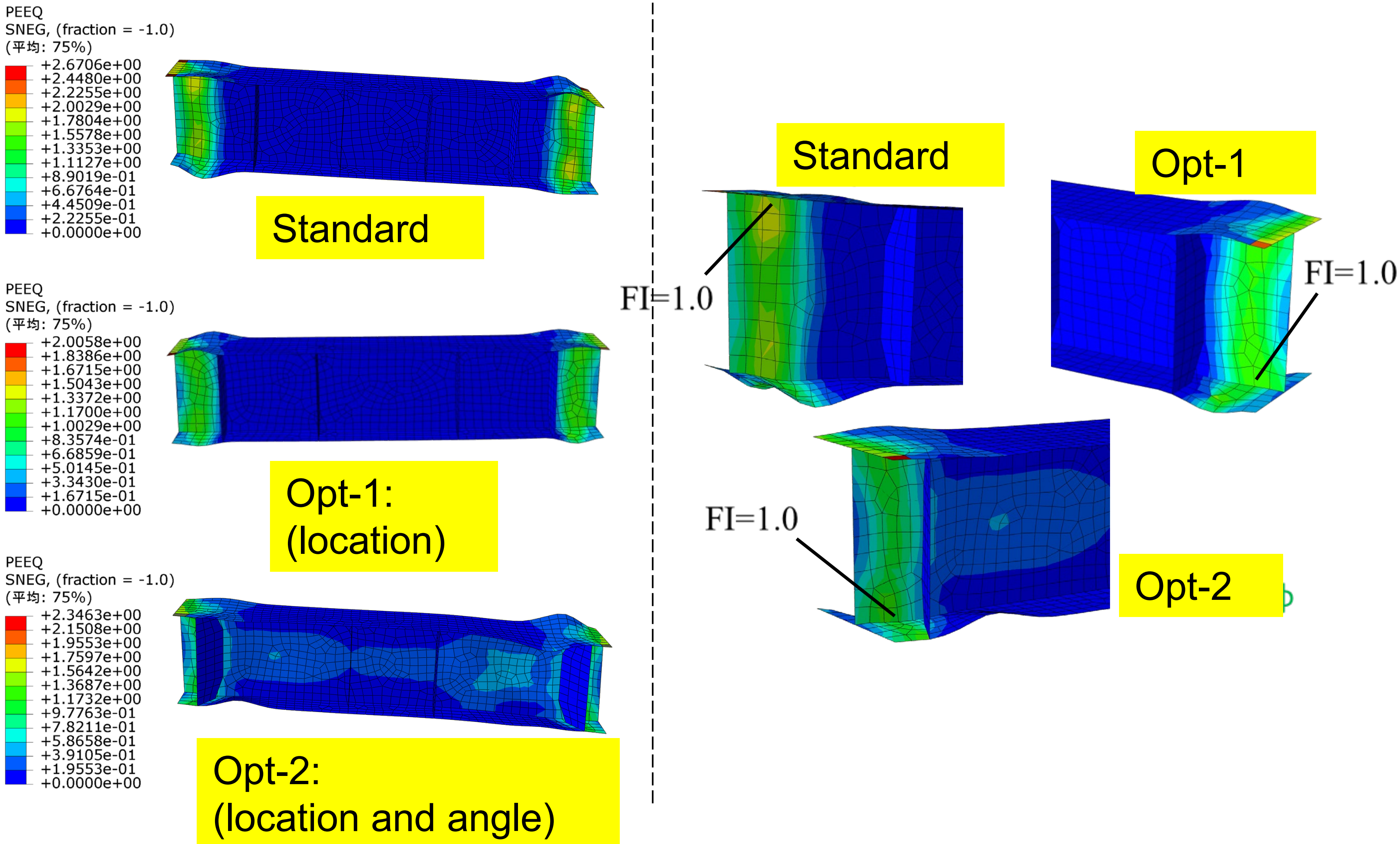
(6) Submit to ABAQUS

Simulation ABAQUS/Standard

Postprocessing (Python Script)

Dissipated energy
Equivalent plastic Strain
Compute objective and constraint functions

Optimization of location and thickness of stiffeners

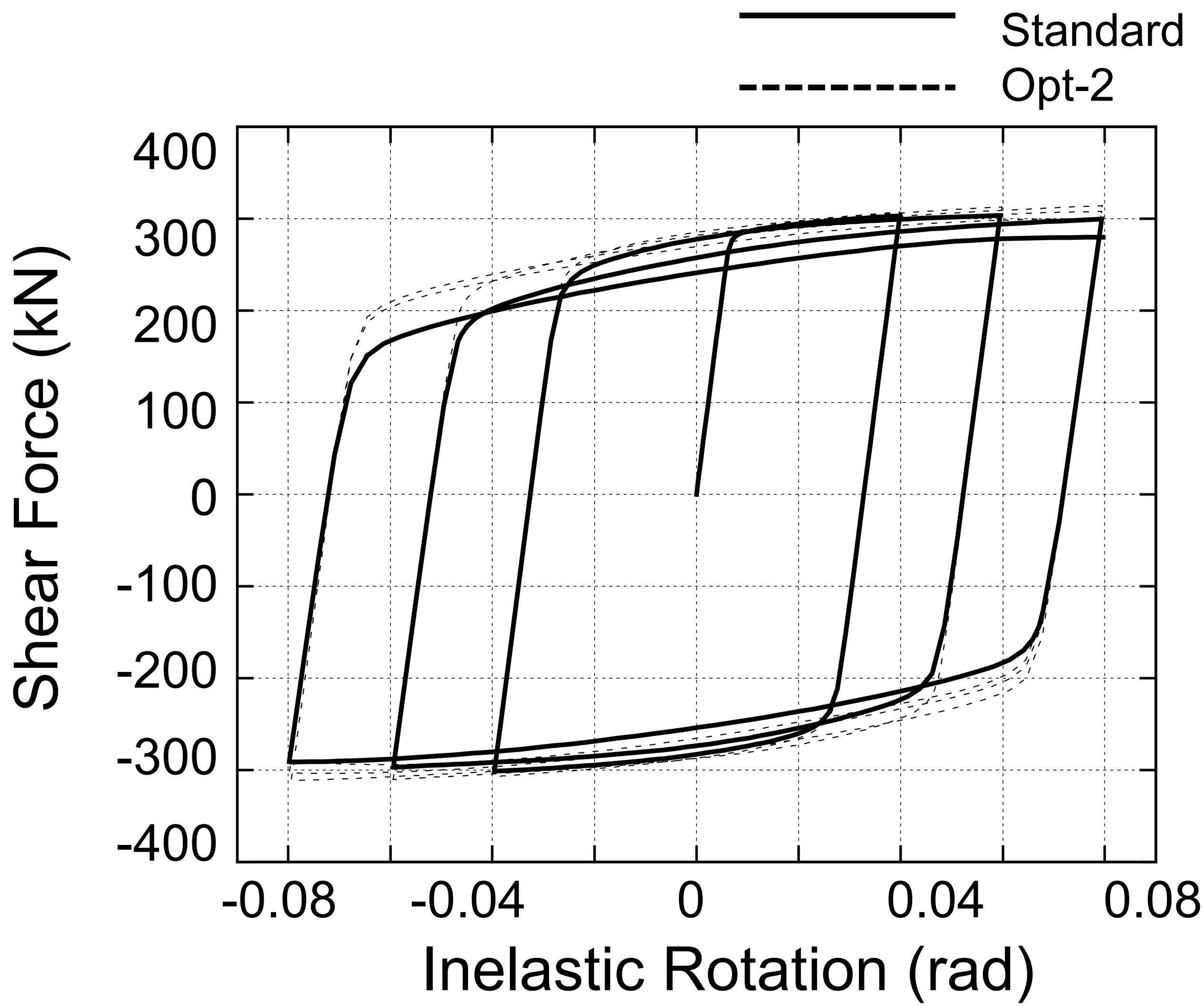


Optimization of location and thickness of stiffeners

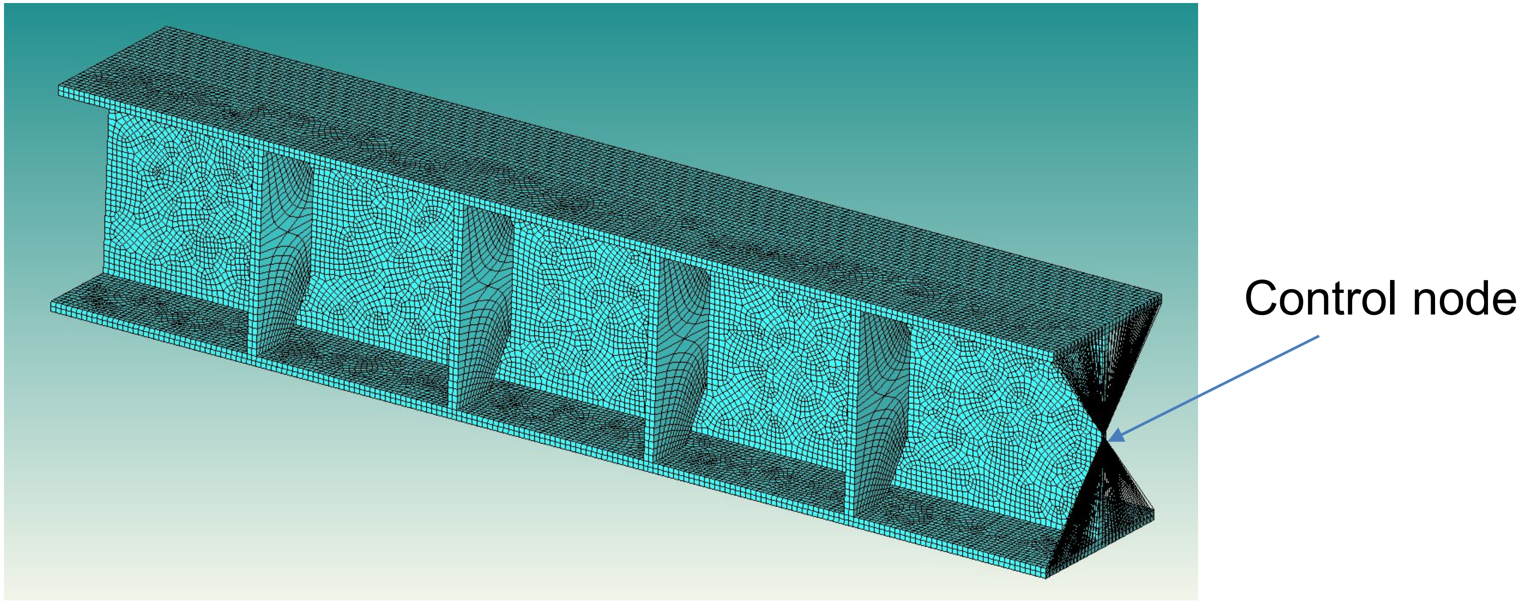
- Increase E_p by increasing N_f
- Dissipated energy E_p^f before failure is 40% larger than standard model

	Number of cycles before failure	Dissipated energy before failure
	N_f	E_p^f
Standard	4.52	238.12 (100.0 %)
Opt-1	5.02	279.81 (117.5 %)
Opt-2	5.52	333.49 (140.1 %)

Force-rotation relation



Analysis using solid elements (ADVENTURECluster)

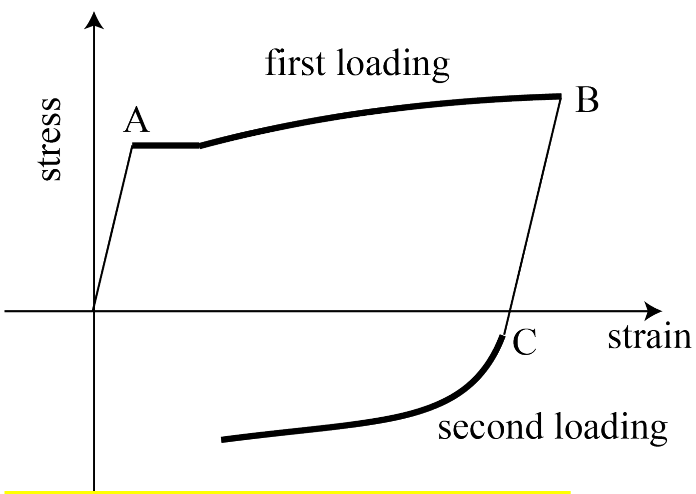


Attach rotational springs of 4.0×10^4MNm/rad at control nodes to simulate flexibility of support frames

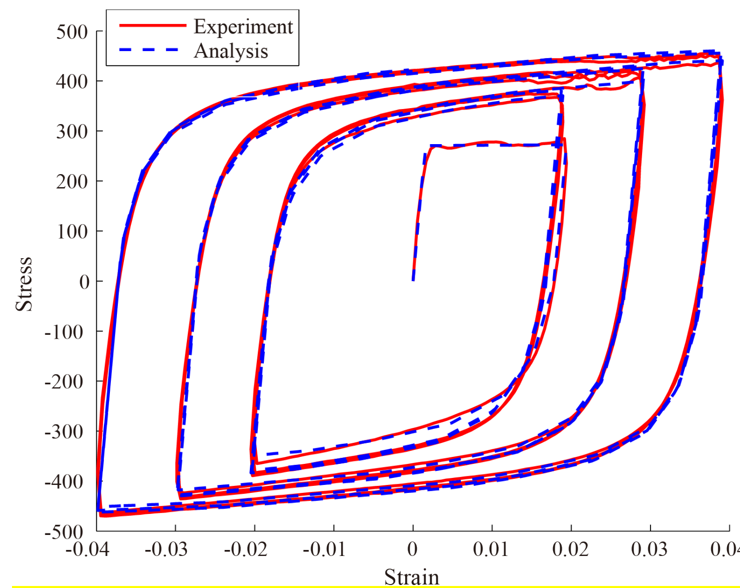
Number of elements: 38,234 including 1,048 rigid bars
Number of nodes: 61,110
Degrees of freedom: 184,128,

Constitutive rule of steel material

- Piecewise linear combined hardening with von Mises yield condition
  → Applicable to large-scale FE-analysis
- Incorporate yield plateau and Bauschinger effect → Different rules for first and second loadings

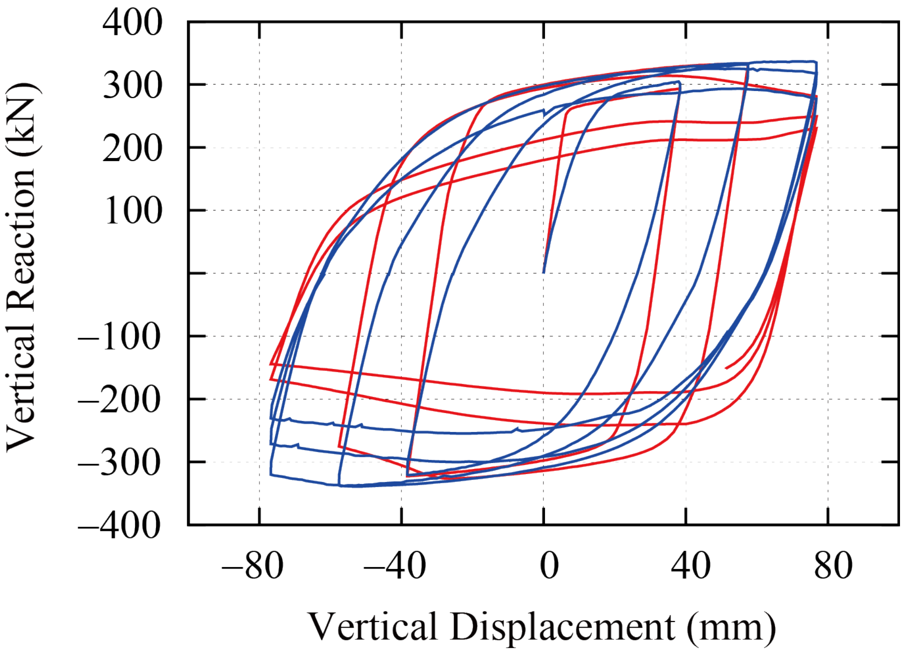


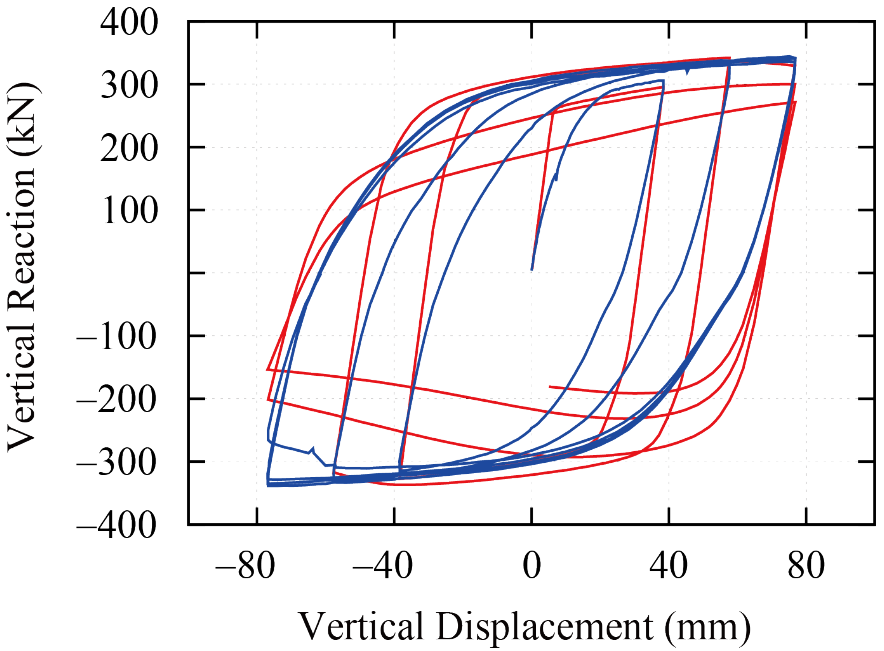
Stress-strain relation for first and second loading



Simulation of cyclic material test

Detailed FE-analysis (fixed boundary)

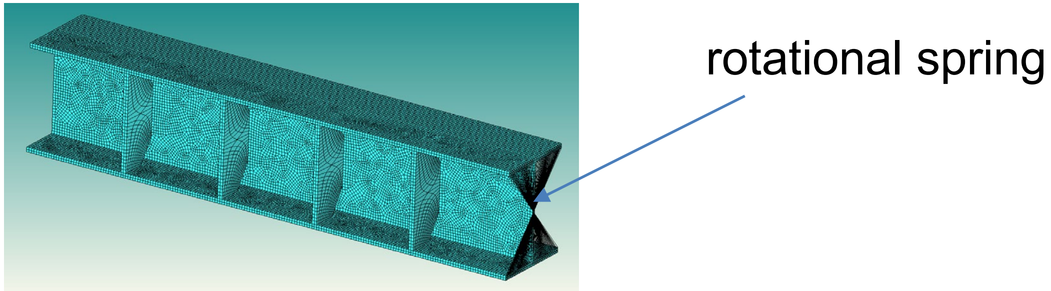


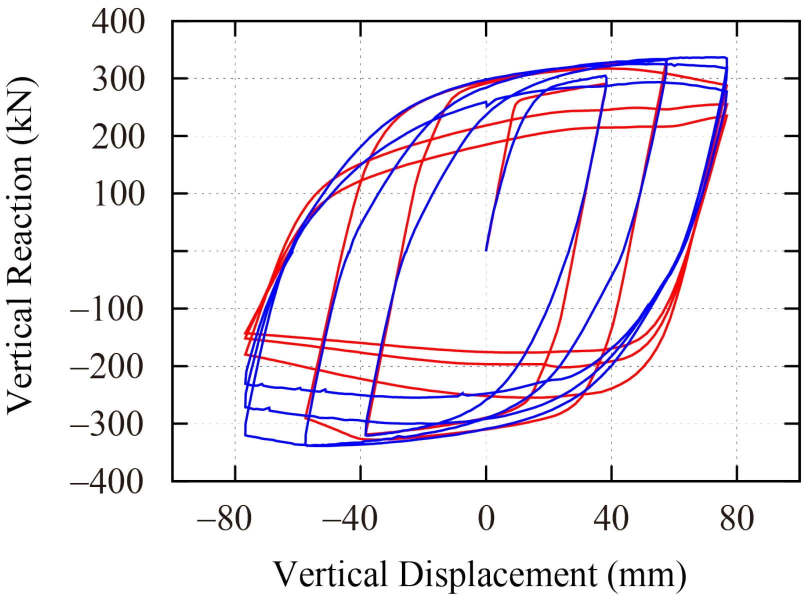


Standard

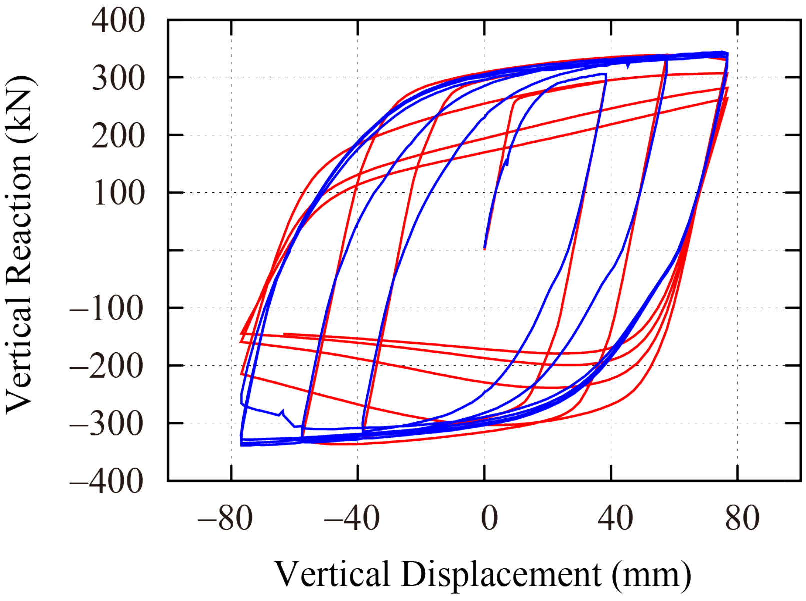
Optimal

Detailed FE-analysis (Rotational spring)



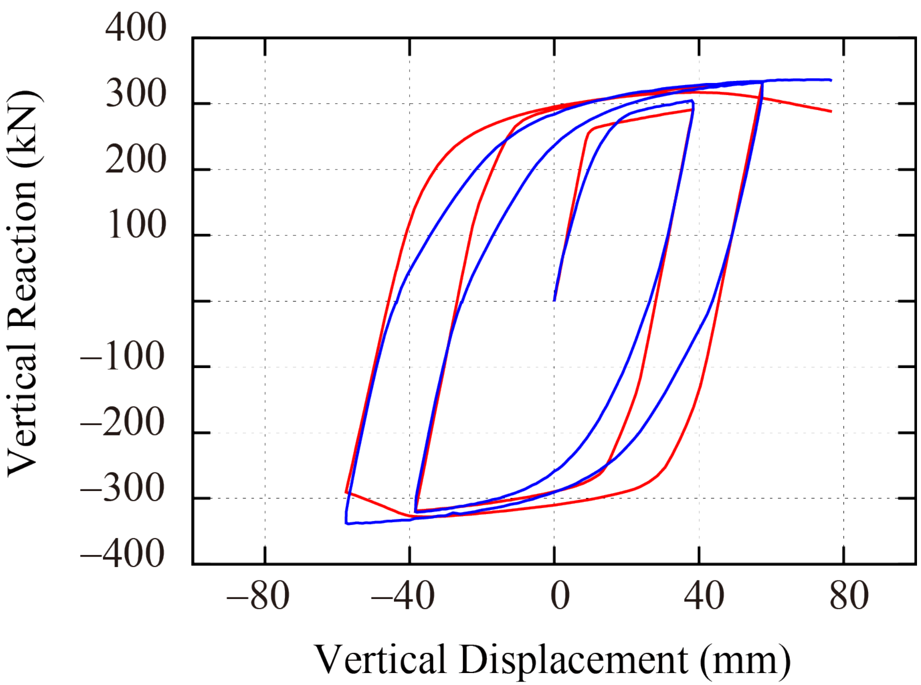


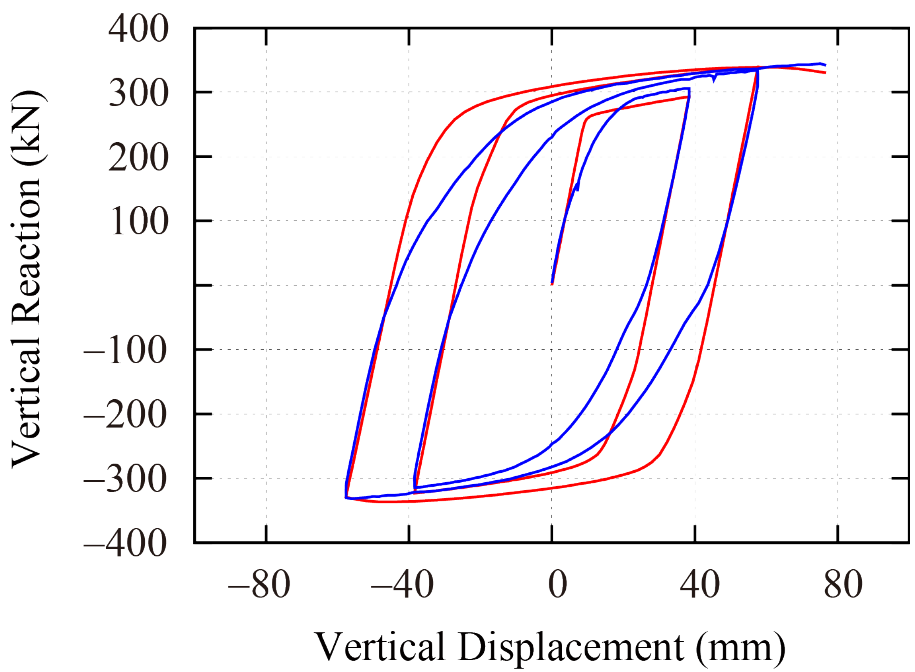
Standard



Optimal

Detailed FE-analysis (rotational spring: first 2 cycles)





Standard

Optimal