OPTIMIZATION OF ENERGY DISSIPATION PROPERTY OF ECCENTRICALLY BRACED STEEL FRAMES

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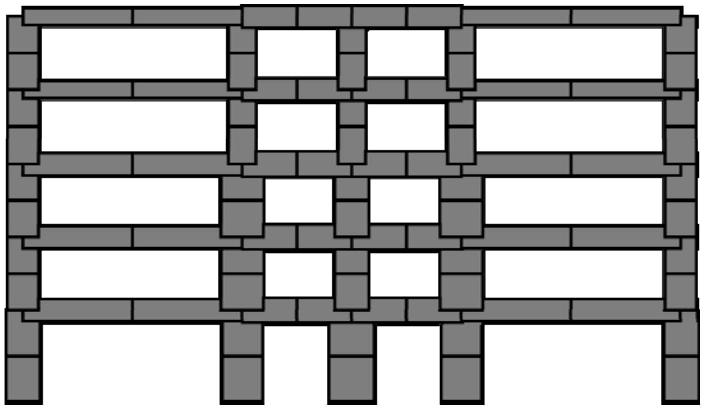
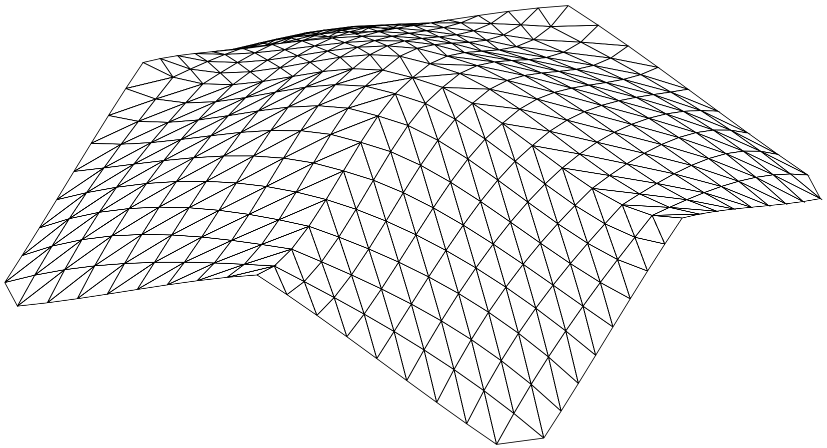
Background

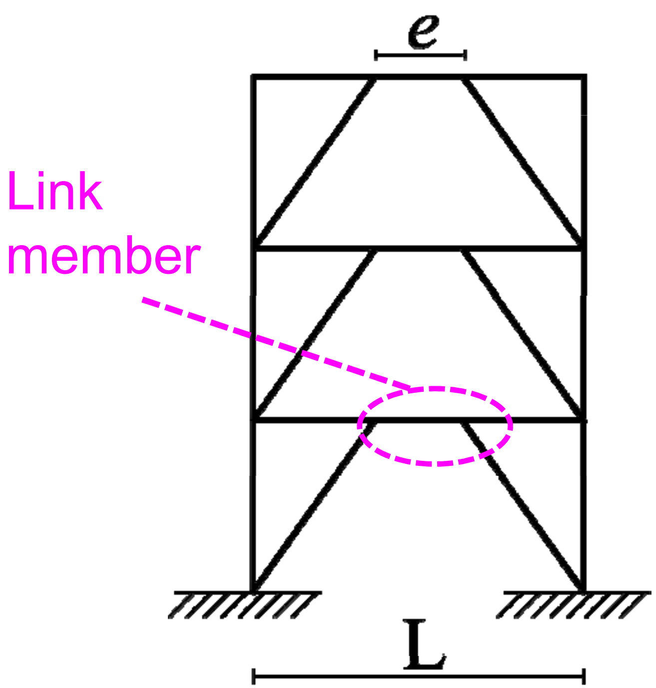
- Difficulty in optimization in building structures:
  Structures are not mass products
  ⇒ cannot spend much cost on optimization
- Shape optimization of special structures
  (long-span truss, free-form shell, etc.)
- Structural parts are mass products
  ⇒ optimization of parts of building frame





Purpose of study

- Optimization of Eccentrically Braced Frame (EBF)
  - Eccentricity between beam-brace connection
  - Dissipate seismic (earthquake) energy in link member between connections



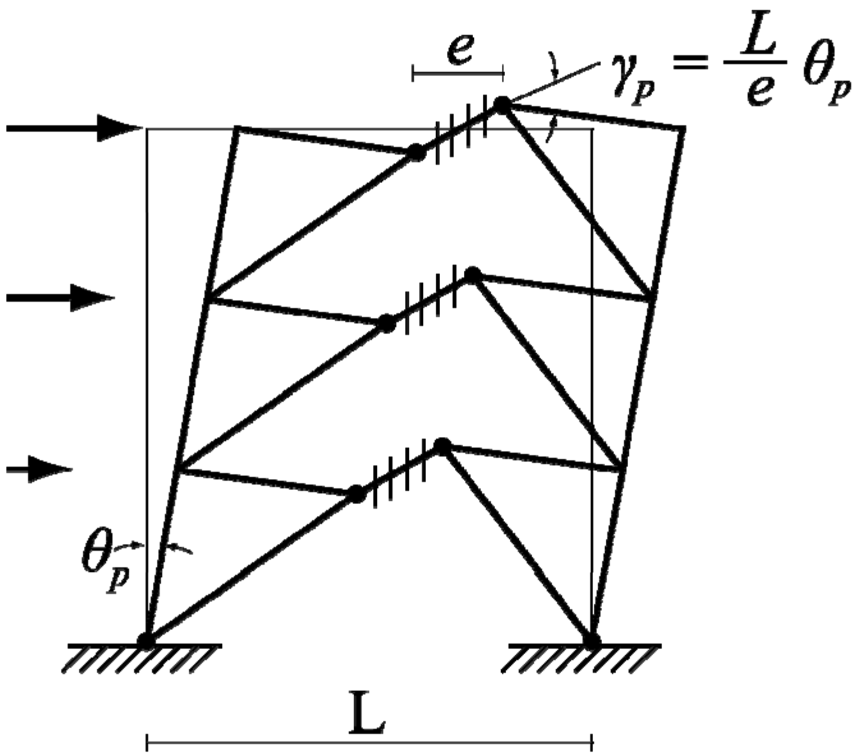
Design specification of EBF

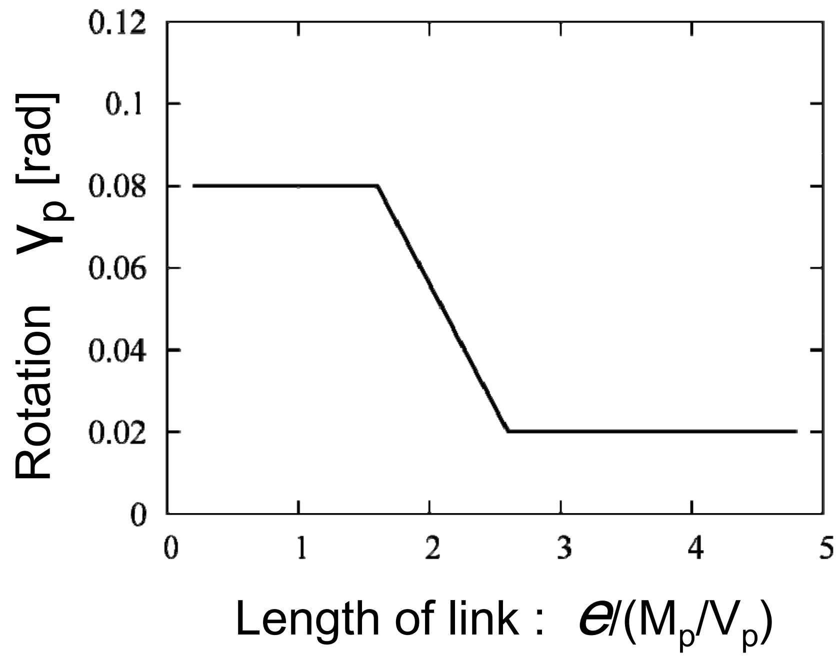
- Demand for large rotation $\gamma_p = \dfrac{L}{e}\theta_p$

  (γ_p : plastic rotation of link， θ_p: interstory drift angle of frame)

- Specification by AISC: 0.02 ~ 0.08 (rad)

  (AISC:American Institute of Steel Construction)





Optimization approach

Optimization of structural parts

- Mathematical programming → Geometrical/material nonlinearity → Poor convergence
- Population-based heuristic approach → High computational cost → Evaluate response many times

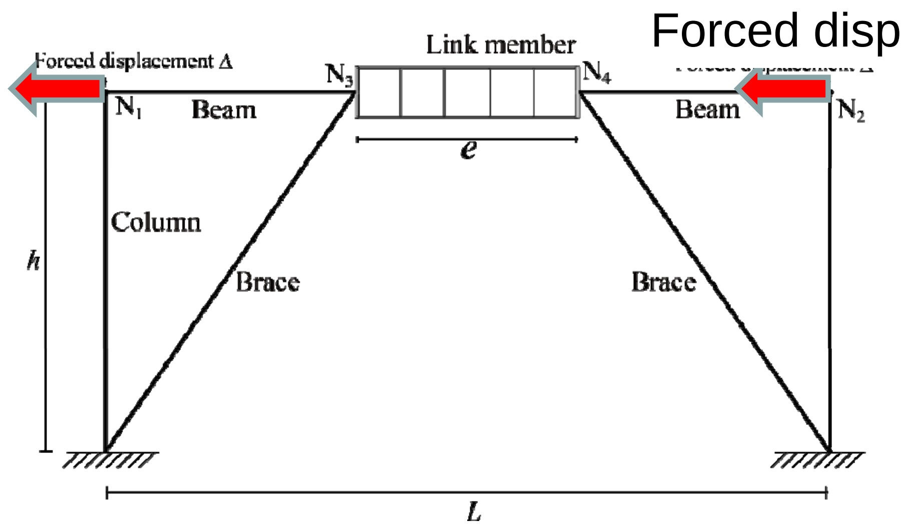
Tabu search:

single-point search heuristics based on local search

Optimization of link member

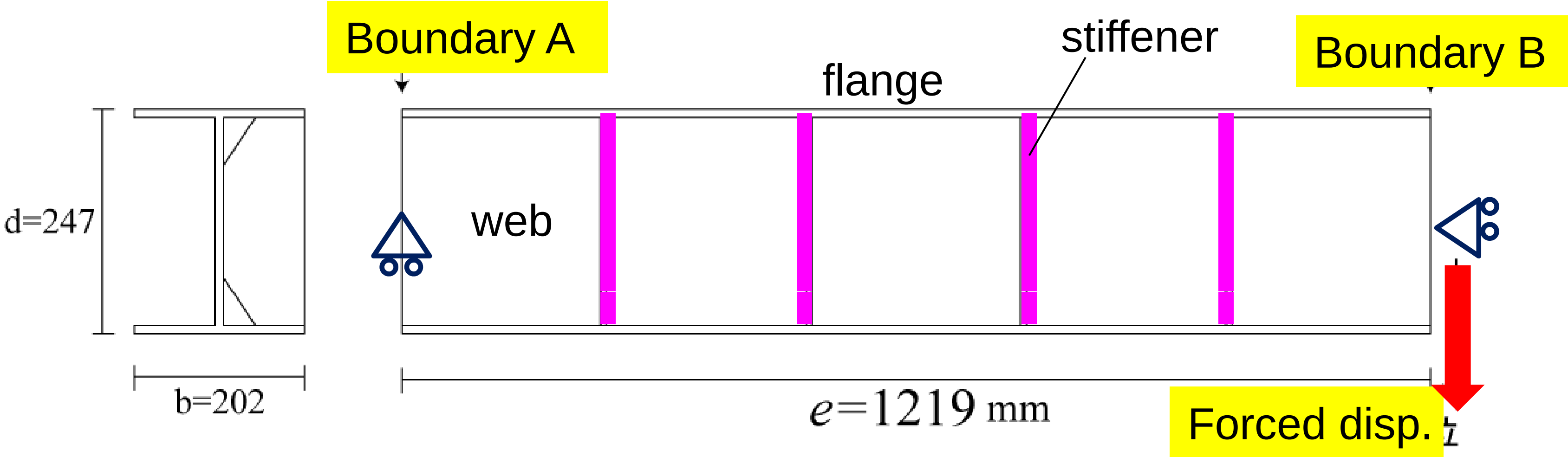
- Increase plastic energy dissipation
- Prevent buckling and collapse near connections

1. Optimize location and thickness of stiffeners
2. Optimize length of link member in a frame
3. Tabu search:
   Approximate optimal solution with small number of analyses



Analysis model

- Wide-flange section (H-247×202×7×11)
  - Elastic modulus: 200.0 GPa , Yield stress: 359.0 Mpa
    Tensile strength: 592.0 MPa
  - Link length: *e* =1219 mm (intermediate length)
  - Stiffeners: four, 10mm
- Shell element: nominal size 25mm
  - Forced vertical displacements
  - FEM code: ABAQUS



Failure Index

- 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

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

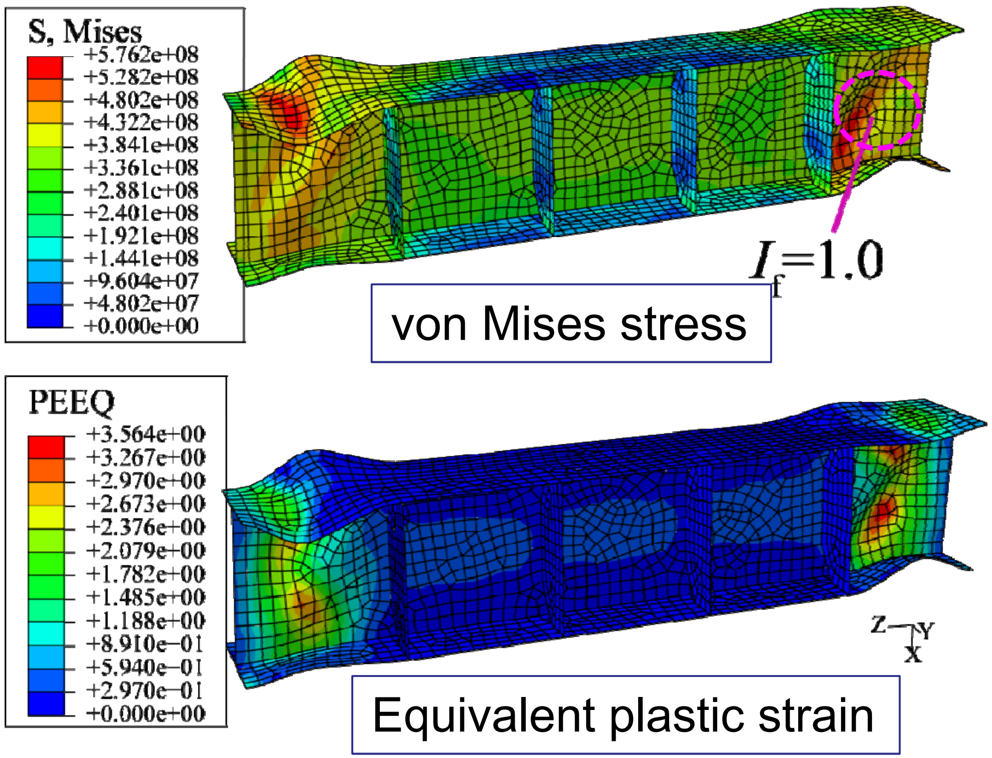
- Fracture occurs if FI=1.0

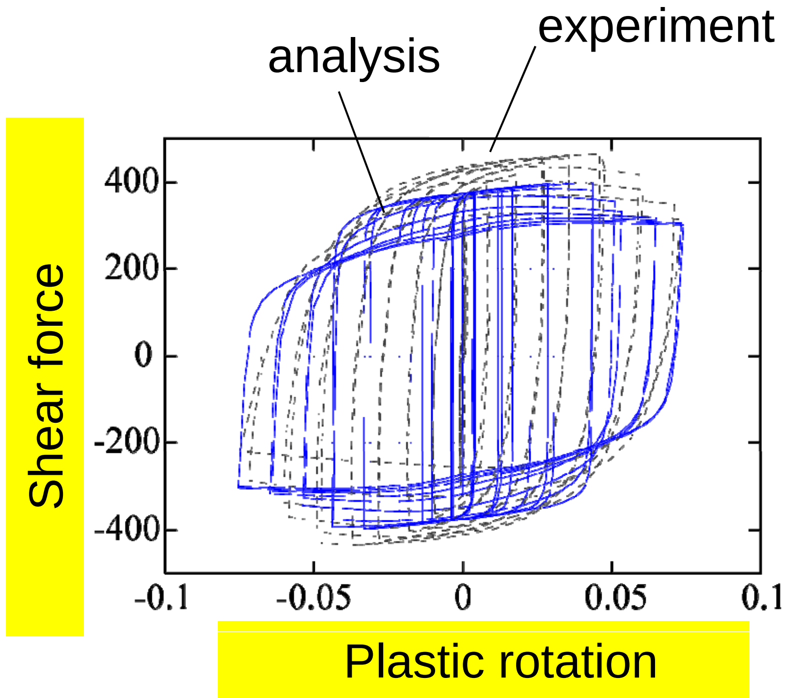
- Compute FI of all elements and find the max. value I_f

Verification with experimental results

- FE-analysis
  - Local buckling of flange and web
  - Cyclic softening
  - Location of element with I_f =1.0

Good accuracy





Optimization problem

Objective function

Plastic energy dissipation

Constraint

Max. value I_f of FI is less than 1.0

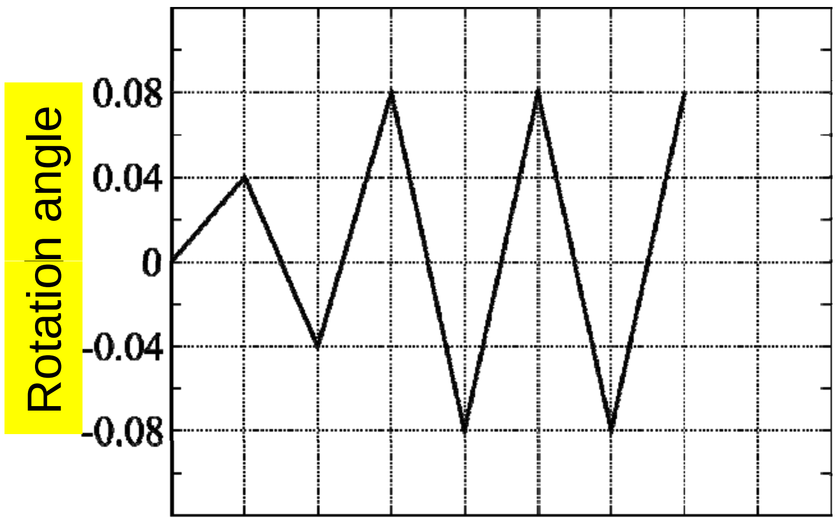
Design variables

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

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

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

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



Tabu search （TS）

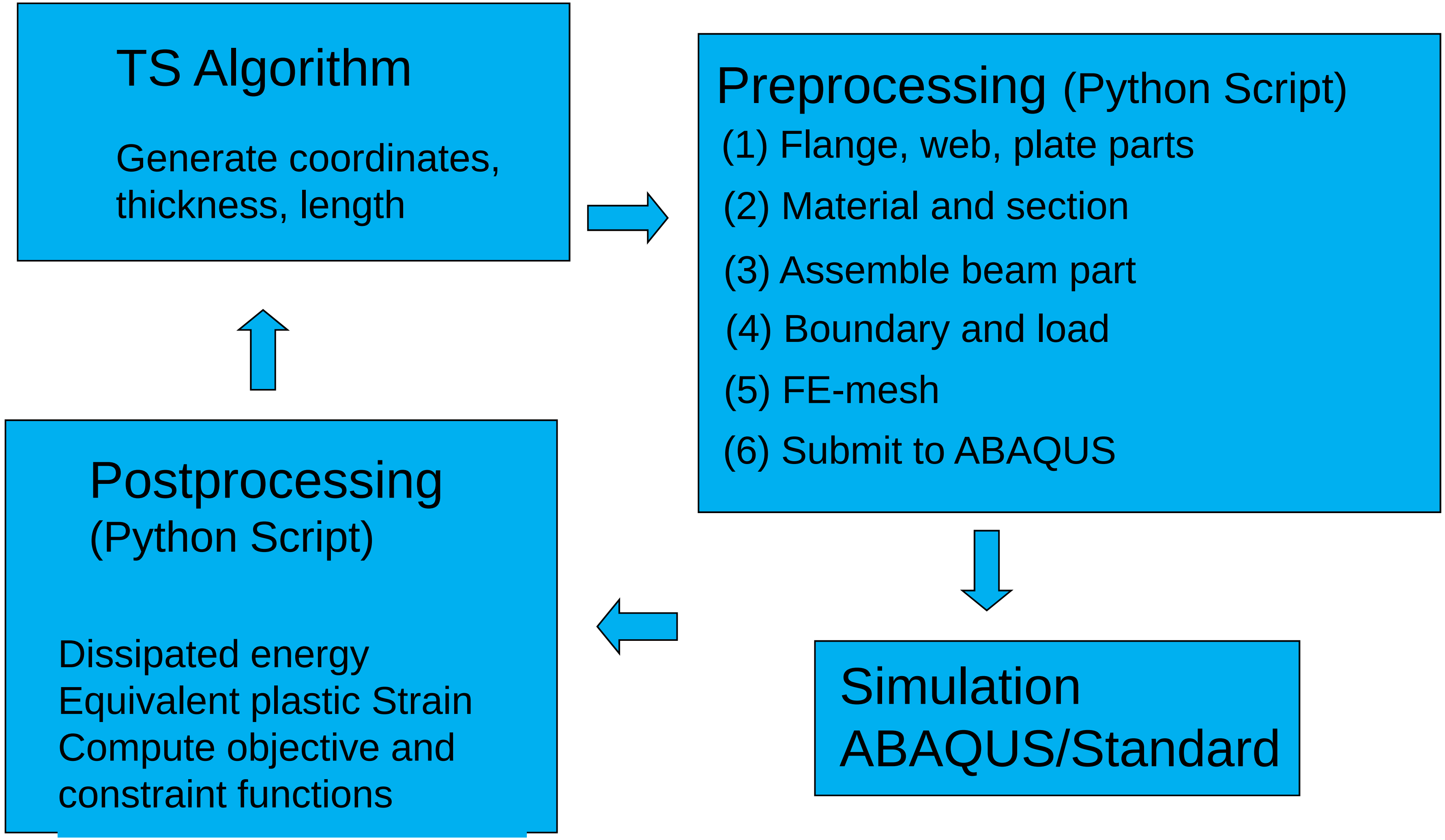
1. Randomly generate initial seed solution
   Initialize tabu list T as empty list
2. Generate neighborhood solutions $\boldsymbol{N} = \{ \boldsymbol{J}_j^N \mid j = 1,...,q \}$
3. Evaluate objective functions and constraints
   (penalty function for constraints)
4. Best solution in $\boldsymbol{N}$ that is not included in tabu list $\boldsymbol{T}$
   ⇒ Next seed solution
5. Add the seed solution to $\boldsymbol{T}$
6. Go to step 2 if termination conditions are not satisfied;
   otherwise, output the best solution satisfying constraints.

Parameters of TS

1. Number of neighborhood solutions: 3
2. Number of steps: 5
3. Length of tabu list: 5

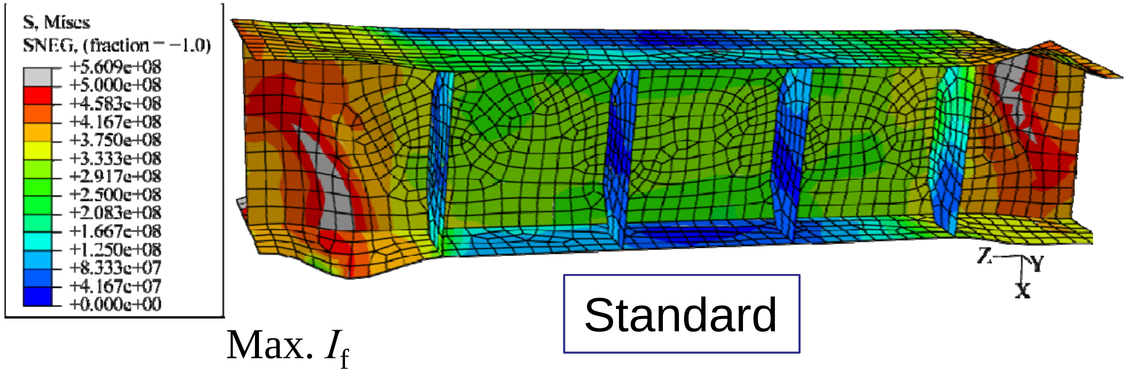
4. Carry out TS five times from different random seeds.
5. Total number of analyses: 5 x 5 x 3 = 75

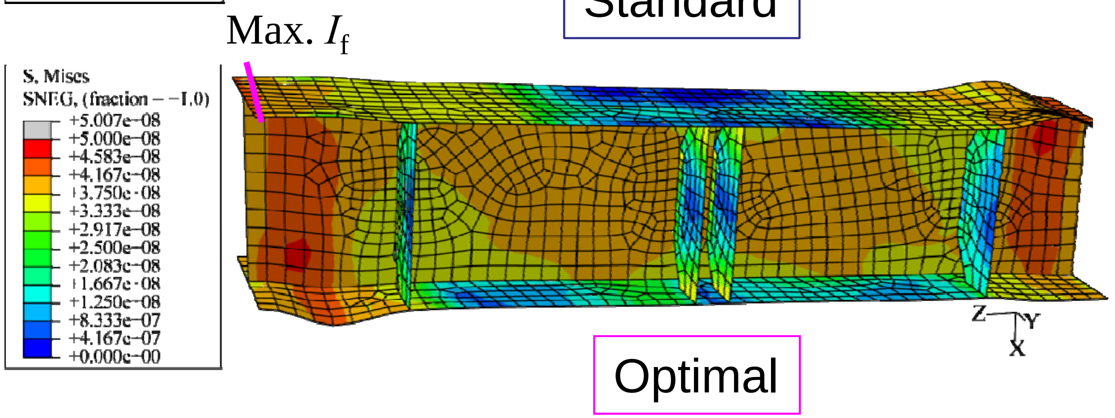
Optimization using ABAQUS

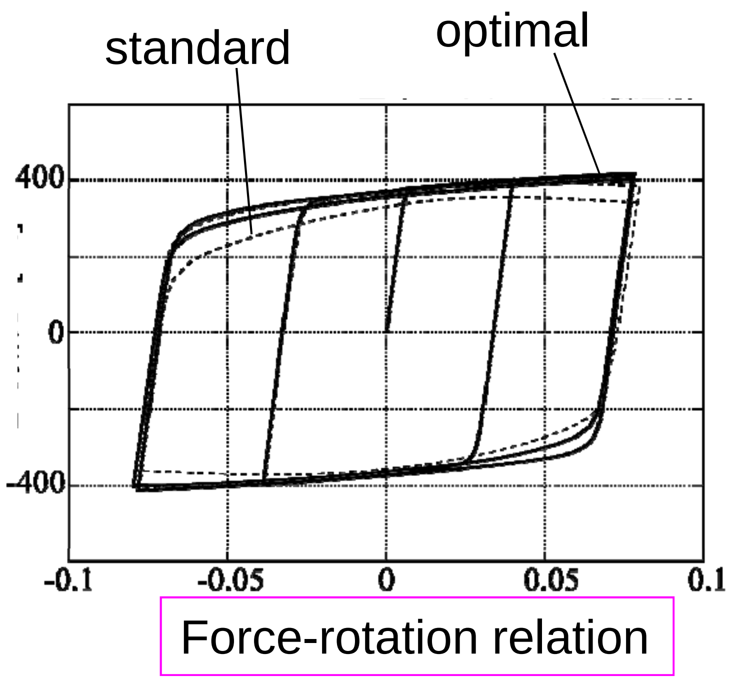


Optimization of location and thickness of stiffeners

- Stiffeners are located near center and ends
- Shear (reaction) force is incerased







Location (mm)	- 40.0	+80.0	- 80.0	+40.0
Thickness (mm)	17.0	6.0	6.0	17.0

Optimization of location and thickness of stiffeners

- Increase E_p, decrease I_f
- Dissipated energy E_p^f before failure is 42% larger than standard model

	Objective function	Failure index	Dissipated energy before failure
	E_p	I_f	E_p^f
Standard	336.0	1.06	323.0
Optimal	347.0	0.67	459.9

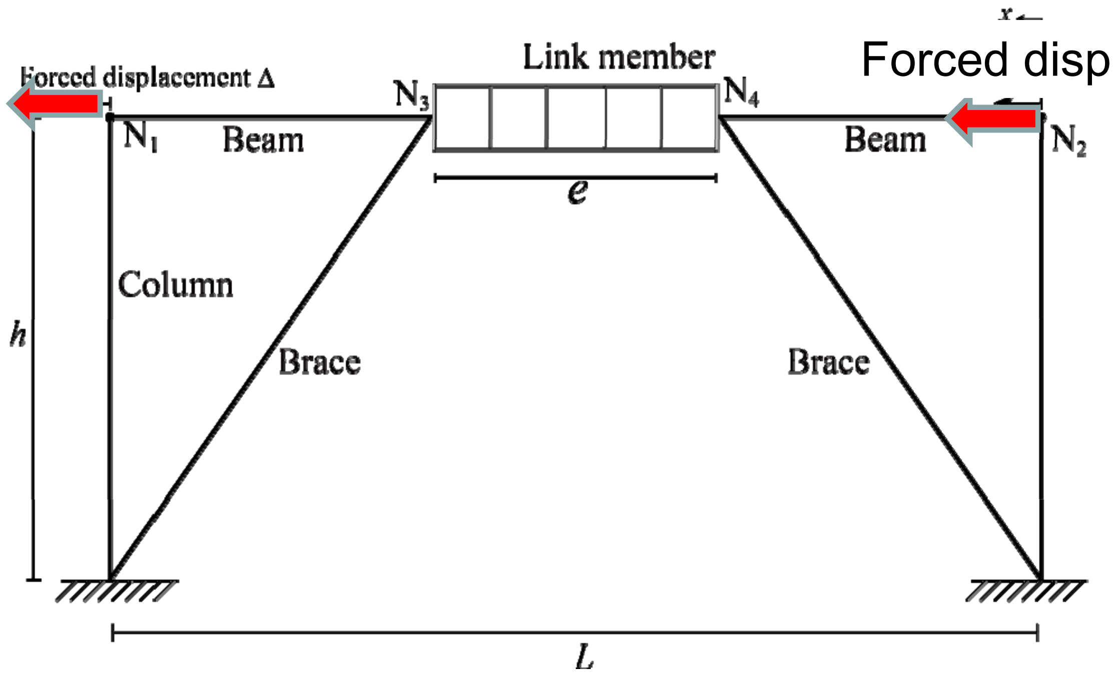
+42%

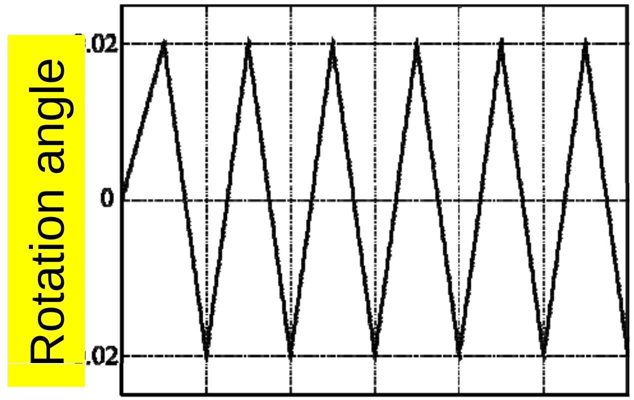
(kN・ m)

E_p^f : dissipated energy before I_f reaches 1.0

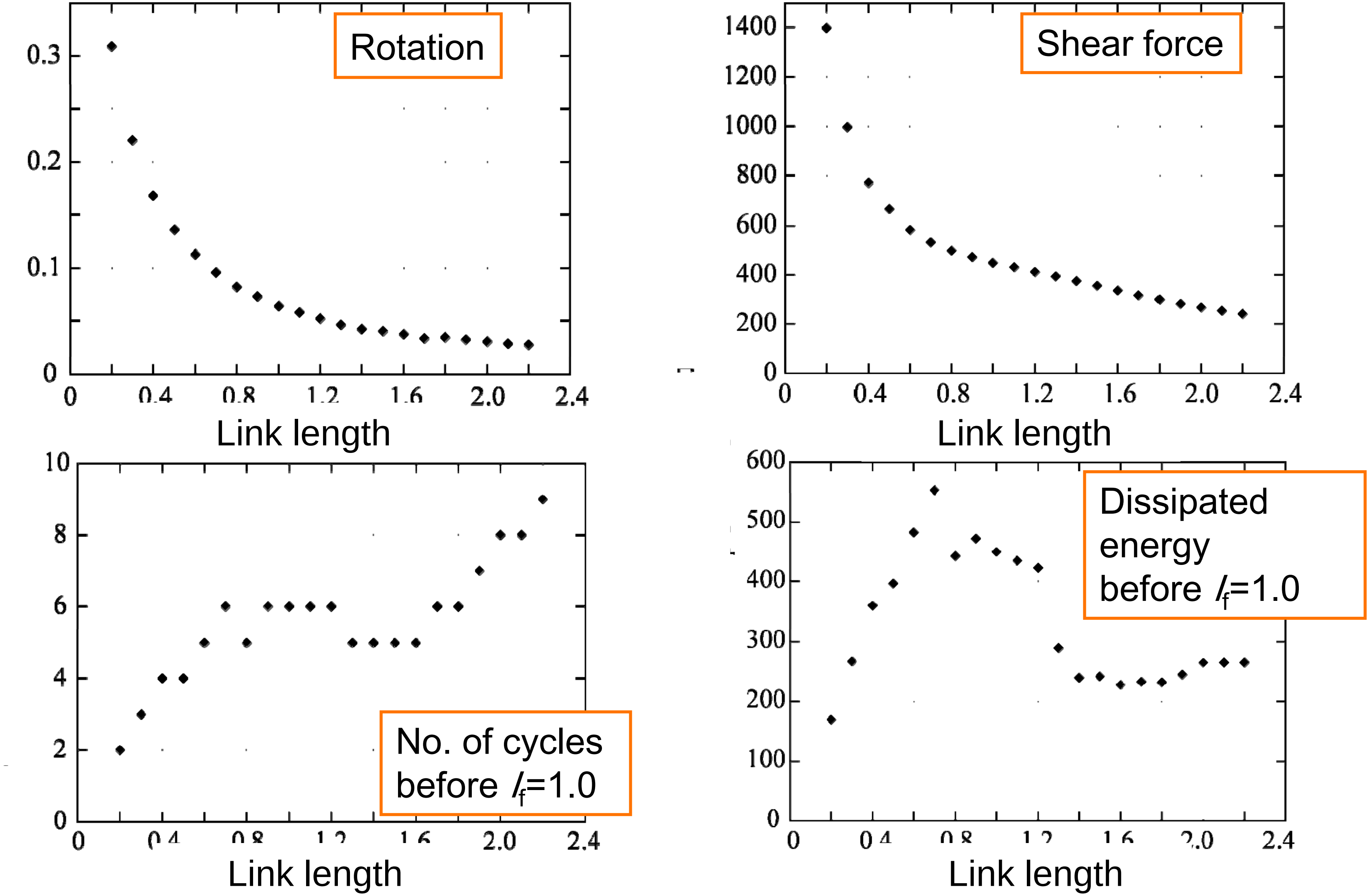
Eccentrically braced portal frame

- Span L=4.0m， height 2.0m
- FE-model:
  Link: shell element; Beam, column: beam element;
  Brace: truss element
- Assign story drift （=1/50） and maximize dissipated energy E_p^f before reaching I_f=1.0





Relation between length and responses



Optimization problem

Objective function

Plastic energy dissipation before reaching I_f =1.0

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

$$\text{subject to} \quad J_i \in \{1, 2, ..., s\}$$

Design variables

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

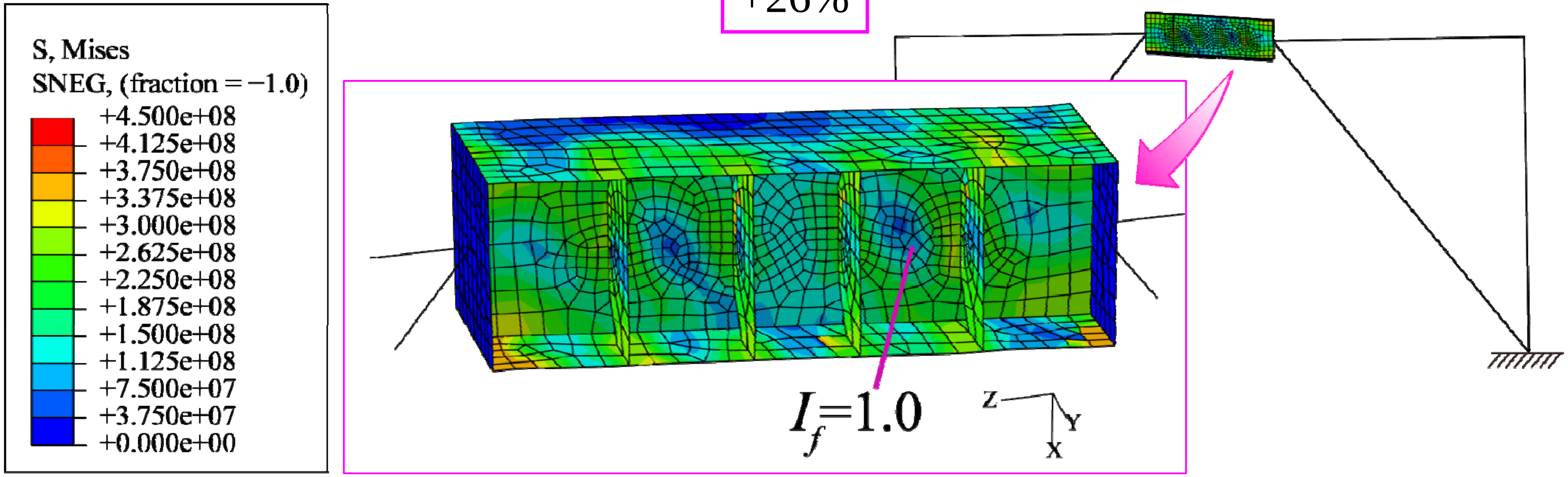
- Upper bound of length: e =1400 mm

Optimization of link length, location and thickness of stiffeners

	standard				optimal			
Location	0.0	0.0	0.0	0.0	+18.0	+18.0	−18.0	−18.0
Thickness	10.0	10.0	10.0	10.0	16.0	13.0	13.0	16.0

Model	Length	Plastic energy	Cycles	Angle	Shear force
	e (mm)	E_p^f (kN・m)	N_{cycle} (times)	γ^{max} (rad)	V_L^{max} (kN)
Standard	1219	470.2	7	0.051	409.4
Optimal	800	593.0	7	0.083	505.5

+26%



Conclusions

1. Shape optimization of link beam
   - Combine FEM (ABAQUS) and optimization algorithm (TS)
   - Maximize energy dissipation under constraint on failure index
   - Optimize location and thickness of stiffeners
   - Tabu search for improvement:
     Approximate optimal solution with small computational cost
2. Optimization of portal EBF
   - Optimize length of link beam
   - Energy dissipation has been drastically improved