Optimization of flexible supports for seismic response reduction of long-span structures

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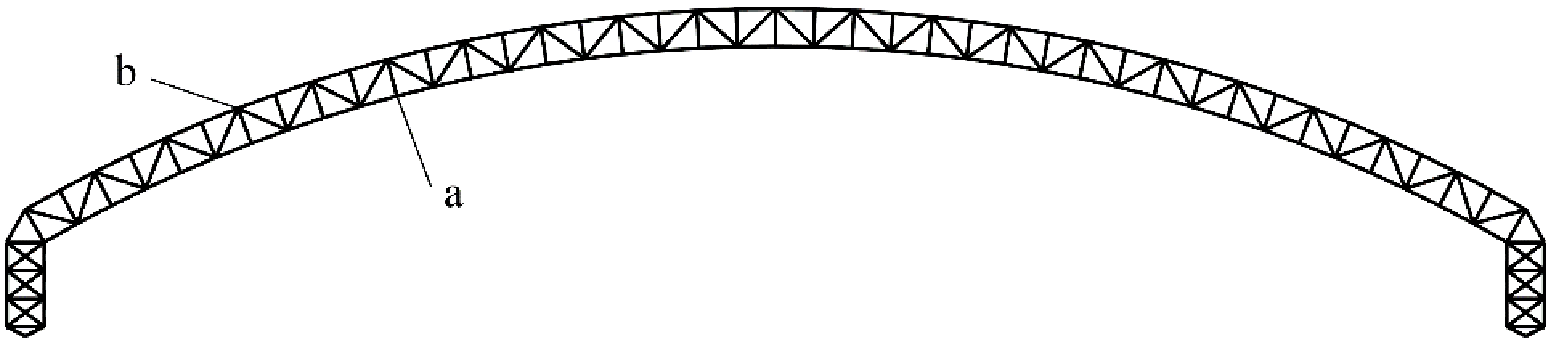
Purpose

1. Optimization of supporting structure of long-span structures subjected to seismic excitation.
2. Reduction of acceleration and deformation of upper structure.
3. Utilization of
   - Flexibility of support.
   - Geometrical nonlinearity.

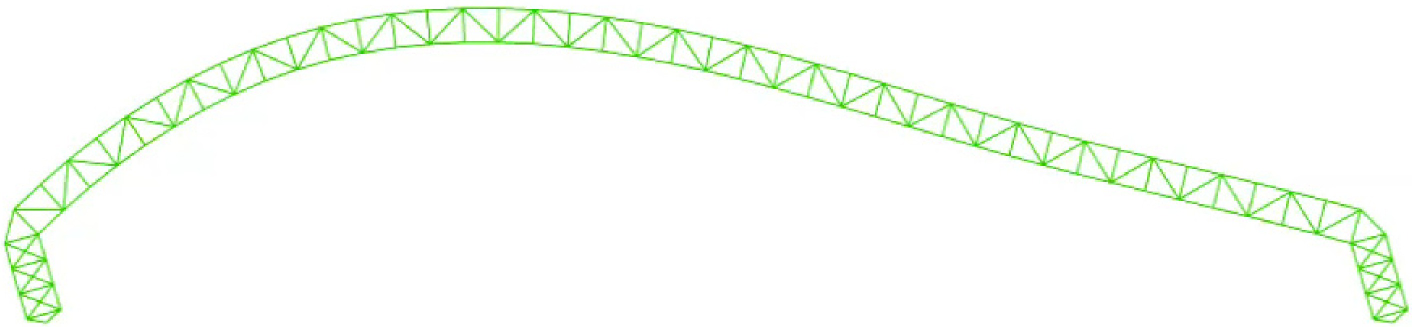
Background

- Complex dynamic property of arch-type structure.
  – Interaction of multiple modes.
  – Dependence on flexibility of support.
- Base isolation.
  – Difficult for vertical excitation.

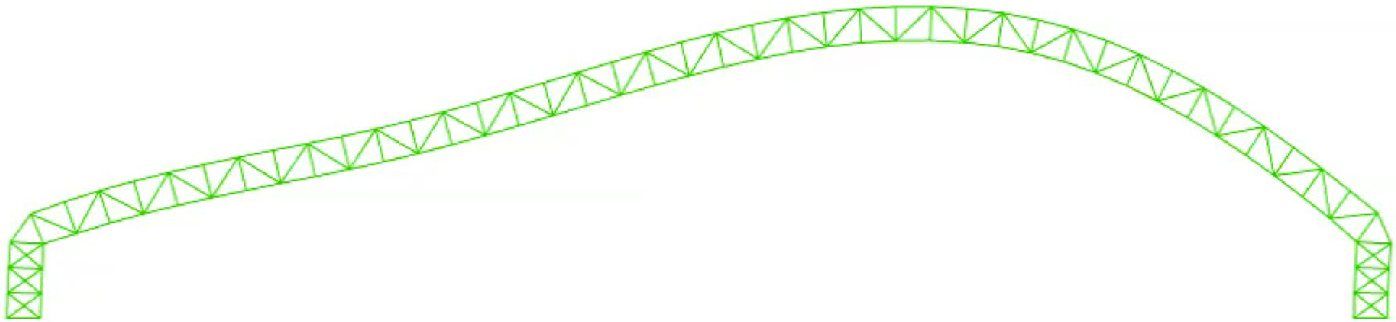


1st mode

Pin

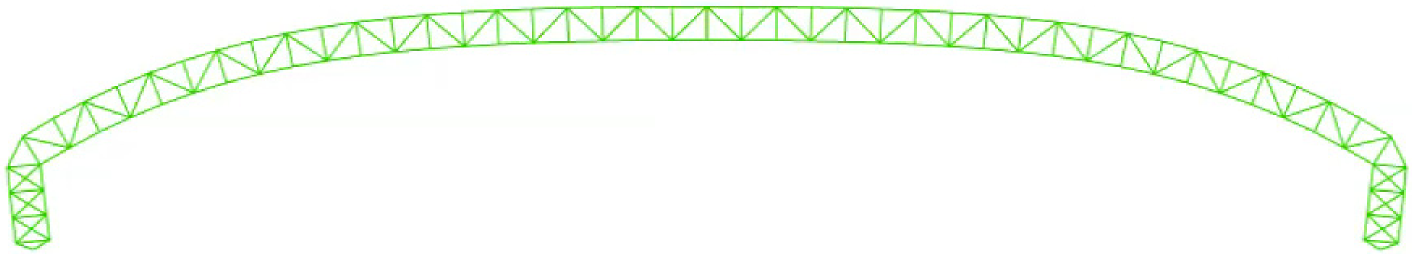


Fixed

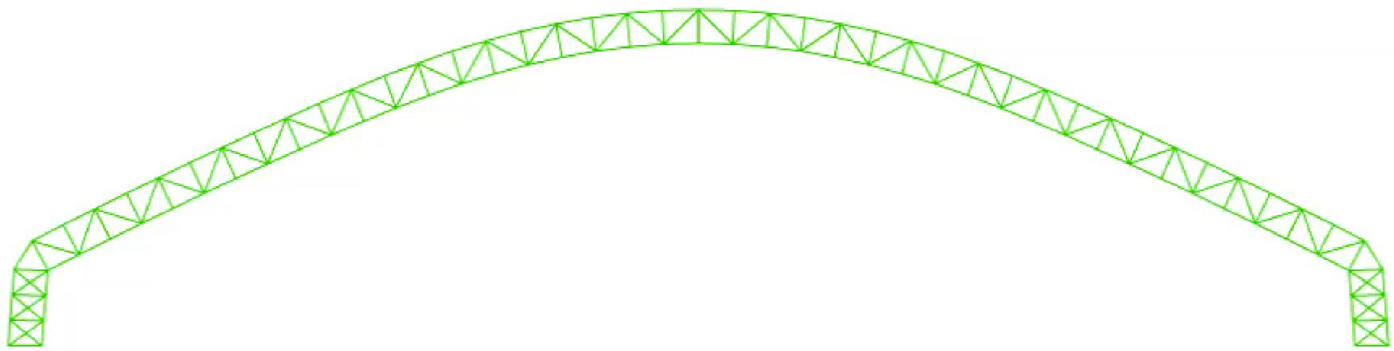


2nd mode

Pin

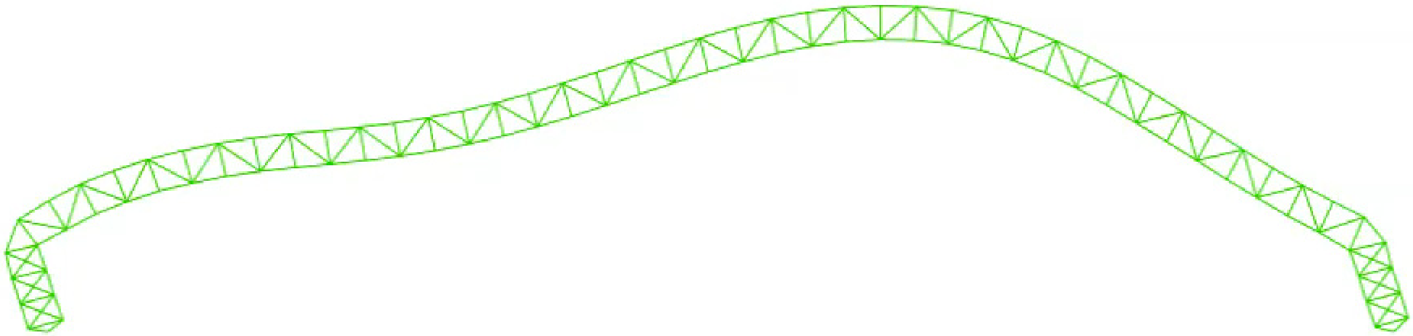


Fixed

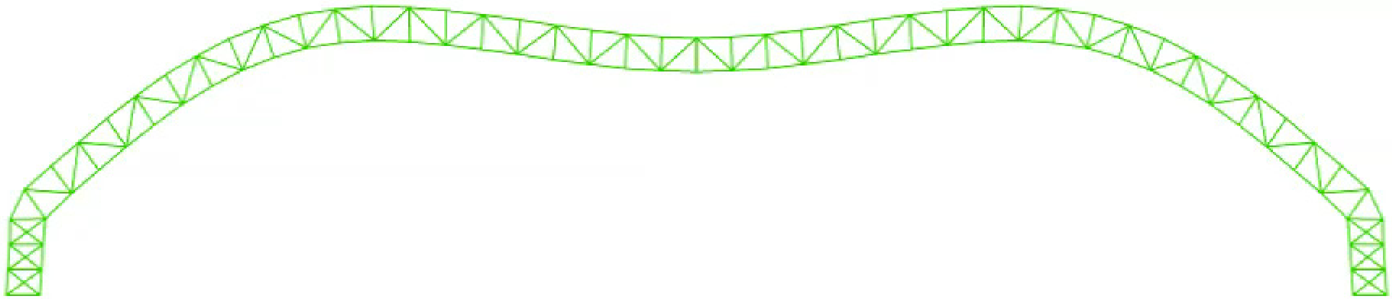


3rd mode

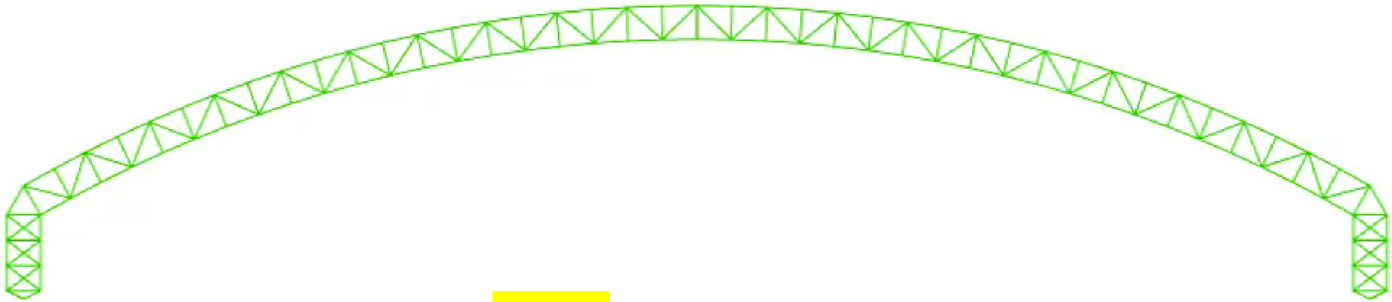
Pin



Fixed



Seismic response



Pin

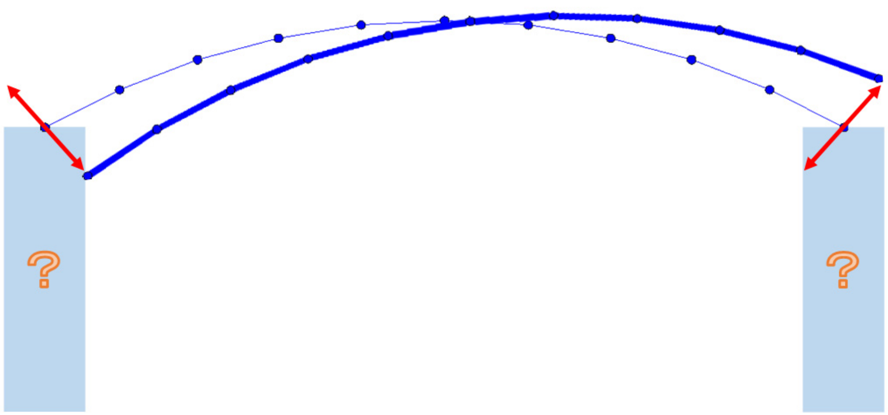
Fixed

Optimization of supporting structure (geometrically linear model)

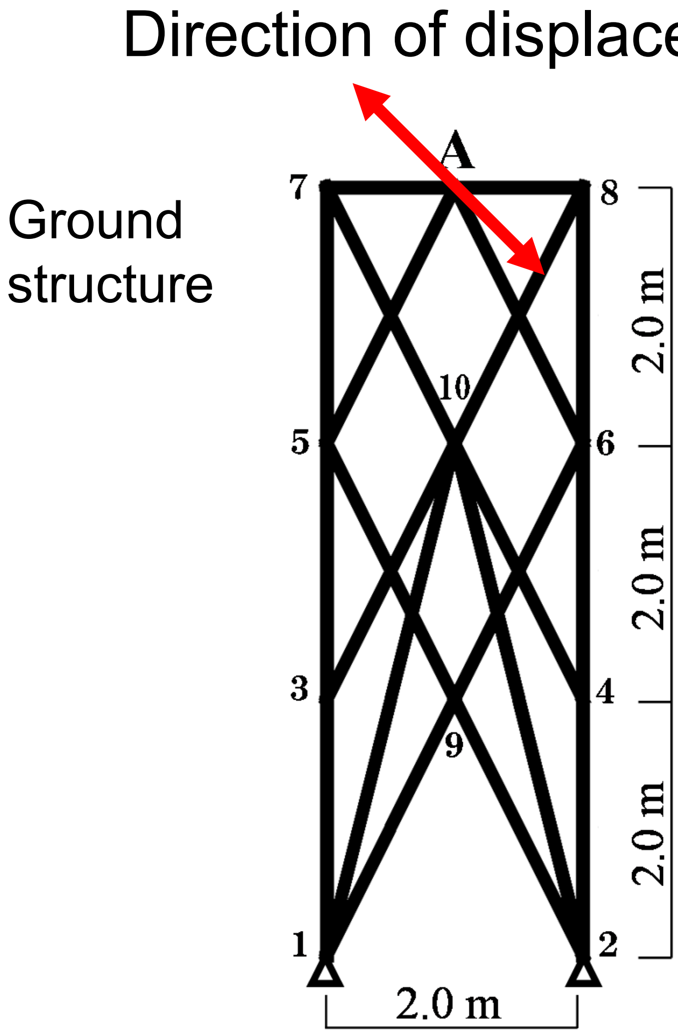
Step 1: Topology optimization of truss model considering static response.

Step 2: Cross-sectional optimization for reduction of acceleration and deformation of upper structure.

Deformation in normal direction of arch



Geometrically linear model



- Pin-jointed truss
- Young's modulus: 2.05×10^5 N/mm^2
- Mass at node A: 1800kg
- Mass at nodes 3～10: 600kg

- Variable: cross-sectional area
- Standard ground structure approach

Optimization problem

Maximize upward disp. due to horizontal forced disp.

Forced displacement: Node A, 0.06m

F_h : Horizontal reaction force

D_{A}^{v} : Vertical disp. due to self-weight

$$
\begin{aligned}
&\text{Maximize} && U_{\mathrm{A}}(\boldsymbol{A}) \\
&\text{subject to} && D_{\mathrm{A}}^{v}(\boldsymbol{A}) \le 0.005m,\ F_h(\boldsymbol{A}) \ge 200kN \\
& && 0.19cm^2 \le A_i \le 76cm^2 \quad (i = 1,..,20)
\end{aligned}
$$

←Horizontal and vertical stiffness

Reduce number of members

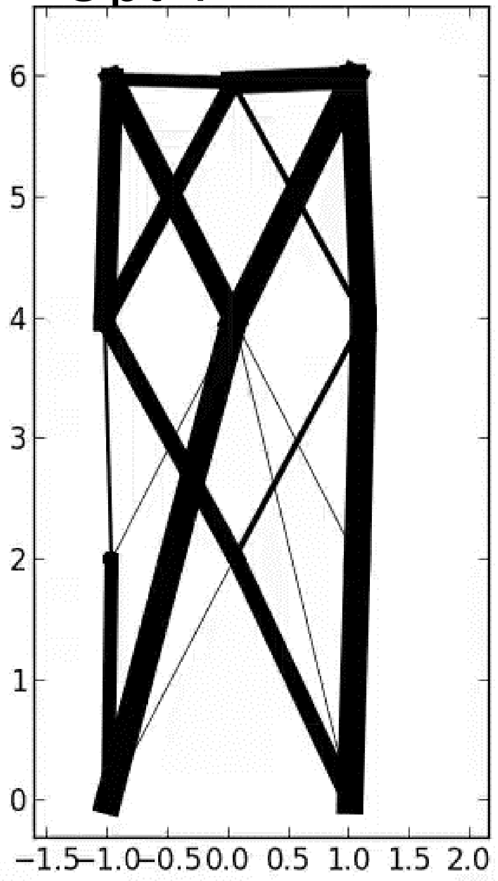
Minimize structural volume

$$
\begin{aligned}
&\text{Minimize} && V(\boldsymbol{A}) \\
&\text{subject to} && U_{\mathrm{A}}(\boldsymbol{A}) \ge U_{\mathrm{A}}^{OPT} \\
& && D_{\mathrm{A}}^{v}(\boldsymbol{A}) \le 0.005m,\ F_h(\boldsymbol{A}) \ge 200kN \\
& && 0.19cm^2 \le A_i \le 76cm^2 \quad (i = 1,..,20)
\end{aligned}
$$

←Constraint on vertical disp.
Optimal value of step 1

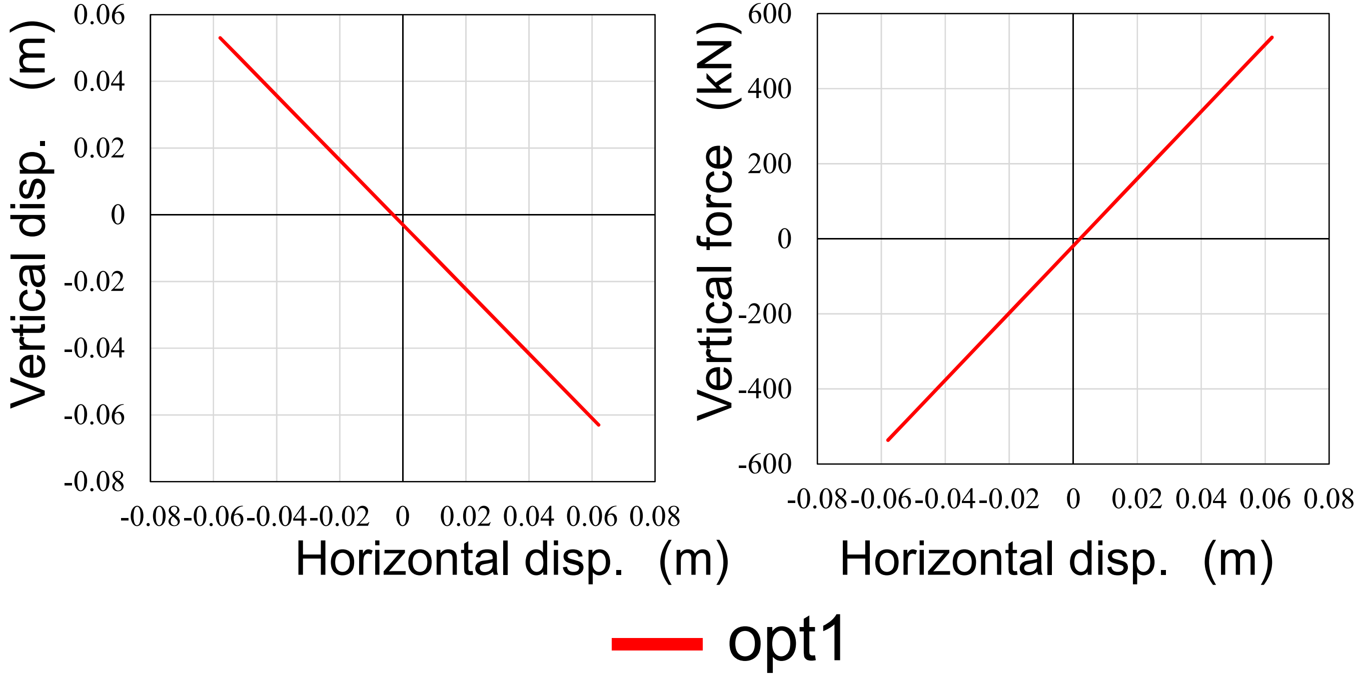
Optimization result 1

Opt 1



deformation (×5)

Response of node A



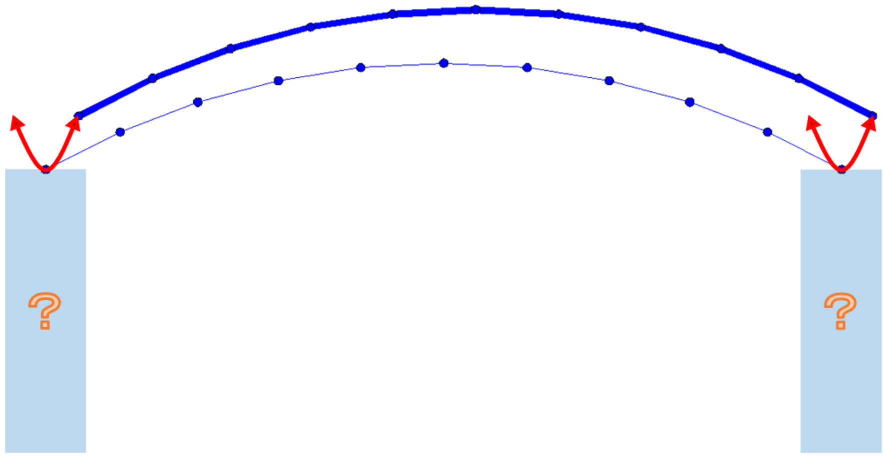
H-disp (self-weight) (m)	V-disp. (self-weight) (m)	H-reaction (kN)	V-disp. (m)
0.0021	−0.0050	536.76	0.06300

Optimization of supporting structure (geometrically nonlinear model)

Topology optimization of truss model considering geometrical nonlinearity.

Optimization of cross-section and nodal location.

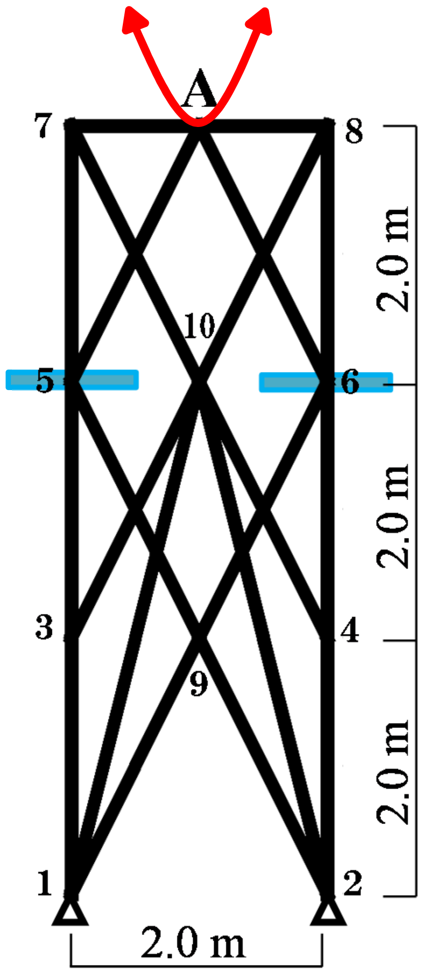
Deformation like reverse pendulum



Geometrically nonlinear model

Upward deformation for both right and left displacements.

Ground structure



Forced displacement: node A, 0.06 m

Maximize upward displacenent U_A^U

$$\text{Maximize} \quad U_A^U(\boldsymbol{A}, \boldsymbol{X})$$

$$\text{subject to} \quad D_A^v(\boldsymbol{A}, \boldsymbol{X}) \le 0.005\,m, \; F_h(\boldsymbol{A}, \boldsymbol{X}) \ge 200\,kN$$

$$0.19\,cm^2 \le A_i \le 76\,cm^2 \quad (i = 1,..,10)$$

$$-0.5\,m \le X \le 0.5\,m$$

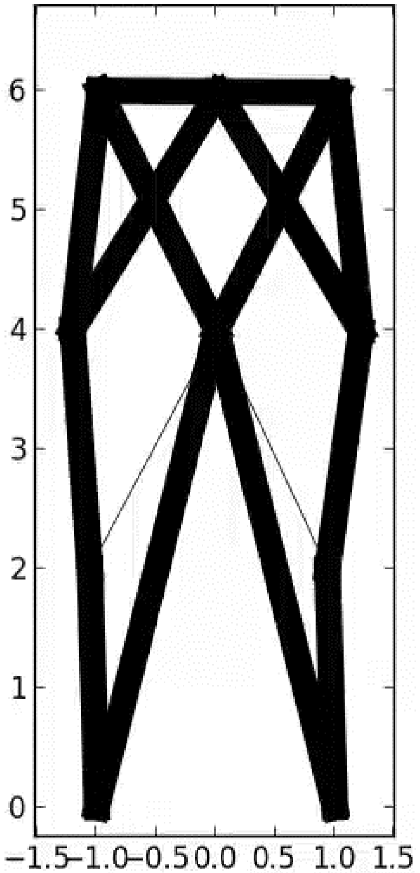
Symmetric structure

Variables: cross-sectional area

nodal location

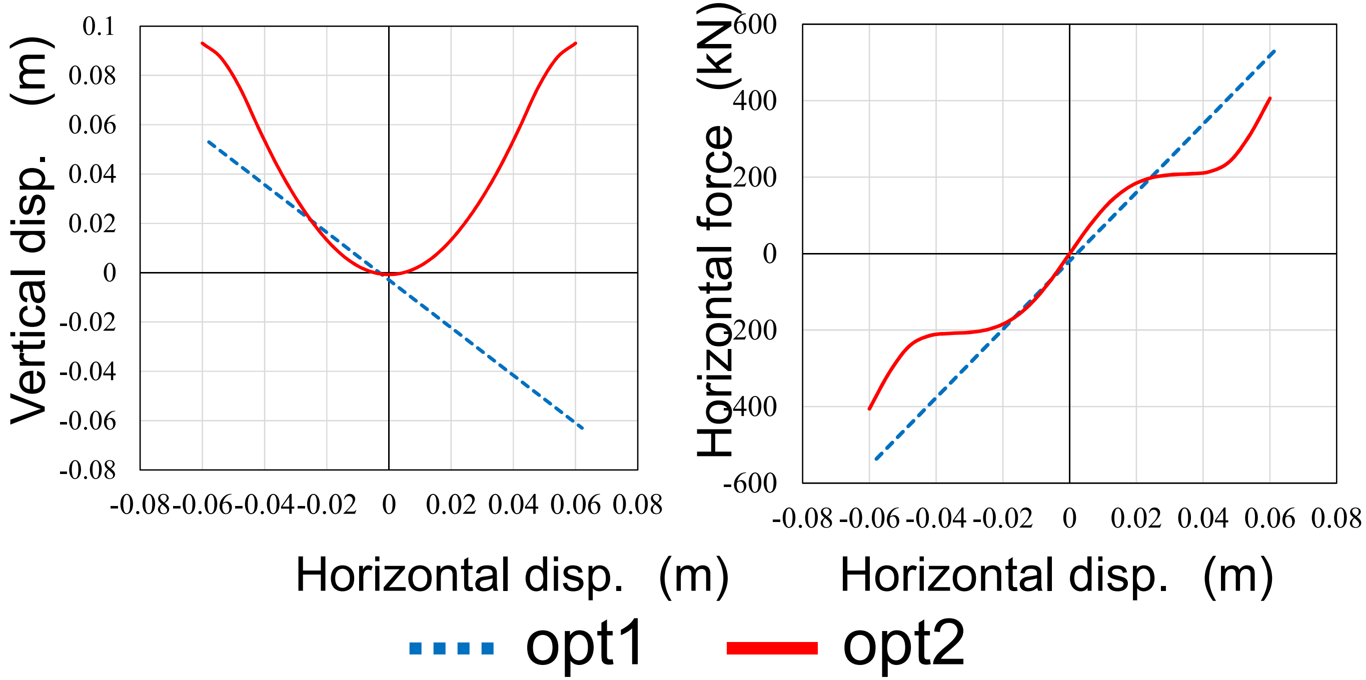
Optimization result 1

Opt 2



Deformation (×5)

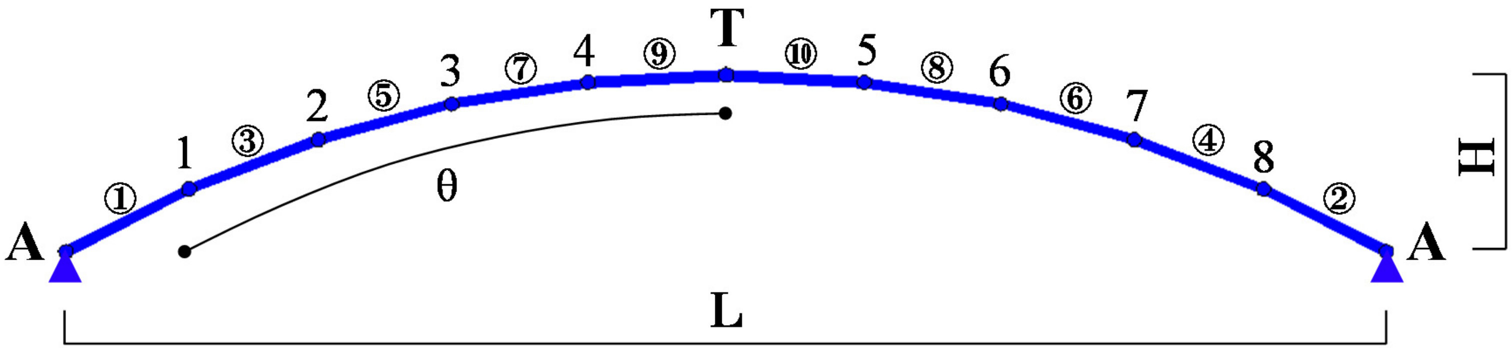
Response of node A



H-disp (self-weight) (m)	V-disp. (self-weight) (m)	H-reaction (kN)	V-disp. (m)
0.000	−0.0007	406.06	0.0930

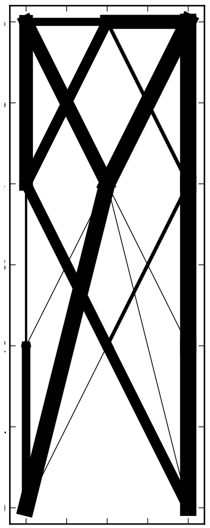
→ Small horizontal reaction
Nonlinear horizontal stiffness

Arch model



- Span L=19.5 m
- Rise H=2.613 m
- Open angle θ=60°
- Member section H-300×150×6.5×9
- Member length 2.04 m
- Young's modulus 2.05×10^5 N/mm^2
- Mass: nodes A, T 800 kg
  nodes 1〜8 800 kg

opt1



Attach arch to opt 1, and carry out further optimization

Optimization problem

Minimize $\quad F^N(\boldsymbol{A}) = \sqrt{\sum_{i=1}^{9} \left| \alpha_i^N \right|^2}$ Max. acceleration of node $\boldsymbol{i}$: α_i^N

subject to $\quad D_A^h \leq 0.01m,\ D_A^v \leq 0.01m$ ←Stiffness against self-weight

$0.19cm^2 \leq A_i \leq 76cm^2 \quad (i = 1,..,20)$

D_A^v: Vertical disp. at node A against self-weight

D_A^h: Horizontal disp. at node A against self-weight

Objective function:

Square norm of acceleration in normal direction.

Modal analysis: CQC method

Rayleigh damping with h=0.02 for 1st and 2nd modes.

CQC method
(complete quadratic combination)

Max. acceleration of node ***i***: $\left|\alpha_i^N\right|$

$$\left|\alpha_i^N\right| = \sqrt{\sum_{s=1}^{N}\sum_{r=1}^{N}\left(\beta_s\,{}^{\mathrm{N}}\phi_s^i S_s\left(T_s, h_s\right)\right)\rho_{sr}\left(\beta_r\,{}^{\mathrm{N}}\phi_r^i S_r\left(T_r, h_r\right)\right)}$$

β_s : participation factor T_s : natural period h_s : damping factor

S_s : acceleration response spectrum ω_s : natural circular frequency

${}^{\mathrm{N}}\phi_s^i$: normal displacement component at node ***i***

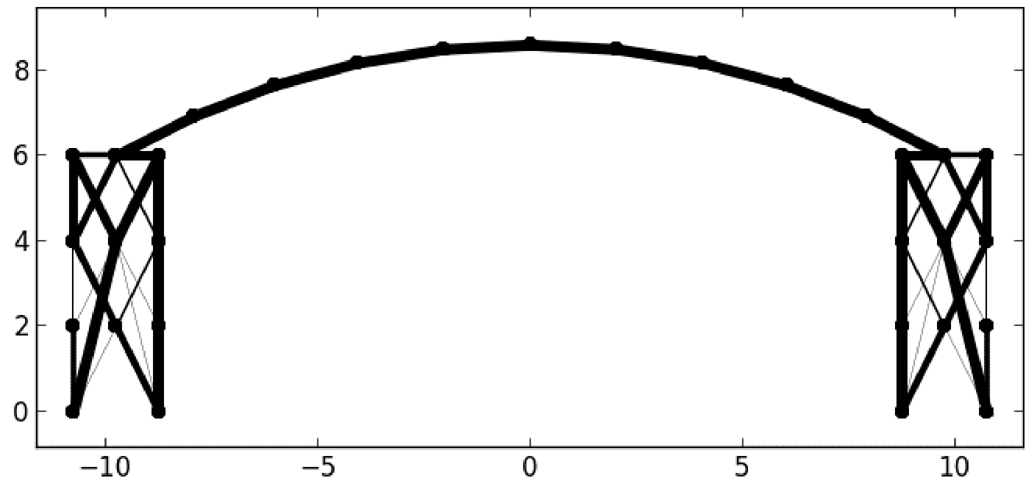
ρ_{sr} : modal correlation coefficient

$$\rho_{sr} = \frac{8\sqrt{h_s h_r}\left[h_r + \chi^3 h_s + 4\chi h_s h_r\left(h_r + \chi h_s\right)\right]\sqrt{\chi}}{\sqrt{\left(1+4h_s{}^2\right)\left(1+4h_r{}^2\right)}\alpha}$$

$$\alpha = \left(1-\chi^2\right)^2 + 4\chi h_s h_r\left(1+\chi^2\right) + 4\left(h_s{}^2 + h_r{}^2\right)\chi^2 \qquad \chi = \omega_r / \omega_s$$

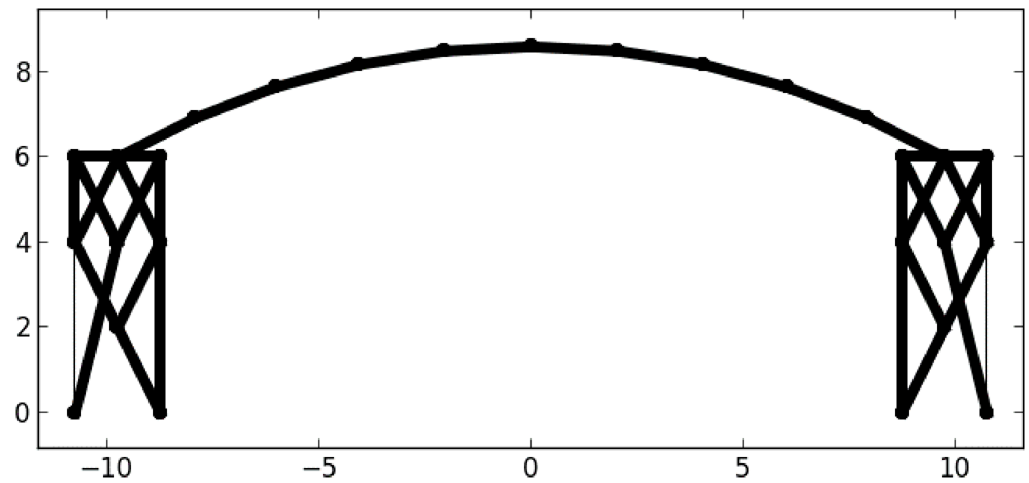
Optimization result

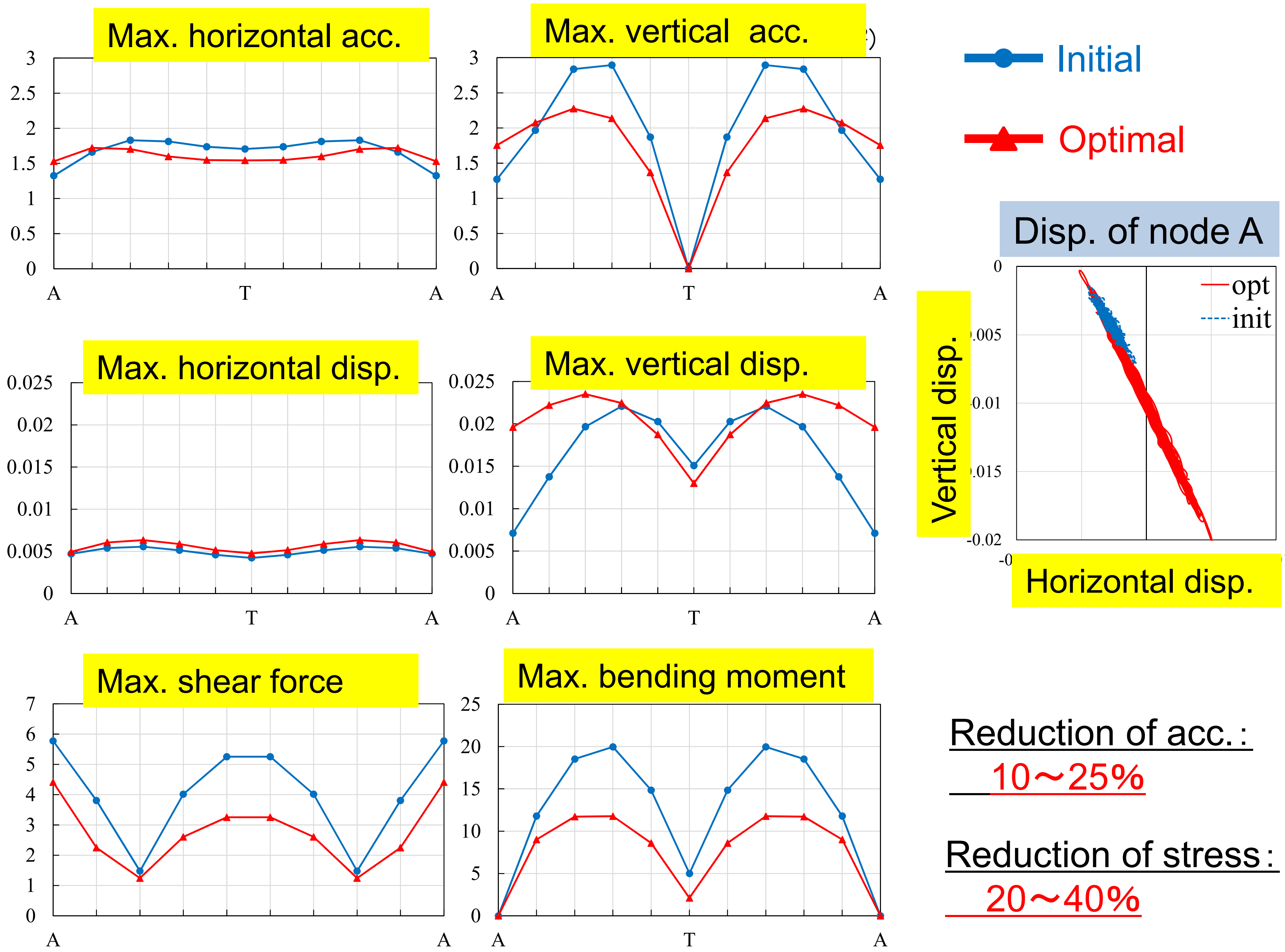
Initial



Optimize

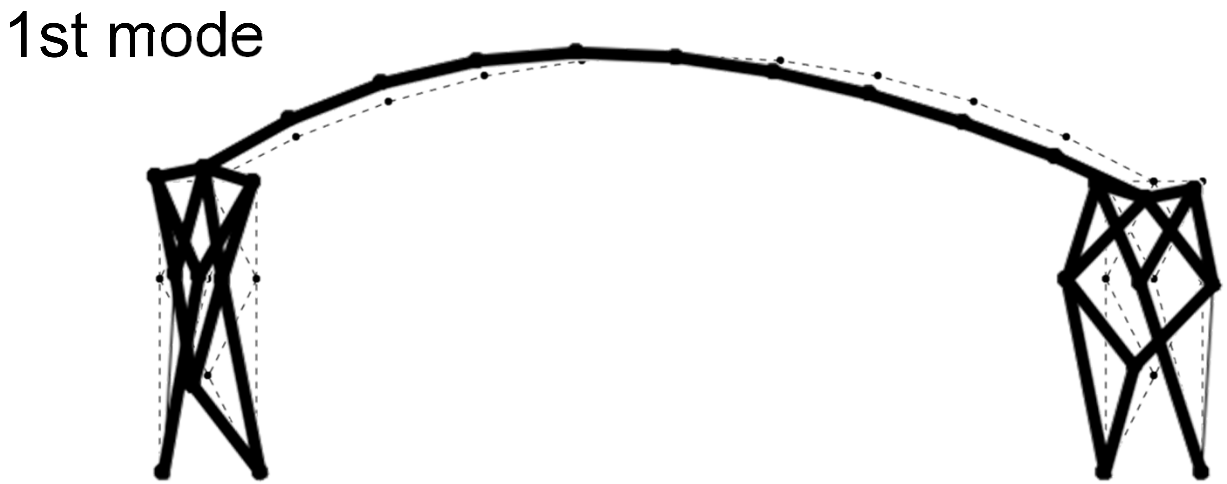
Optimal





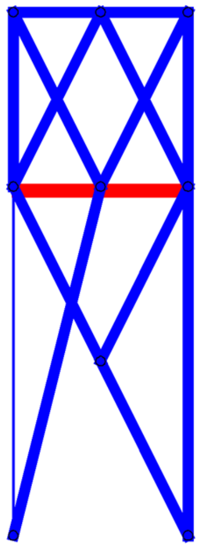
Reduction of acc.: 10～25%

Reduction of stress: 20～40%



Mode	Period	Frequency	Effective mass ratio	
	T (s)	F (Hz)	Horizontal (%)	Vertical (%)
1	0.506	1.976	29.62	0.0
2	0.441	2.268	0.0	2.29
3	0.321	3.115	0.04	0.0
4	0.236	4.237	0.0	38.23
5	0.145	6.897	0.0	6.77
6	0.114	8.772	62.26	0.0

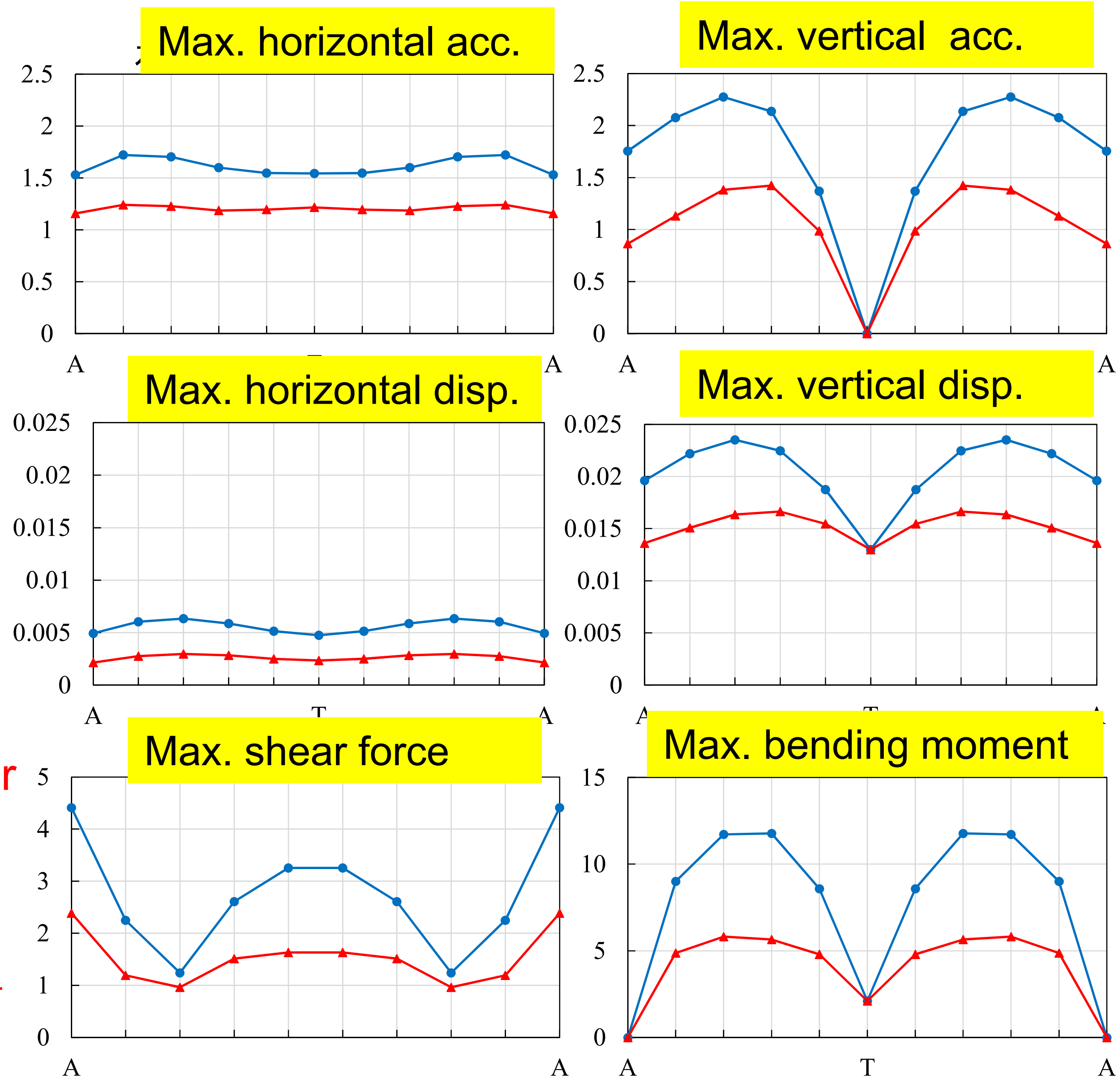
Optimal model with damper



Damping coefficient:
c=5000 N·s/m

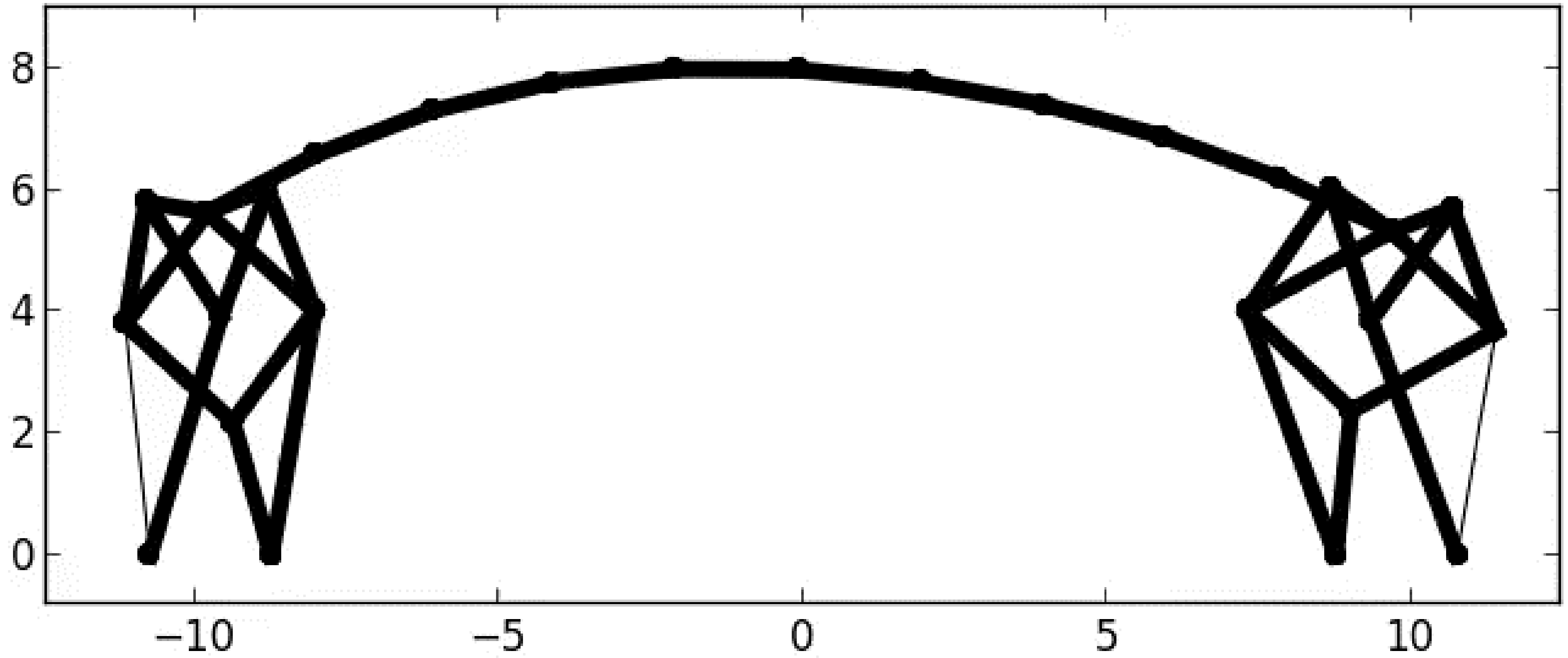
With damper

Without damper



Acc., disp, stress:
Reduction of 30～50%

Response of optimal model



(Deformation ×50)

Conclusions

- Flexibility of supports can be effectively utilized for reduction of seismic responses of structures.
- Two-stage procedure:
  - 1st stage: static optimization
    maximization of vertical displacement:
    variable: cross-sectional area
    minimization of structural volume:
    variable: cross-sectional area, nodal location
  - 2nd stage: dynamic optimization
    seismic response reduction
    variable: cross-sectional area