SHAPE OPTIMIZATION OF SHEAR PANEL DAMPER CONSIDERING PLASTIC ENERGY DISSIPATION

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Background

- Main difficulty in optimization of 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

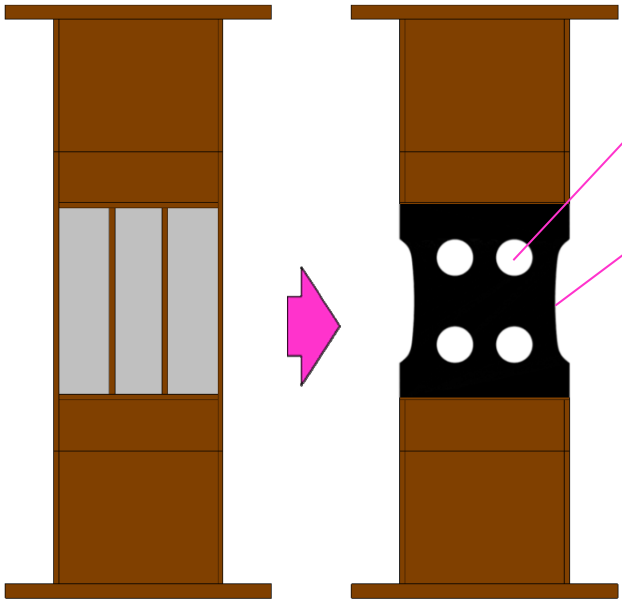
Objective of Study

- Optimization of steel panel dampers for seismic response reduction of building frames.
- Shape optimization of opening of perforated panel using conventional steel material.
- Parametric representation of hole shape using radial basis function.
- Combine heuristic optimization algorithm and FE-analysis.

Shear panel damper with opening

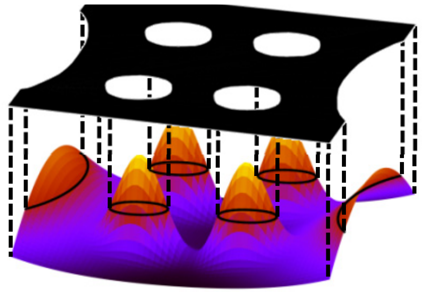
Low-yield steel
Expensive
Difficult to obtain

Normal steel
Inexpensive
Easy to obtain



Opening　Boundary shape

Shape of panel is defined using Gaussian functions and Bezier function



Maximize plastic dissipated energy under constraint on equivalent plastic strain

Use normal steel
Reduce stiffness and strength with opening

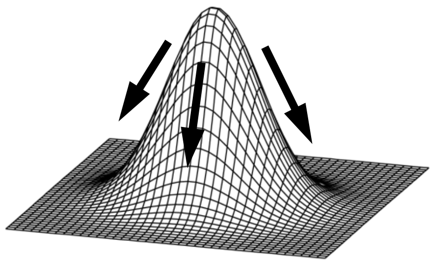
Gaussian function and Bezier function

Two dimensional Gaussian function

center

$$g_k(x,y) = \exp\left(-\frac{(x - x_k)^2 + (y - y_k)^2}{2r_k^2}\right)$$

Standard deviation



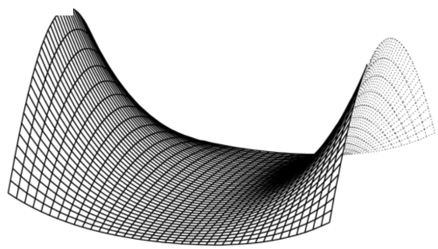
Bezier function

Control points

$$P(x,y) = \sum_{i=0}^{n} \sum_{j=0}^{n} B_i^n(x) B_j^n(y) q_{ij}$$

$$B_i^n(x) = {}_nC_i (1 - x)^{n-i} x^i$$

Bernstein polynomial

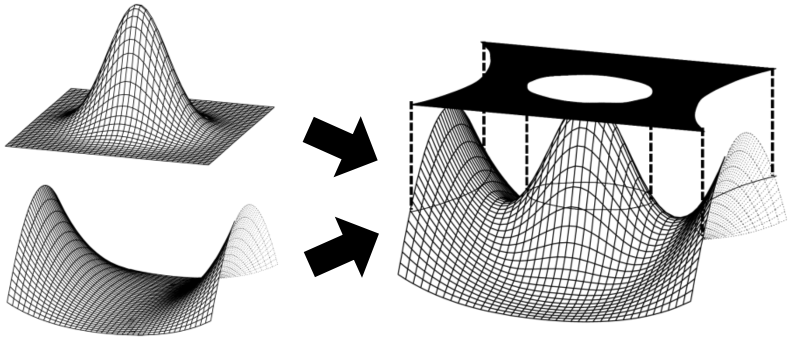


Boundary representation using level set function

Level set function

Add Gaussian function and Bezier surface

$$\Phi(x,y) = \sum_{k=1}^{m} g_k(x,y) + P(x,y)$$

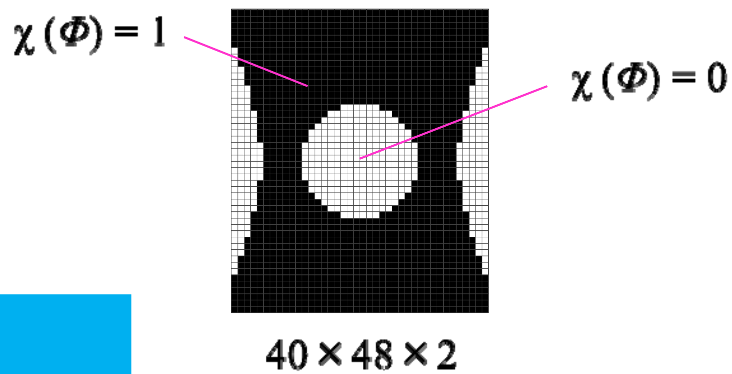


FE-model of structures mesh

$$\chi(\Phi) = \begin{cases} 1 & \text{if } \Phi(x,y) < \alpha \\ 0 & \text{if } \Phi(x,y) \geq \alpha \end{cases}$$

$$\alpha = 0.5 \cdot \Phi_{\max}(x, y)$$

Maximum value of level set function

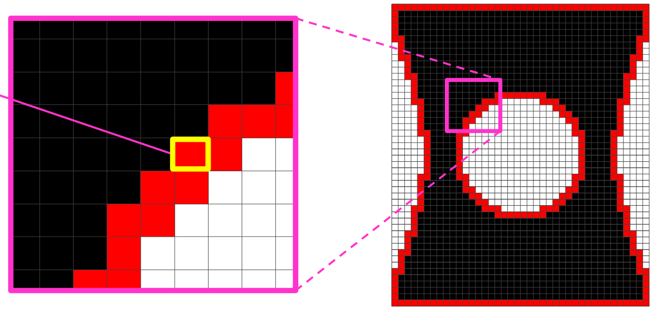


Index of ductile fracture

Simple measure using equivalent plastic strain

FE-model of structures mesh ➡ Non-smooth boundary shape ➡ Unrealistic strain at boundary

Exclude boundary elements for checking fracture

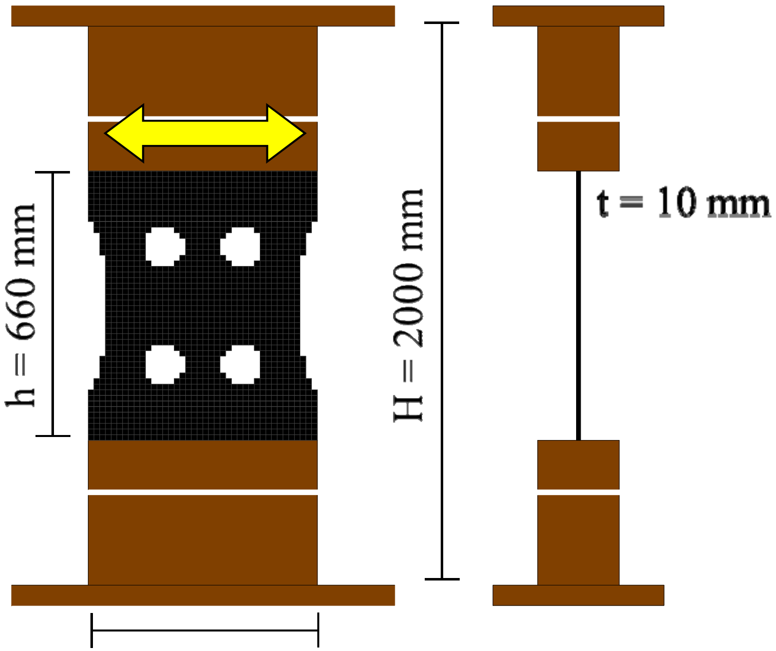


Analysis of steel panel damper

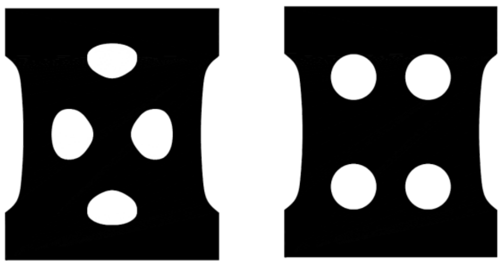
FE-analysis using ADVENTURECluster

Yield stress = 235 N/mm2
Kinematic hardening
Hardening coefficient
= 0.05 E

Vertical disp. = h/2000
Horizontal disp. = h/200



Locations of opening



Panel-A Panel-B

Design variables

Two dimensional Gaussian function

Center → Design variable

$$g_k(x,y) = \exp\left(-\frac{(x-x_k)^2+(y-y_k)^2}{2r_k^2}\right)$$

Std. variation → Design variable

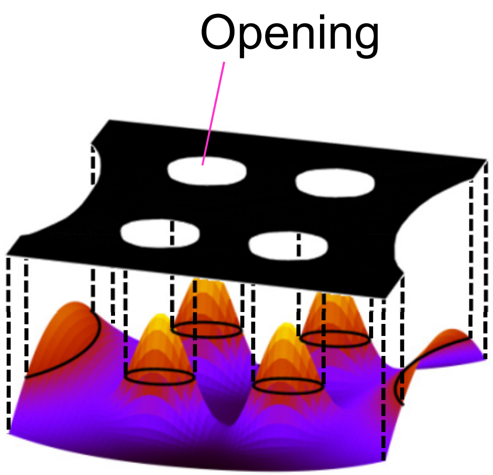
Bezier function

$$P(x,y) = \sum_{i=0}^{n}\sum_{j=0}^{n} B_i^n(x) B_j^n(y) q_{ij}$$

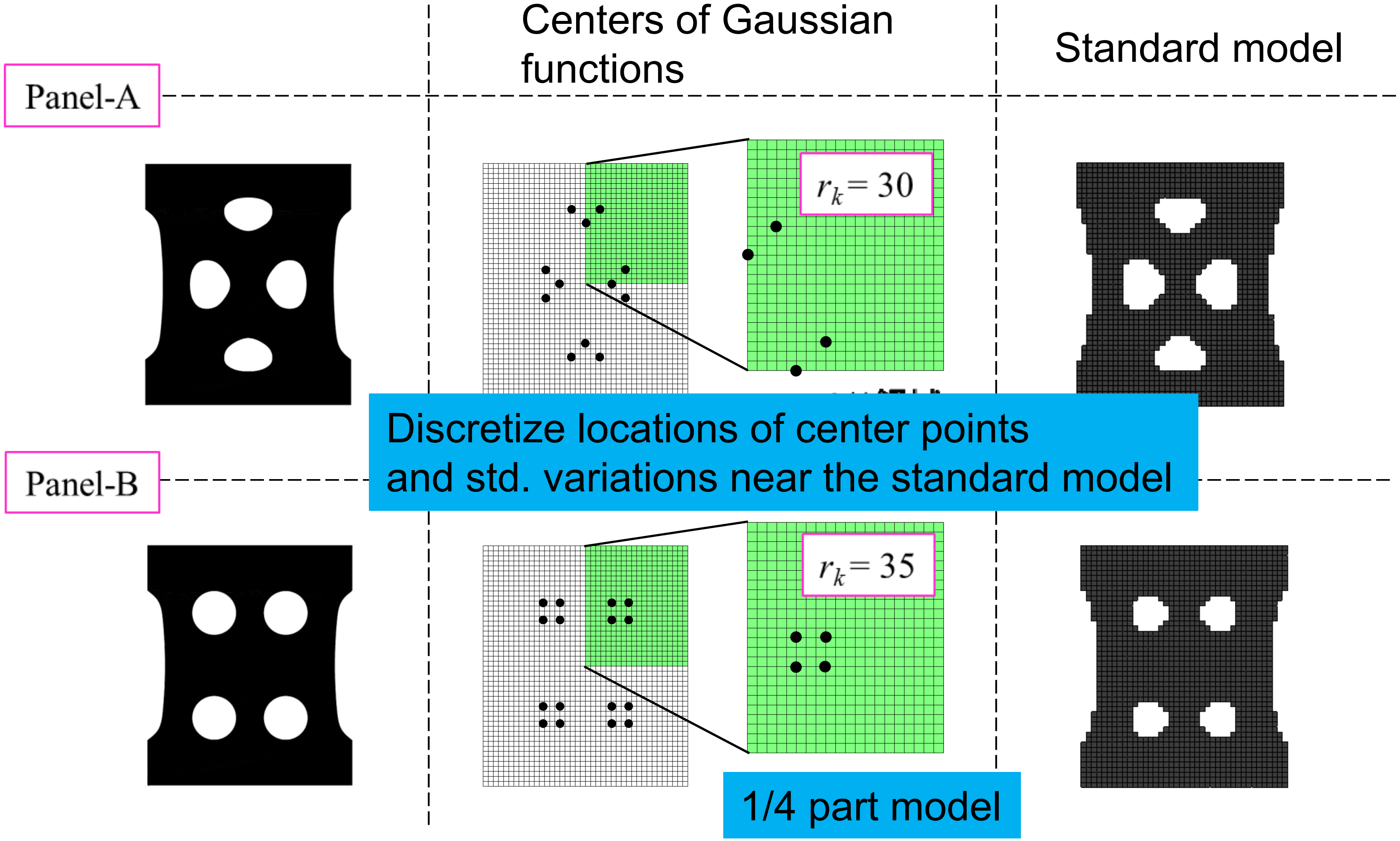
$$B_i^n(x) = {}_nC_i (1-x)^{n-i} x^i$$

$$ {}_nC_i = \frac{n!}{(n-i)!\,i!}$$

Control points → Fix control points



Parameters of Gaussian function



Variables: std. dev. and x,y-coordinates; three for each point

Optimization problem 1

Larger reaction → larger plastic energy dissipation

Specify lower-bound of reaction

$\hat{E}_{\mathrm{p}}(\mathbf{J})$: dissipated energy before $\varepsilon_{\max}(\mathbf{J})$ reaches the specified value

$$\text{Maximize} \quad F(\mathbf{J}) = \frac{\hat{E}_{\mathrm{p}}(\mathbf{J})}{R_{\max}(\mathbf{J})}$$

$$\text{subject to} \quad g(\mathbf{J}) = \frac{R_{\max}^{0}}{R_{\max}(\mathbf{J})} \leq 1$$

Specified value of reaction

$$J_i \in \{1, 2, \cdots, d_i\} \quad (i = 1, 2, \cdots, m)$$

Discretize variables into integer values

Tabu search （TS）

1. Randomly generate initial seed solution
   Initialize tabu list T as empty list
2. Generate neighborhood solutions $\boldsymbol{N} = \{ \boldsymbol{J}_j^N \mid j = 1,\ldots,q \}$
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 variables: 12
2. Number of neighborhood solutions: 12
3. Number of steps: 20
4. Length of tabu list: indefinite

5. Carry out TS three times from different random seeds.
6. Total number of analyses: 12 x 20 x 3 = 720

Optimization using ADVCluster

TS Algorithm

Modify variables

Preprocessing (Fortran)

(1) Bezier function, RBF
(2) Compute level-set function
(3) Find non-existent elements
(4) Submit to
ADVENTURECluster

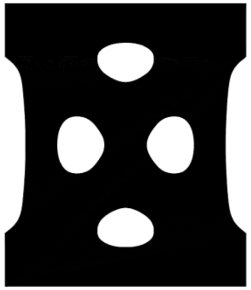
Simulation using ADVENTURECluster

Postprocessing
(Perl Script)

(1) Convert binary data to
text data using
‘hddmmrg’ tool.
(2) Compute reaction,
maximum plastic strain,
total plastic energy

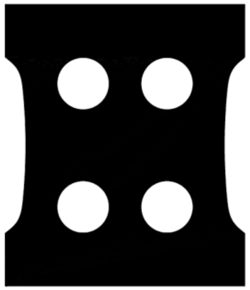
Optimization result

Panel A



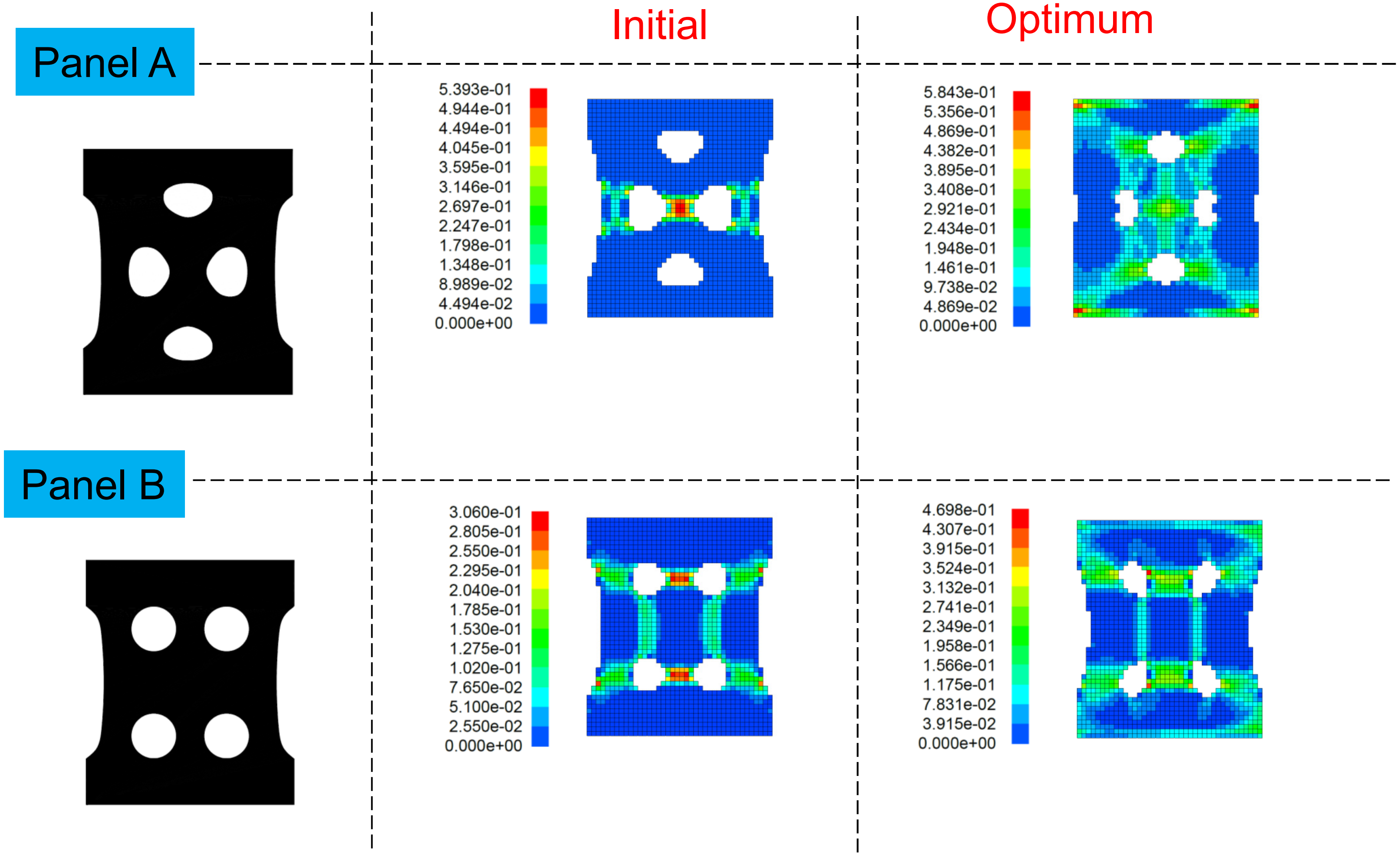
	Dissipated energy	Maximum plastic strain	Maximum reaction	Cycles
Initial	15.10	0.539	354.24	1.00
Optimum	53.21	0.539	476.50	3.43

Panel B



	Dissipated energy	Maximum plastic strain	Maximum reaction	Cycles
Initial	19.33	0.306	402.08	1.00
Optimum	43.94	0.306	455.94	2.59

Optimization result



Equivalent plastic strain

Optimization problem 2

Number of cycles may be large before dissipated energy reaches specified value

Dissipated energy in first cycle

$$\text{Maximize} \quad F(\mathbf{J}) = \frac{E_{\mathrm{p}}(\mathbf{J})}{\varepsilon_{\max}(\mathbf{J}) R_{\max}(\mathbf{J})}$$

Specified value of reaction

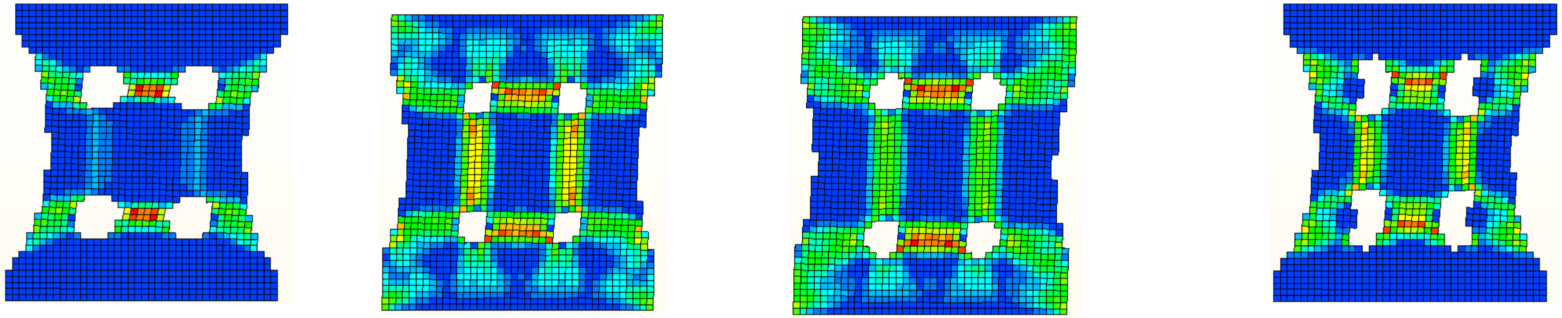
$$\text{subject to} \quad g(\mathbf{J}) = \frac{R_{\max}^{0}}{R_{\max}(\mathbf{J})} \le 1$$

$$J_i \in \{1, 2, \cdots, d_i\} \quad (i = 1, 2, \cdots, m)$$

Carry out analysis only for 1st cycle

Optimization result

40 x 48 x 3 = 5760 elements

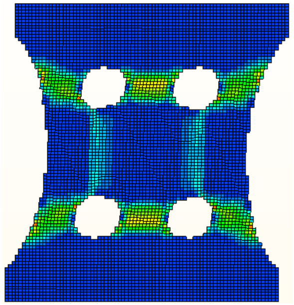


Initial Opt 1 Opt 2 Opt 3

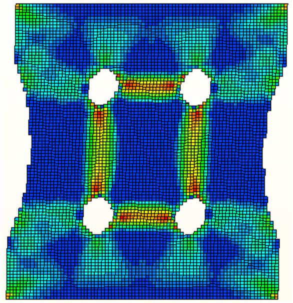
	Objective function	Energy (kN m)	Strain	Reaction (kN)
Initial	137.0	79.7	0.569	1021
Opt 1	310.2	125.7	0.269	1507
Opt 2	297.1	124.5	0.283	1483
Opt 3	264.8	81.0	0.307	995

FE-analysis with fine mesh

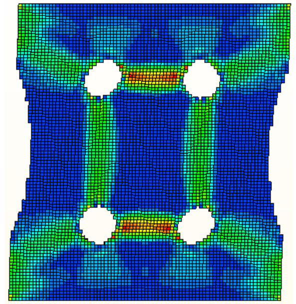
80 x 96 x 6 = 46080 elements



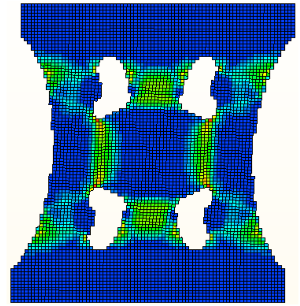
Initial



Opt 1



Opt 2



Opt 3

	Objective function	Energy (kN m)	Strain	Reaction (kN)
Initial	131.2	84.14	0.5994	1070
Opt 1	233.4	126.4	0.3573	1516
Opt 2	214.6	124.1	0.3893	1485
Opt 3	167.2	82.63	0.4817	1026

FE-analysis with fine mesh

1 cycle

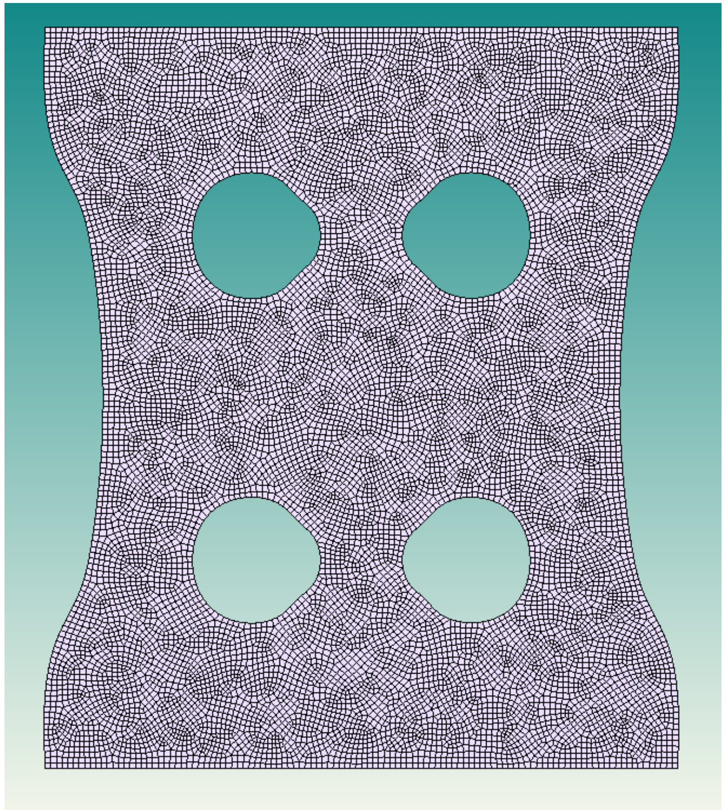
	Objective function	Energy (kN m)	Strain	Reaction (kN)
Initial	131.2	84.14	0.5994	1070
Opt 1	233.4	126.4	0.3573	1516
Opt 2	214.6	124.1	0.3893	1485
Opt 3	167.2	82.63	0.4817	1026

3 cycles

	Objective function	Energy (kN m)	Strain	Reaction (kN)
Initial	128.2	215.7	1.572	1070
Opt 1	229.5	326.5	0.938	1517
Opt 2	211.7	319.9	1.018	1485
Opt 3	165.3	212.4	1.252	1026

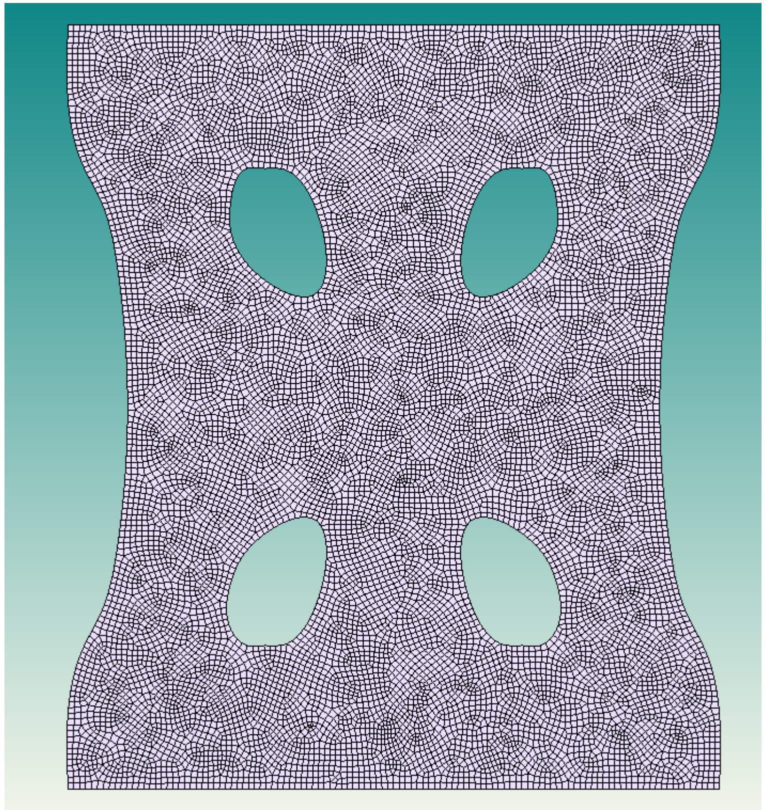
Analysis after Re-meshing

Initial model



Number of nodes = 45,792
Number of elements = 29,752

Optimal model



Number of nodes = 46,806
Number of elements = 30,460

Conclusions

- Energy dissipation properties of passive dampers can be drastically improved through optimization using local search of discretized variables.
- Cost and time for physical tests for development of devices can be reduced using EF analysis and optimization.
- Appropriate choice of optimization algorithm.