Combinatorial Optimization of Latticed Blocks for Seismic Retrofit of Building Frames

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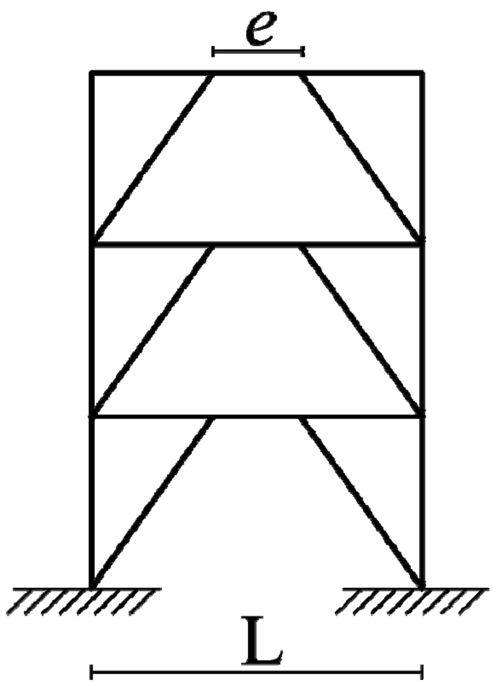
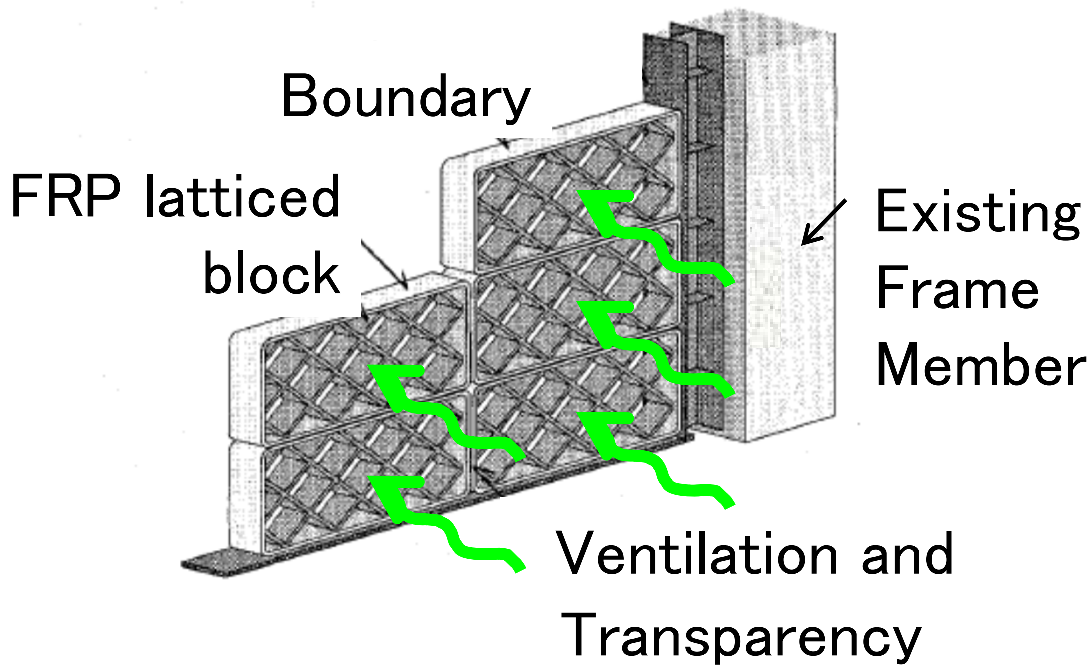
Seismic retrofit of building frames

- Add braces, viscous dampers, friction dampers
- Base-isolation
- Remove upper stories
- Add shear wall



Conventional latticed blocks

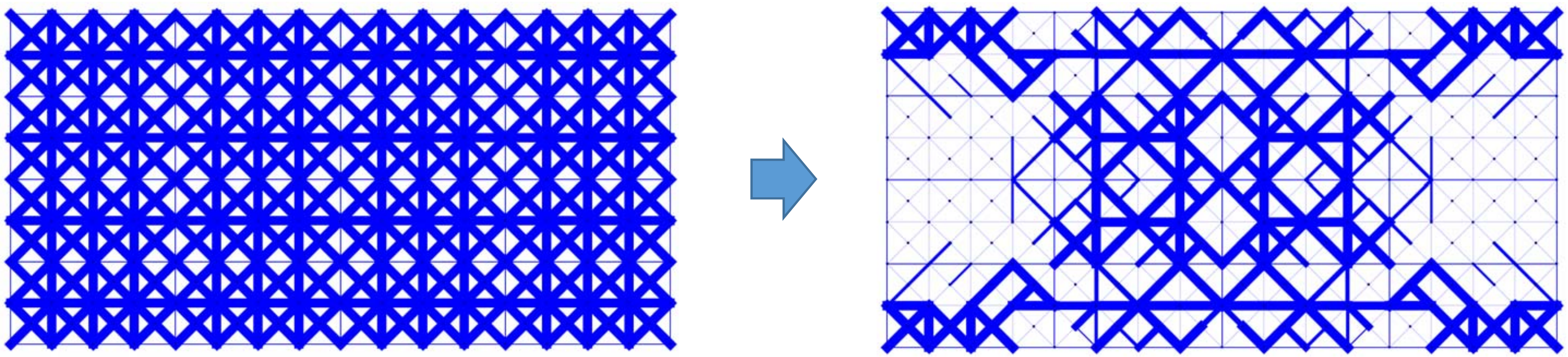
- Improve stiffness and strength by connecting FRP blocks
- Efficiency in ventilation and transparency
- Shapes of members and openings are fixed.
- Effect to existing frame is not considered



Previous study

Optimization using nonlinear programming

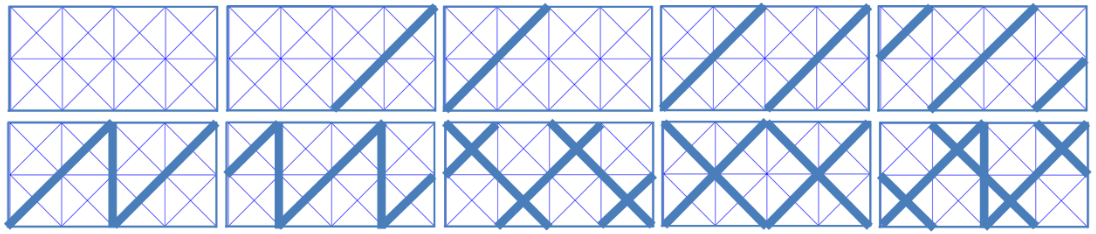
Continuous variables: width of member



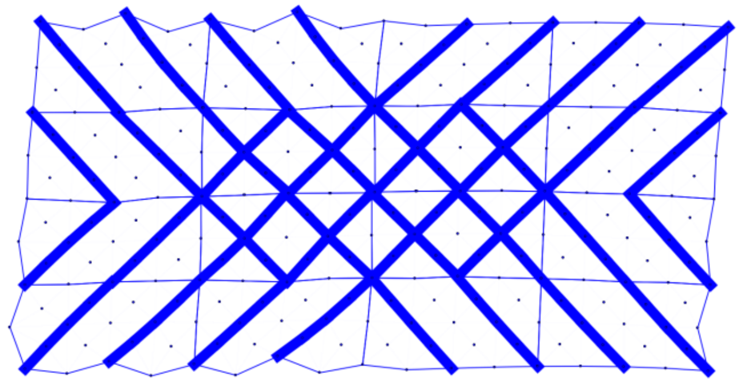
- Complex optimal solution
- Difficult to manufacture

Purpose of study

Combinatorial optimization using simulated annealing



List of unit blocks

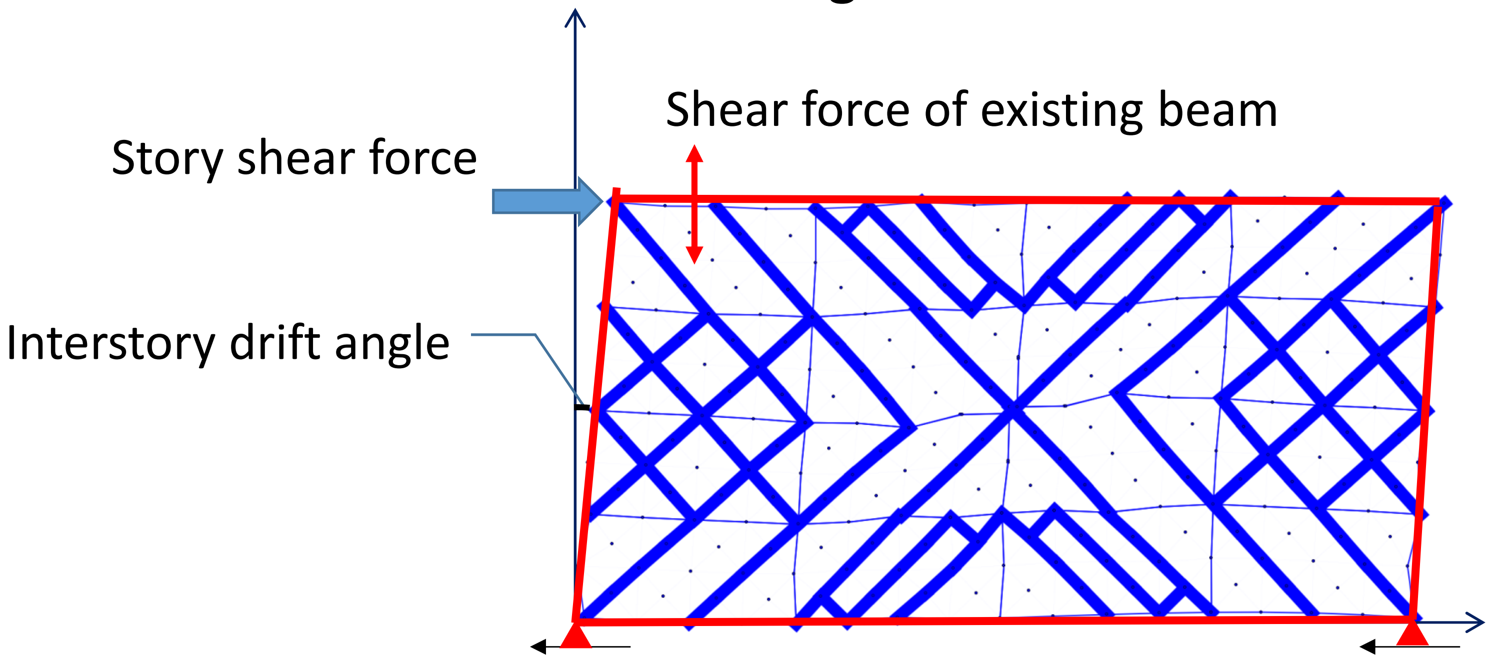


Deformed shape of optimal solution

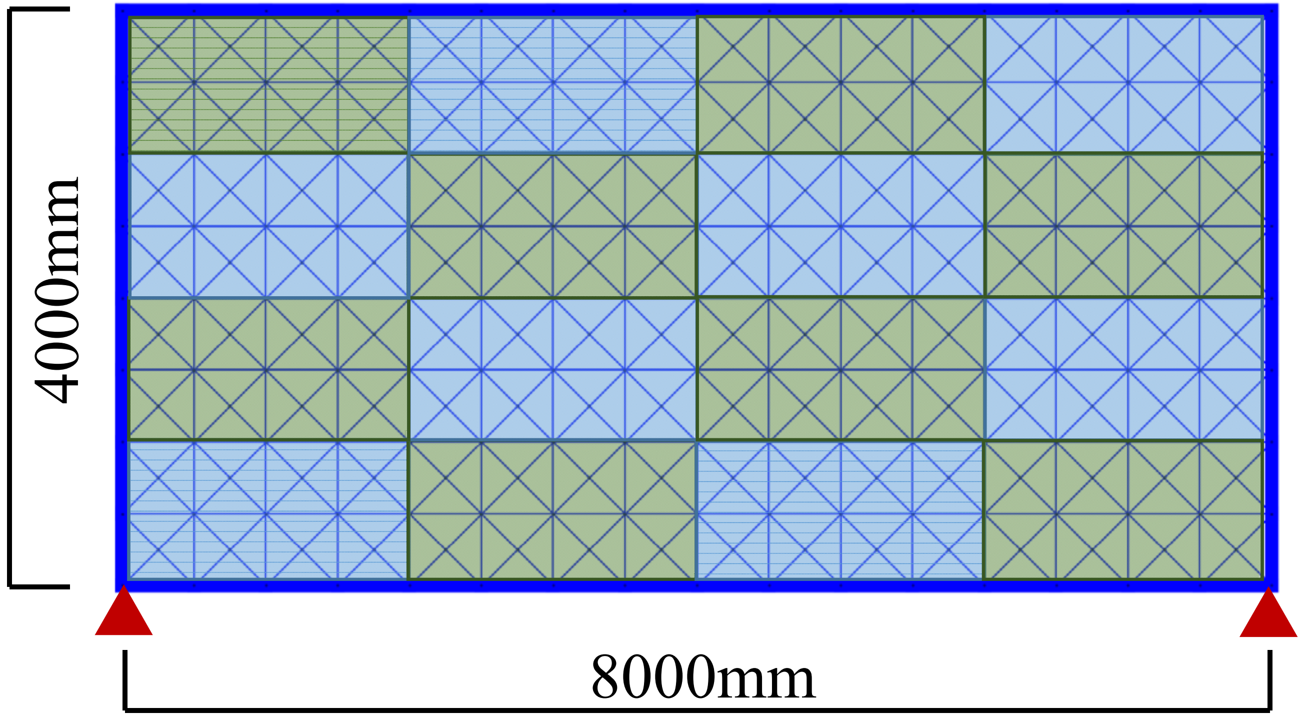
Purpose of study

Shape optimization of blocks under various objective function and constraints

- Minimize total structural volume.
- Maximize story shear force.
- Minimize shear force of existing beam.

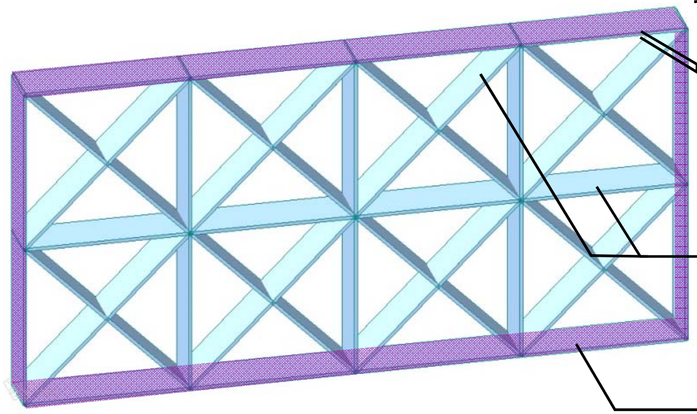


Model of existing frame



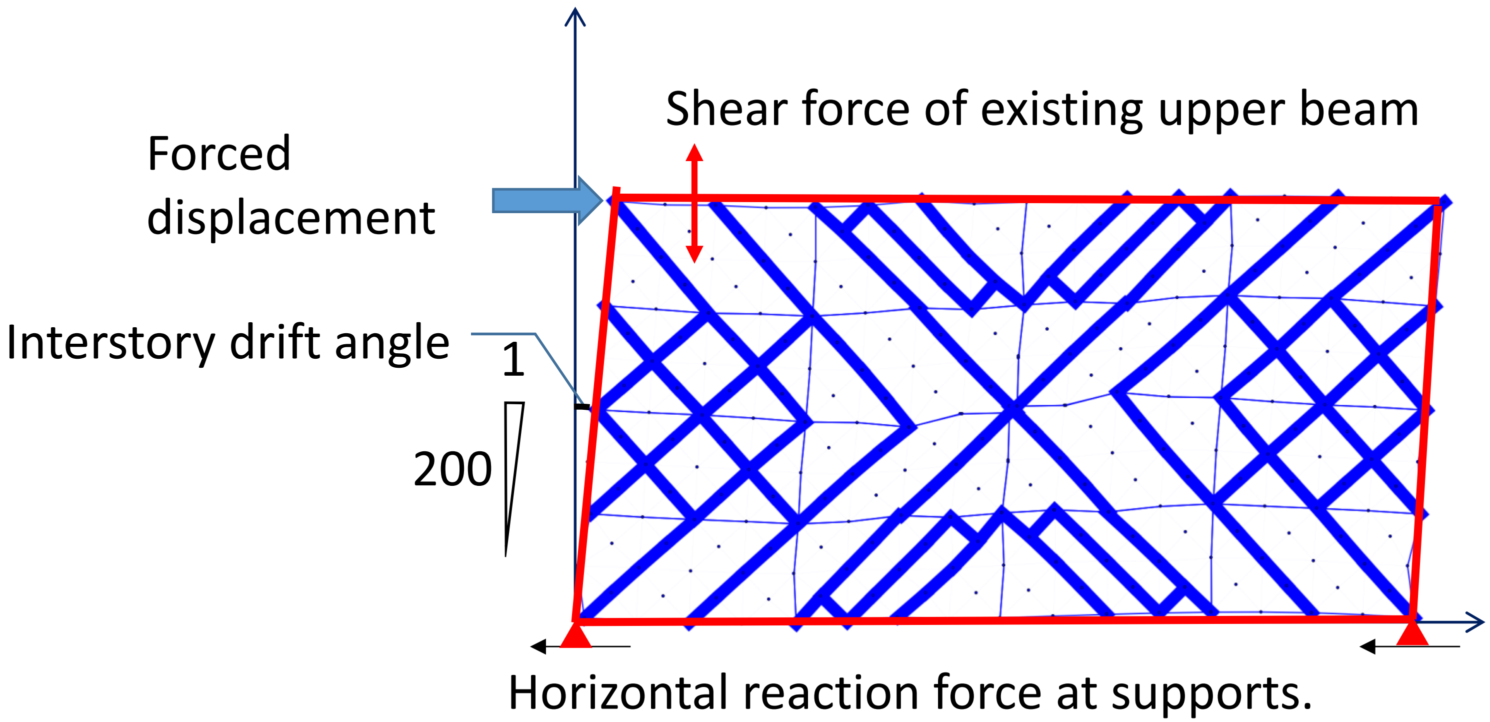
	Width B (mm)	Depth D (mm)	Area A (mm^2)	Second moment of area I (mm^4)	Young's moduls E (N/mm^2)
Column	700	700	490000	2.00×10^{10}	20000
Beam	400	700	280000	1.14×10^{10}	20000

Models of latticed blocks



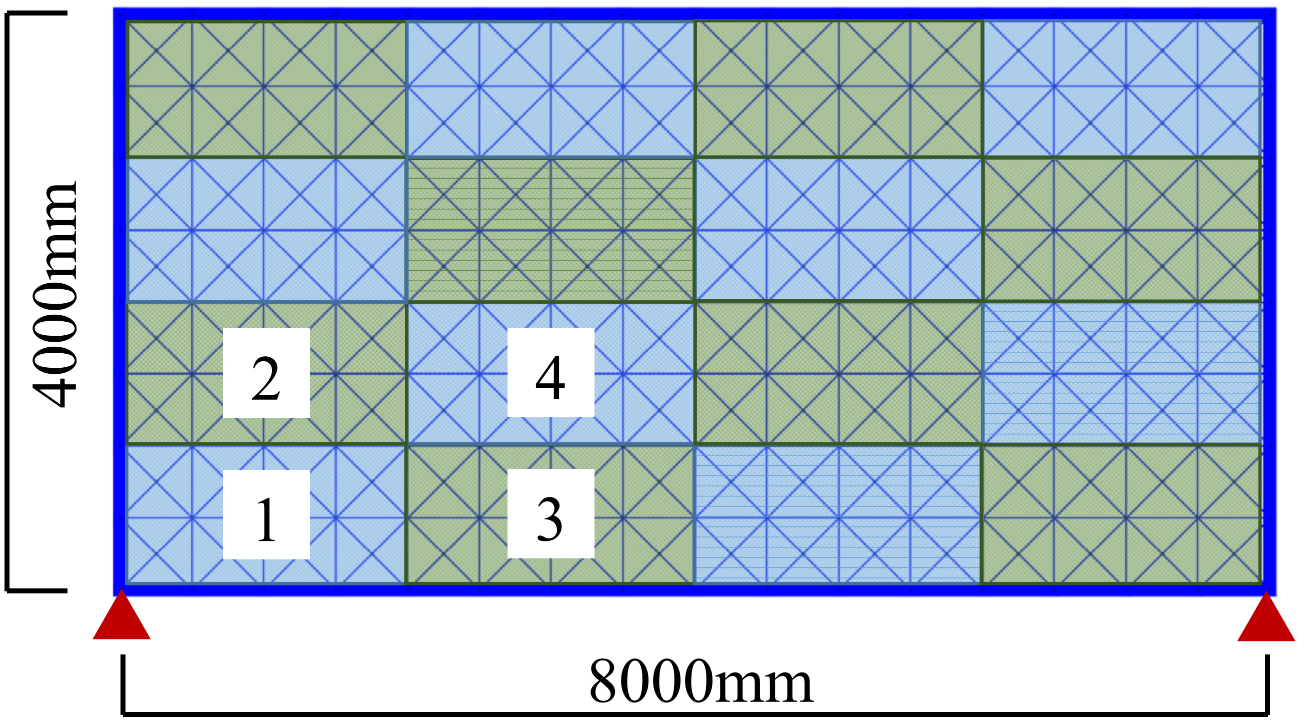
	Width B (mm)	Depth D (mm)	Area A (mm^2)	Second moment of area I (mm^4)	Young's moduls E (N/mm^2)
Boundary	80	10	800	6.67×10^3	20000
Lattice	80	0.1 or 100	8 or 8000	6.67^{-3} or 6.67×10^6	20000

Static response analysis



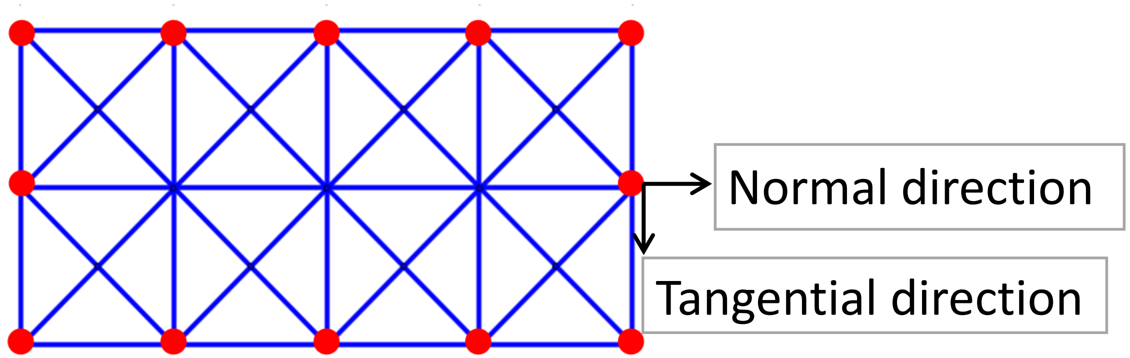
Displacement control
Incremental analysis
Software: OpenSees

Design variables

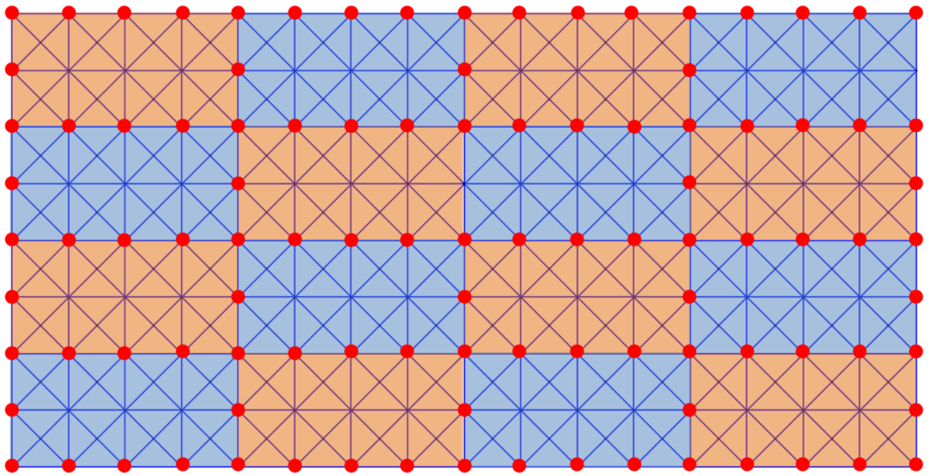


Type of unit block at 1, 2, 3, and 4

Connection using epoxy glue



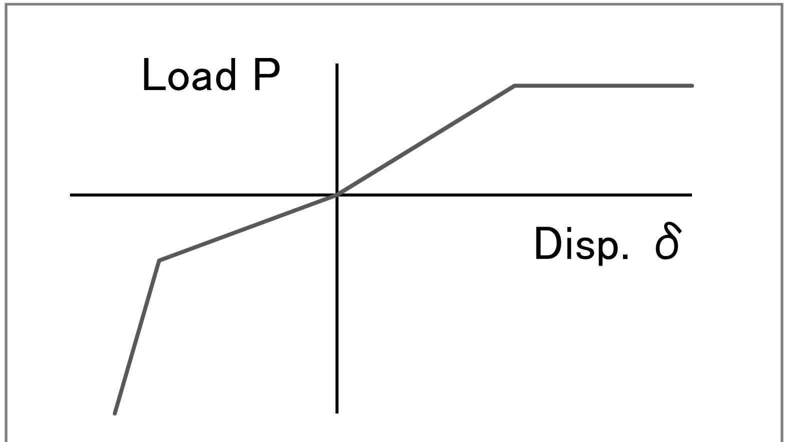
Contact element



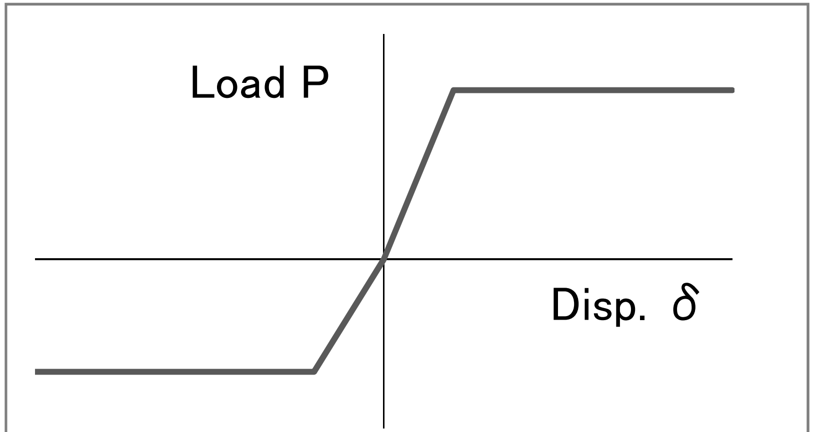
Material property

	Tensite strength σ_t (N/mm²)	Compressive strength σ_B(N/mm²)	Shear strength σ_s(N/mm²)
Concrete	**2.7**	24	4
Epoxy	**27**	—	10
FRP	**335**	319	—

Contact element



Normal direction

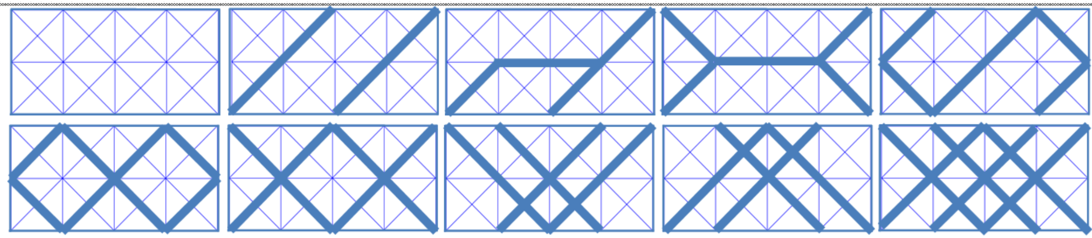


Tangential direction

Unit block types

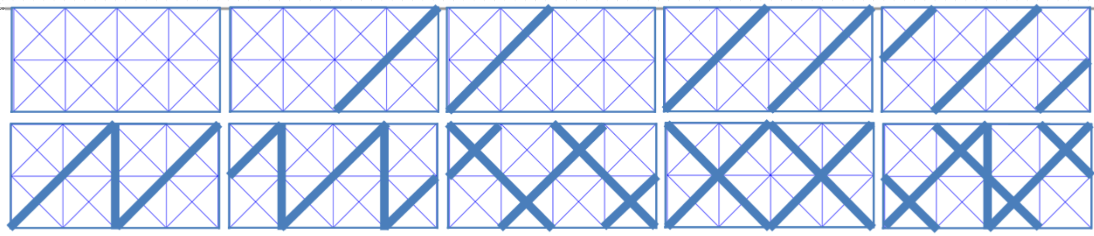
Select types of unit blocks at four regions of wall.

Group 1: ten types defined from results of optimization using NLP.



Group 2:

Re-select ten types in view of optimization results of Group 1.



Reference model (maximum thickness)

V_0 (m^3):

Total volume of boundary and lattice members.

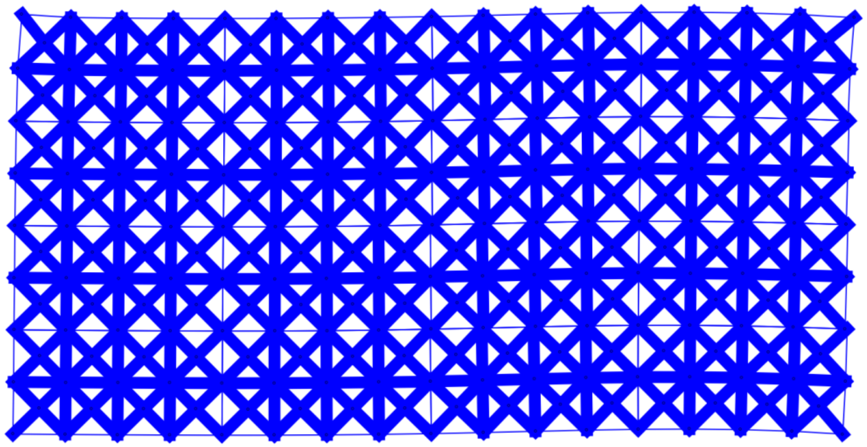
R_0 (kN):

Horizontal support reaction force.

Q_0 (kN):

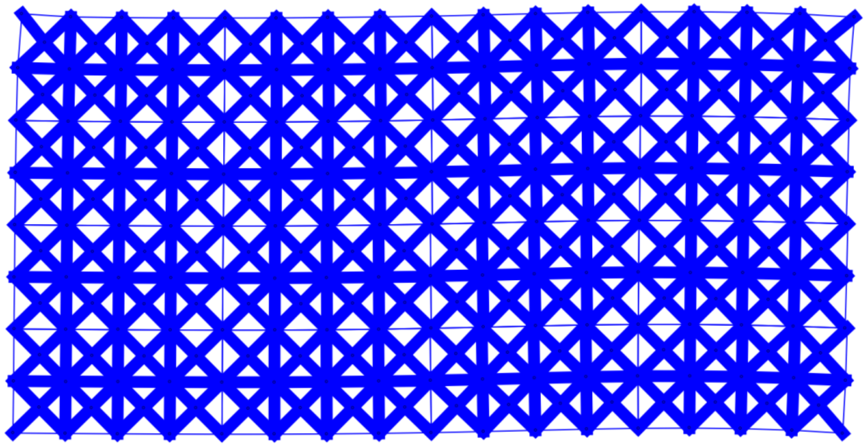
Maximum shear force of upper beam.

→ Effect on existing frame.

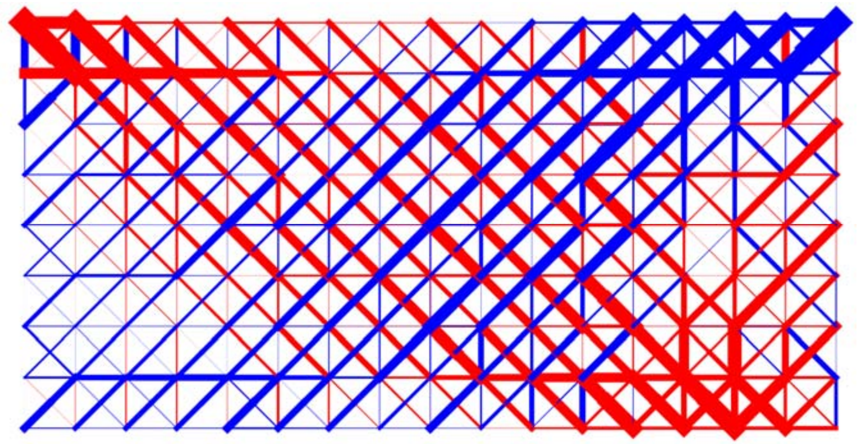


Reference model

V_0 (m^3)	R_0 (kN)	Q_0 (kN)	σ_0(N/mm^2)	N_0 (kN)
2.16	2267	615	123	180

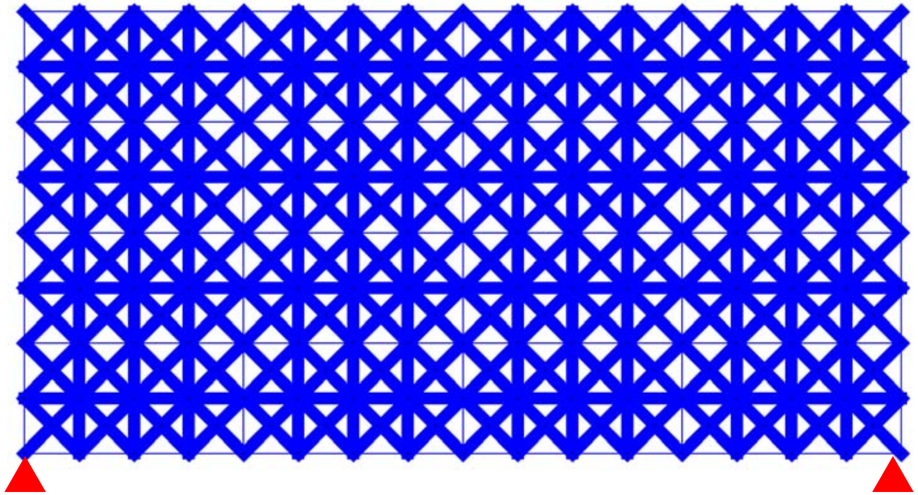


Reference model



Axial force

Effect of reinforcement



R_0 (kN)
1325

R (kN)
2267

Increase horizontal load to 171%

Simulated annealing

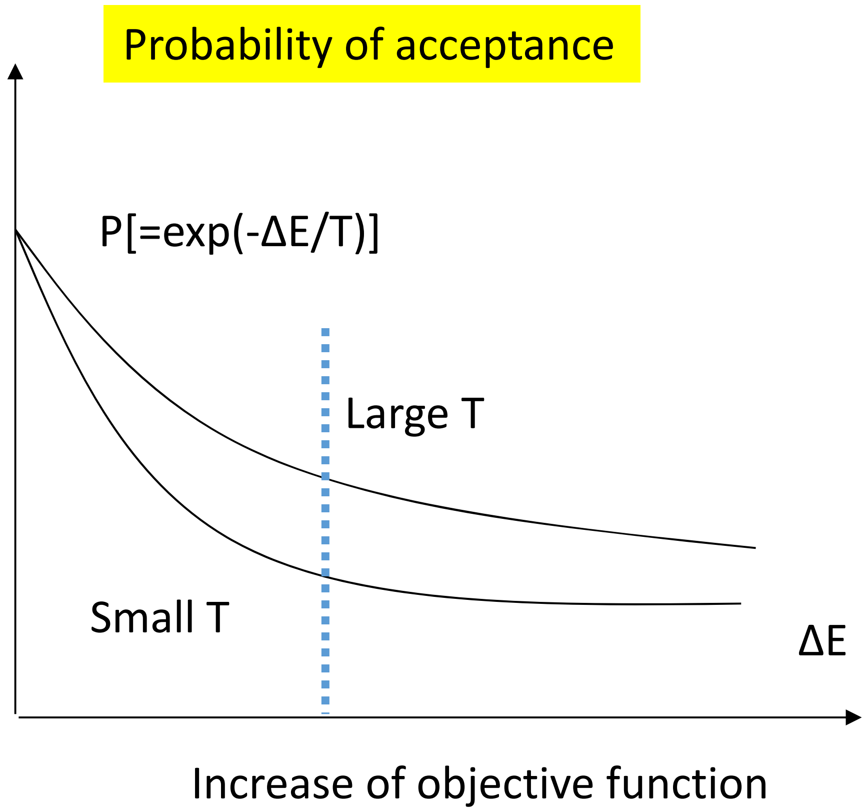
- Step 1: Set parameters T others, and generate initial solution
- Step 2: Randomly generate a neighborhood solution by
- Step 3:

  Objective function improved

  ⇨ Accept new solution

  Not improved

  ⇨ Metropolis criteria
- Step 4: Repeat (2)-(3) until criteria satisfied.



Test functions

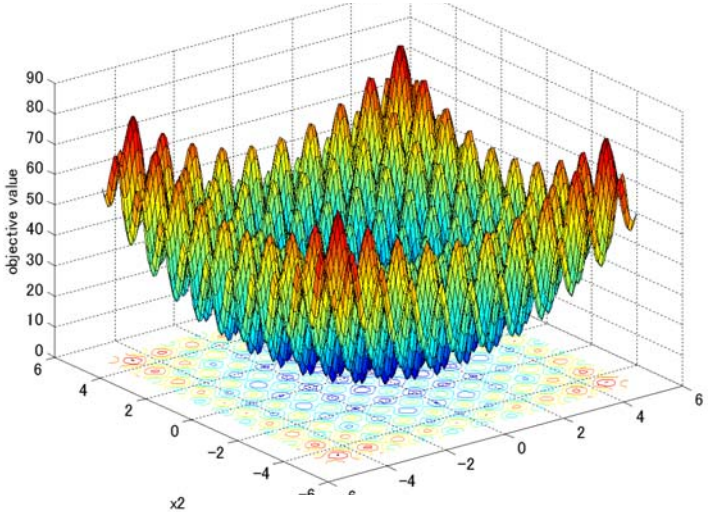
1. Rastringin function
2. Griewank function
3. Rosenbrock function
4. Sphere function
5. Ackley's function
6. Schwefel function 1
7. Schwefel function 1.2
8. Step function
9. Schwefel function
10. Levy function
11. Circle function
12. Test2N function

Number of variables = 5

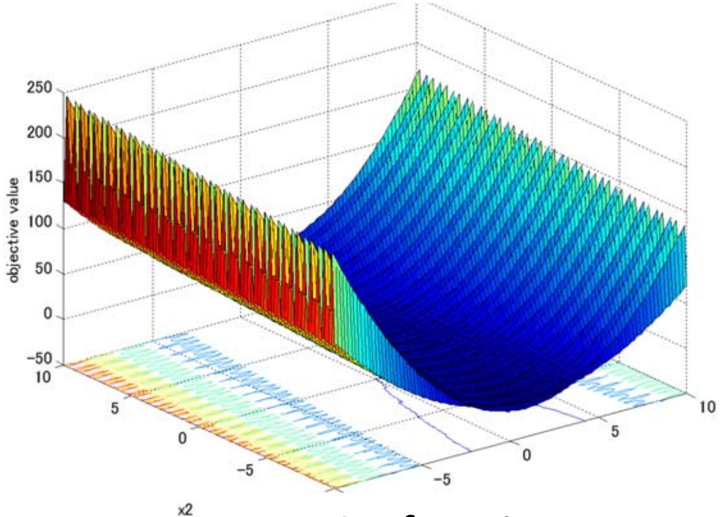
Parameters

- Cooling ratio
- Ratio of shrinking search region

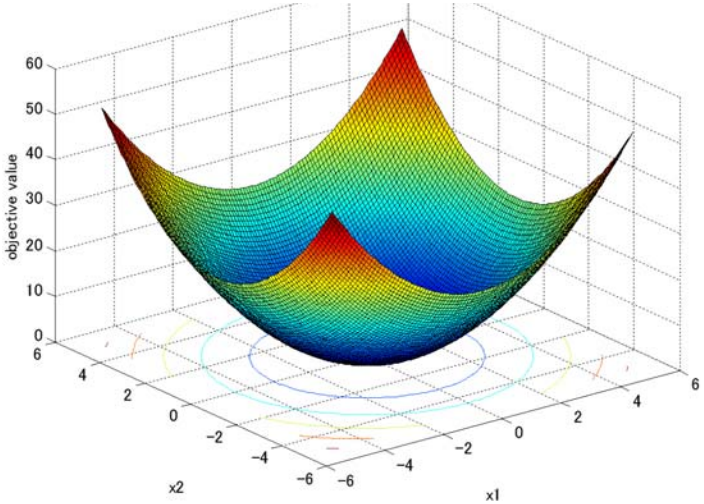
Rastringin function



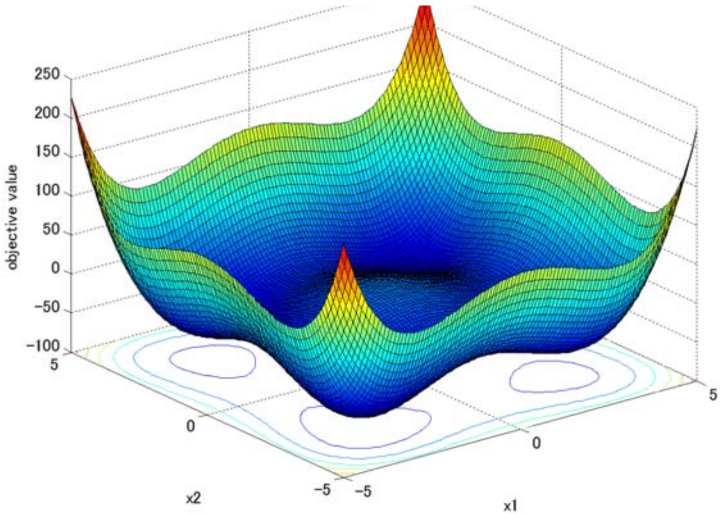
Levy function



Sphere function



Test2N function



Effect of parameter values

Normalize variables between -1 and 1

Initial temperature = 1

	Temperature reduction ratio	Search region reduction ratio
Case 1	0.925	0.925
Case 2	0.900	0.950
Case 3	0.950	0.900
Random	[0.900, 0.950]	[0.900, 0.950]

Best values among 10 trials

Objective values

	Case 1	Case 2	Case 3	Random
F1	6.964934	3.017175	7.959675	1.989932
F2	0.102599	0.199663	6.35E-02	5.89E-02
F3	1.018332	2.451342	1.491235	0.730874
F3	2.34E-06	1.59E-04	2.73E-09	2.12E-08
F5	1.17E-02	0.209504	7.45E-04	1.38E-03
F6	4.15E-03	3.58E-02	4.27E-04	4.65E-04
F7	1.15E-03	0.23173	1.19E-06	1.40E-05
F8	0.00E+00	0.00E+00	0.00E+00	0.00E+00
F9	-1738.08	-1758.82	-1738.08	-1858.04
F10	-21.3828	-21.446	-21.2876	-21.4665
F11	8.87E-02	0.313558	8.69E-02	8.72E-02
F12	-78.3323	-78.3268	-72.6776	-78.3323

Best values among 10 trials

Order among 4 cases

	Case 1	Case 2	Case 3	Random
F1	3	2	4	1
F2	3	4	2	1
F3	2	4	3	1
F3	3	4	1	2
F5	3	4	1	2
F6	3	4	2	1
F7	3	4	1	2
F8	1	1	1	1
F9	3	2	3	1
F10	3	2	4	1
F11	1	4	3	2
F12	1	3	4	1

Optimization problem 1

<u>Volume minimization</u>

$$\text{Minimize} \quad \mathrm{F(x) = V(x)}$$
$$\text{subject to} \quad \mathrm{R(x) \geq R_L}$$
$$\sigma(\mathrm{x}) \leq \sigma_t$$

V(**x**): Volume of block members

R_L: Lower bound for horizontal force R(**x**)

σ_t: Strength of FRP（319N/mm^2）

Optimization problem 2

<u>Maximization of horizontal force</u>

$$\begin{aligned} &\text{Minimize} \quad && \mathrm{F(x)} = \mathrm{R(x)} \\ &\text{subject to} \quad && \mathrm{V(x)} \leq \mathrm{V_U} \\ & && \sigma(\mathrm{x}) \leq \sigma_t \end{aligned}$$

R(**x**): Horizontal force

V_U: Upper bound for volume

σ_t: Strength of FRP（319N/mm^2）

Optimization problem 3

Minimization of shear force of upper beam

$$
\begin{aligned}
\text{Minimize} \quad & F(x) = Q(x) \\
\text{subject to} \quad & R(x) \geq R_L{}' \\
& V(x) \leq V_U{}' \\
& \sigma(x) \leq \sigma_t
\end{aligned}
$$

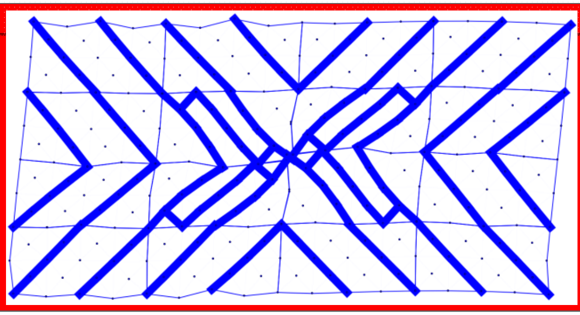
Q(x) : Shear force of left end of upper beam

$R_L{}'$: Lower bound of horizontal force
$V_U{}'$: Upper bound of volume

Result of problem 1 (Group 1)

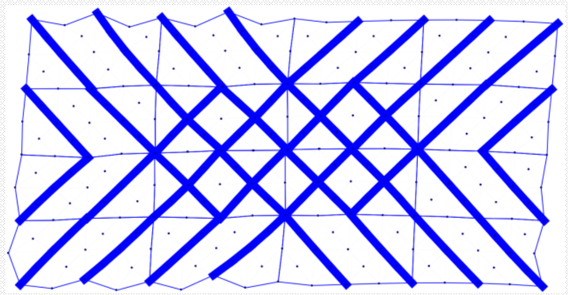
Results of three different random seeds

①



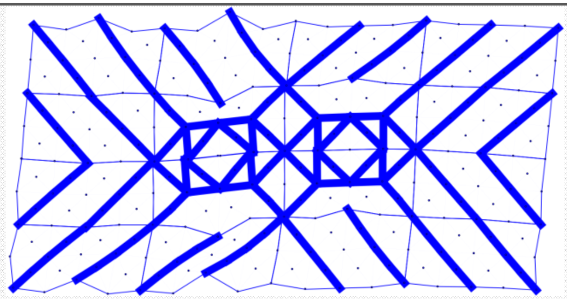
	V(m³)	R(kN)
Opt.	**0.508（23.5%）**	**2036**

②



	V(m³)	R(kN)
Opt.	**0.531（24.5%）**	**2091**

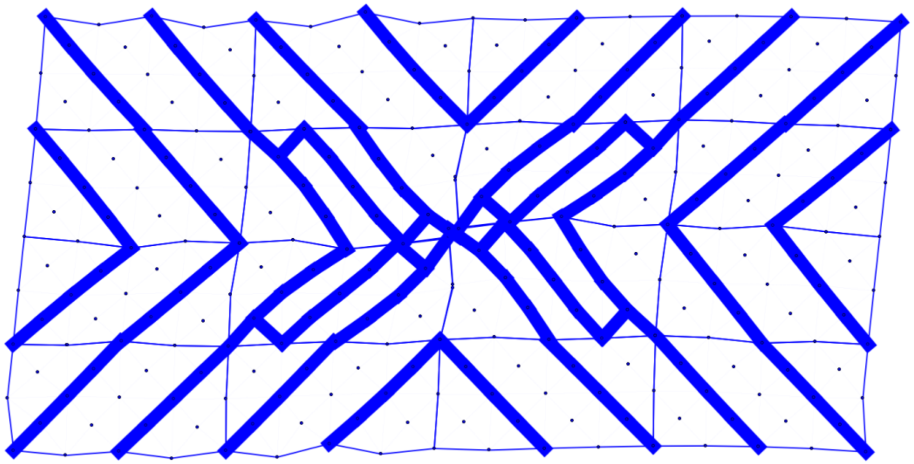
③



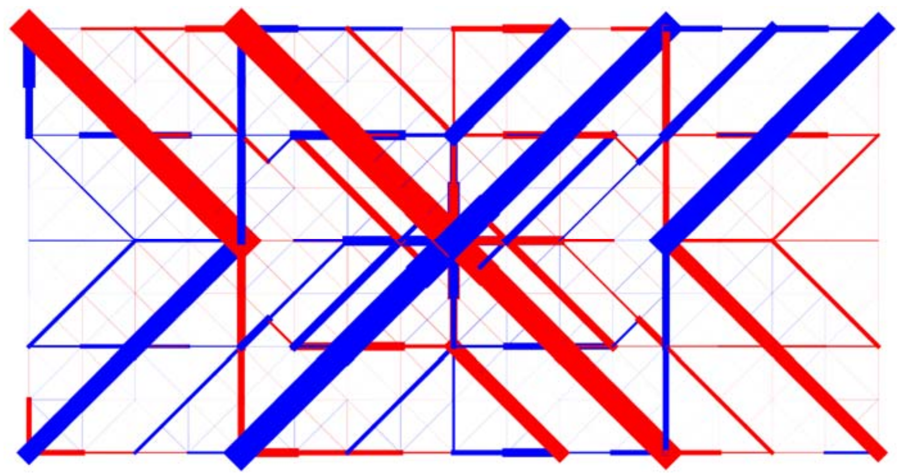
	V(m³)	R(kN)
Opt.	**0.531（24.5%）**	**2038**

Result of problem 1 (Group 1)

Reference: R_0=2267 kN → R_L=2030 kN



Optimal topology

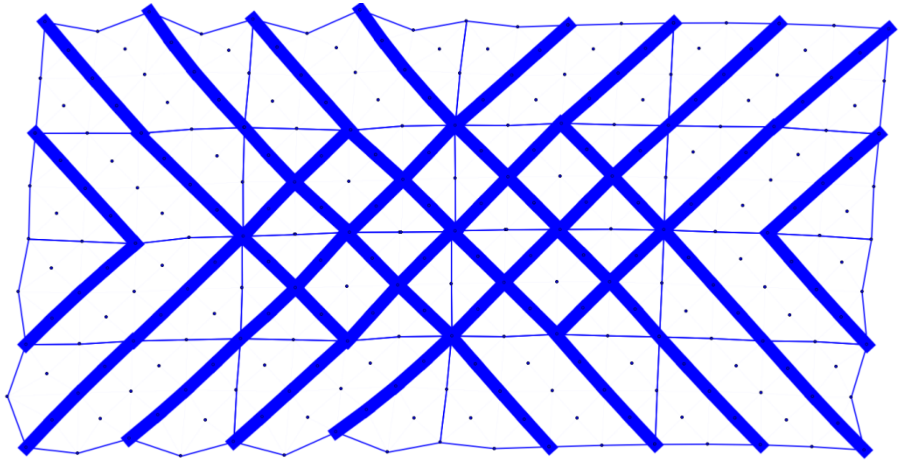


Axial force

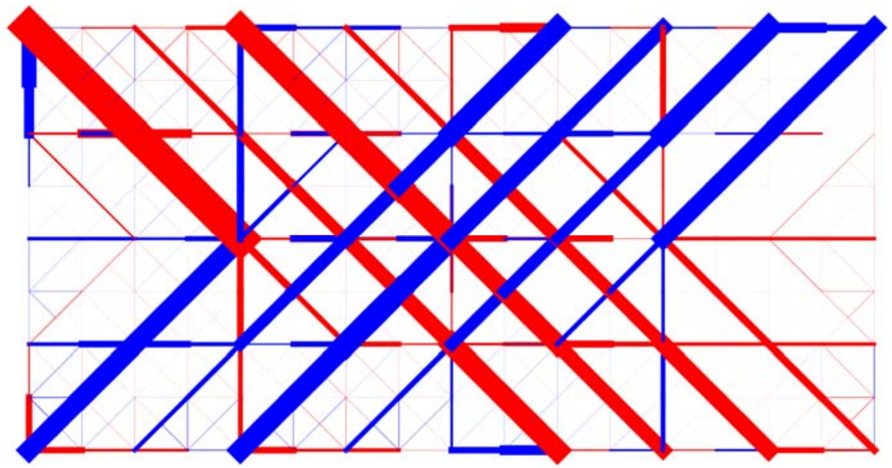
	V(m^3)	R(kN)	Q(kN)	σ(N/mm^2)	N(kN)
Optimal	**0.508** (23.5%)	**2036** (89.8%)	411	112	**228** (126%)
Reference	2.16 (**V_0**)	2267 (**R_0**)	615 (**Q_0**)	123 (σ_0)	180 (N_0)

Result of problem 2 (Group 1)

Problem 1: V=0.508 m^3 $\rightarrow$ 0.55 m^3



Optimal topology

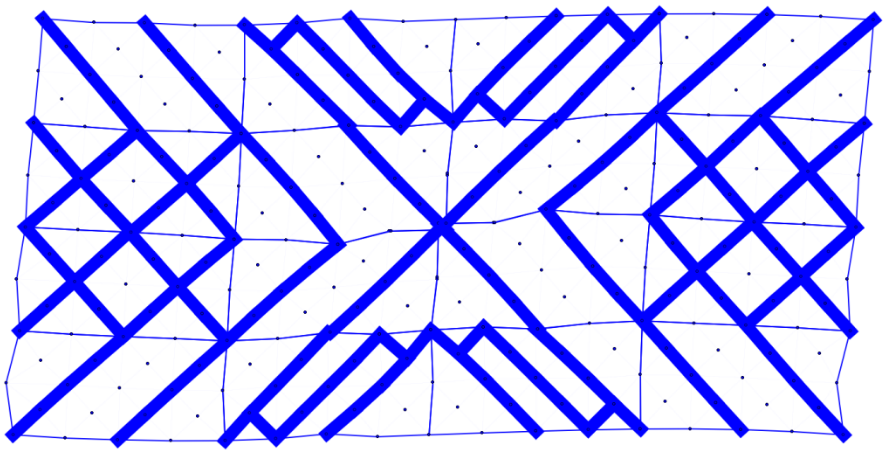


Axial force

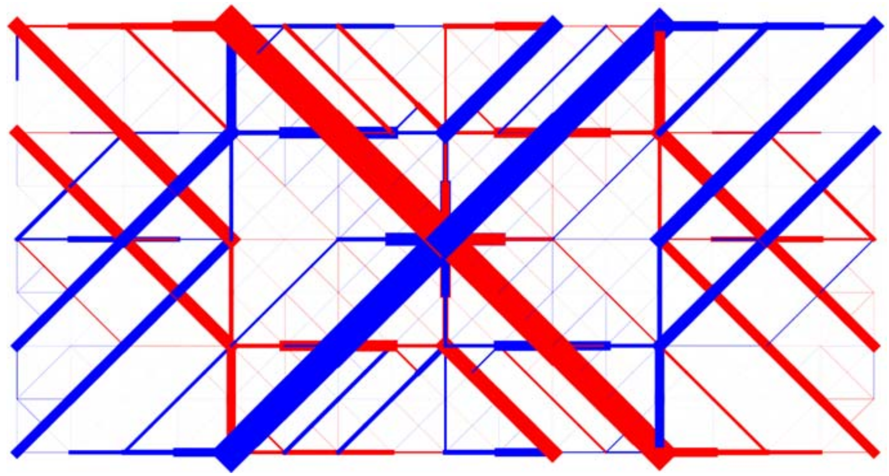
	V(m^3)	R(kN)	Q(kN)	σ(N/mm^2)	N(kN)
Optimal	**0.531** (25%)	**2091** (92.2%)	453	132	**228** (127%)
Reference	2.16 (**V_0**)	2267 (**R_0**)	615 (**Q_0**)	123 (σ_0)	180 (N_0)

Result of problem 3 (Group 1)

Results of Problem 1, 2 $\longrightarrow$ $R_L{}'=1950$ kN, $V_U{}'=0.6$ m^3



Optimal topology



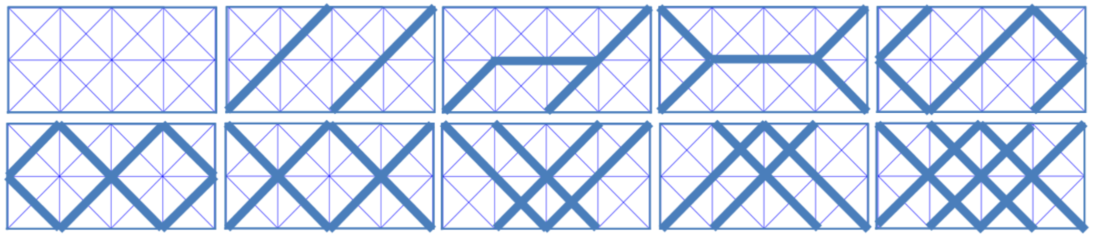
Axial force

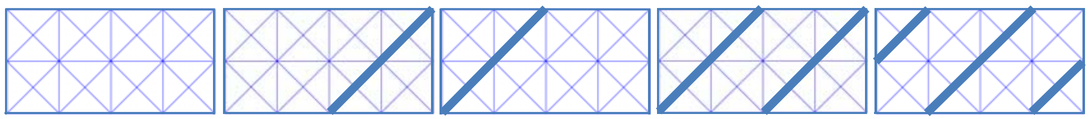
	V(m^3)	R(kN)	Q(kN)	σ(N/mm^2)	N(kN)
Optimal	**0.599** (**27.7%**)	**2038** (**89.9%**)	**378** (**61.4%**)	133	**234** (**130%**)
Reference	2.16 (**V_0**)	2267 (**R_0**)	615 (**Q_0**)	123 (σ_0)	180 (N_0)

Unit block group 2

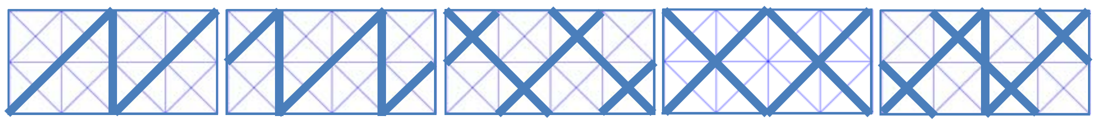
Optimal topology and distribution of axial force

Remove unit type with large volume
Consider connectivity of axial force





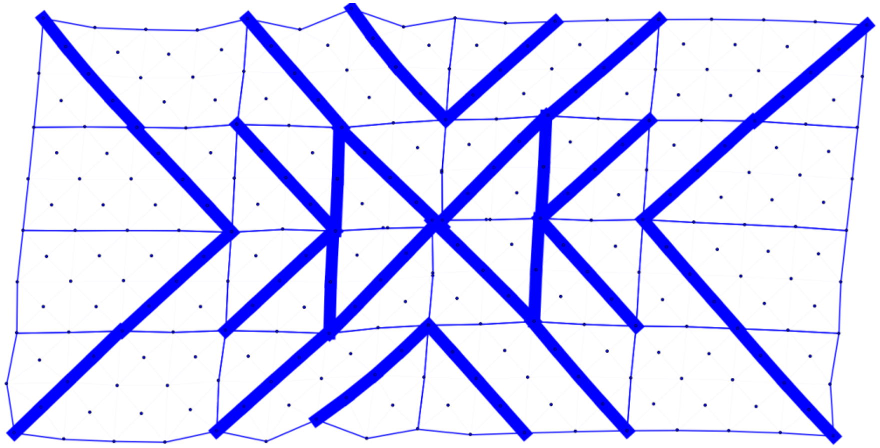
Blocks for connectivity

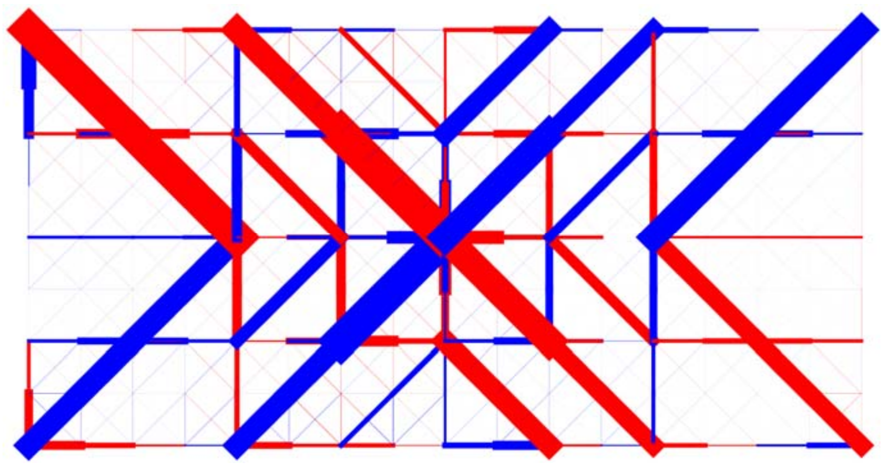


Necessary types

Result of problem 1 (Group 2)

Same lower bound values as Group 1: R_L=2030 kN

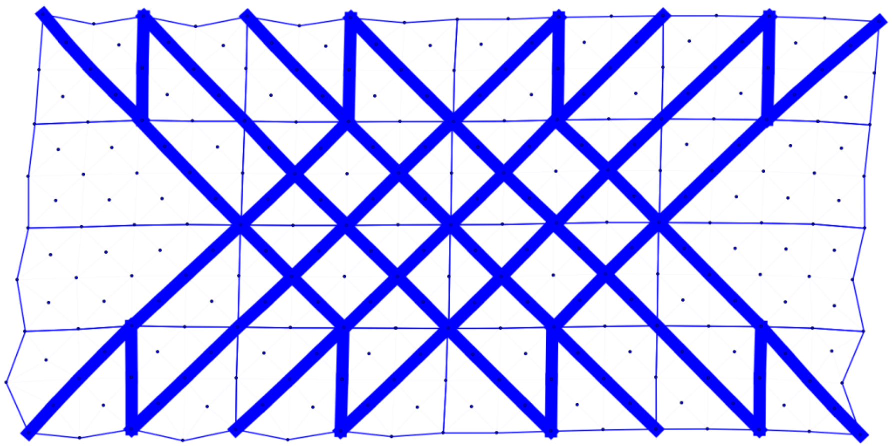


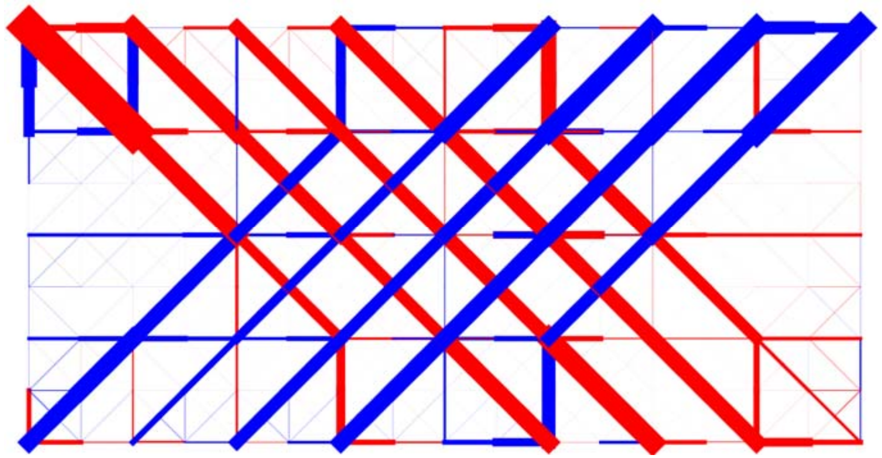


	$V(m^3)$	R(kN)	Q(kN)	$\sigma(N/m^2)$	N(kN)
Optimal (Group 2)	**0.382** (17.7%)	**2035** (89.7%)	386	136	**258** (143%)
Optimal (Group 1)	**0.508** (25.9%)	**2036** (89.8%)	411	112	**228** (126%)

Result of problem 2 (Group 2)

Same lower bound values as Group 1: $V_U = 0.55\ m^3$

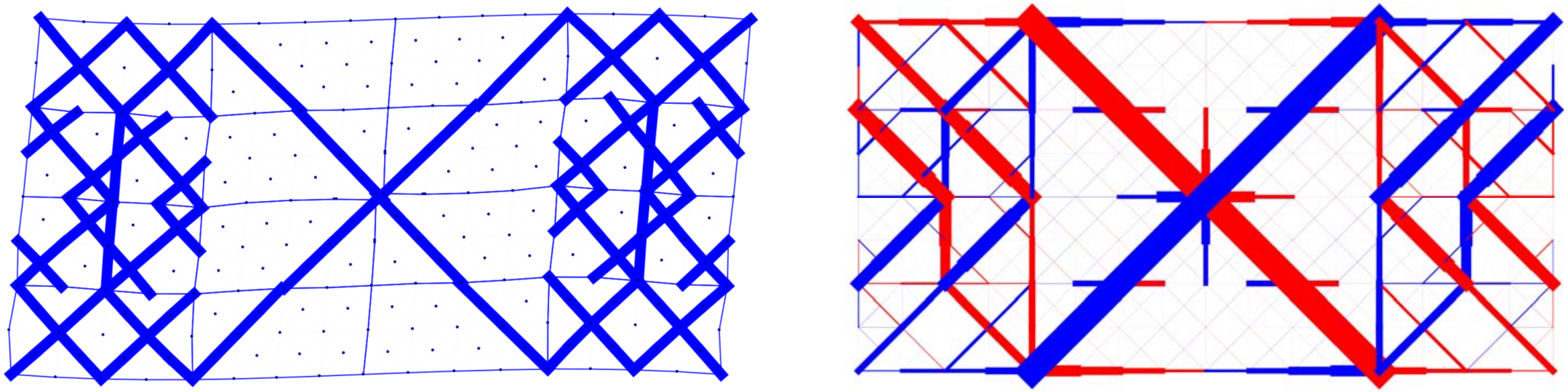




	$V(m^3)$	R(kN)	Q(kN)	$\sigma(N/mm^2)$	N(kN)
Optimal (Group 2)	**0.55** (**25.5%**)	**2131** (**94%**)	419	144	**243** (**135%**)
Optimal (Group 1)	**0.531** (**25%**)	**2091** (**92.2%**)	453	132	**228** (**127%**)

Result of problem 3 (Group 2)

Same lower bound values as Group 1: $R_L{}'=1950$ kN , $V_U{}'=0.6$ m^3



	V(m^3)	R(kN)	Q(kN)	σ(N/mm^2)	N(kN)
Optimal (Group 2)	**0.563** (**27.3%**)	**2011** (**86.3%**)	**333** (**55.7%**)	128	**233** (**129%**)
Optimal (Group 1)	**0.599** (**27.7%**)	**2038** (**89.9%**)	**378** (**61.4%**)	133	**234** (**130%**)

Conclusions

1. Topologies of shear walls consisting of latticed blocks can be found by assembling the various pre-defined unit types.
2. SA can be effectively used for optimization of combinations of latticed blocks.
3. Various optimal solutions can be found depending on the design conditions.
4. Parameters of SA may be randomly given.