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Shape and topology optimization of shear wall consisting of latticed blocks

Toshiaki KIMURA*, Makoto OHSAKI [a], Yuki YAMAOKA [b]

*Assistant Professor, Department of Architecture and Architectural Engineering, Kyoto University
Kyoto daigaku-Katsura, Nishikyo-ku, Kyoto 615-8540, Japan
kimura@archi.kyoto-u.ac.jp

[a] Professor, Department of Architecture and Architectural Engineering, Kyoto University
[b] Graduate Student, Department of Architecture and Architectural Engineering, Kyoto University

Abstract

This paper represents a new method of shape optimization of a shear wall consisting of latticed blocks. The lattice members are discretized with plane stress shell elements, and the location of node and the width of latticed element are adopted as design variables. The blocks are connected with each other using adhesive material, and they are attached to existing beams and columns by contact. Although the target of this study is a shear wall used for seismic retrofit of building structures, the wall consisting of blocks can be used for various types of shell and spatial structures. A design problem is formulated to maximize the lateral reaction force for specified inter-story drift angle. Simulated Annealing (SA) is used for solving the optimization problem. Moreover, to obtain various shapes, force density method is utilized to move the nodes without modifying topology. In this approach, force density is treated as an auxiliary parameter for arrangement of latticed element. The width of lattice members is also considered as design variables, and the members with small width are removed to change the topology before restarting the SA algorithm. Numerical examples are presented to demonstrate effectiveness of the proposed method.

Keywords: shear wall, shape optimization, simulated annealing, force density method

1. Introduction

Among various methods for seismic retrofit, installation of shear wall composed of light weight blocks to existing frame is an effective approach in view of reduction of construction cost, because they can resist with compression (contact to wall) only and complex anchoring and/or welding is not necessary. However, shape of block in practical design tends to be regular in view of simplicity in manufacturing process. The second author developed a method of shape optimization of latticed blocks based on ground structure approach. In the previous paper of the second author [1], it is reported that very thin lattice members exist in the optimal solutions obtained by a nonlinear programming approach. To prevent this difficulty, a combinatorial method has been presented for layout optimization of blocks with given patterns [2]. In both studies, locations of the nodes are fixed, and the latticed block is discretized with beam element.

This paper represents a new method of shape optimization of a shear wall consisting of latticed blocks using Simulated Annealing (SA). The lattice members are discretized with plane stress shell elements, and the locations of nodes and the widths of latticed members are adopted as design variables. The proposed method consists of two phases. Design problem in each phase is formulated to maximize the lateral reaction force for specified inter-story drift angle. In the first phase, to obtain various shapes, force density method is utilized to move the nodes without modifying topology. In the second phase, the width of lattice members are considered as design variables, and the members with small widths are removed to change the topology before restarting the SA algorithm. Numerical examples are presented to demonstrate effectiveness of the proposed method.

2. Optimization problem

In the first phase (Phase 1), the geometry of lattice is optimized with fixed topology and width of lattice members. In the second phase (Phase 2), the widths of lattice members are optimized with fixed topology and geometry. To obtain the optimal configuration, each phase is repeated alternatively, and the thin members are removed after Phase 2 to modify the topology. The design problem in each phase is formulated to maximize the lateral reaction force for specified inter-story drift angle. SA is used for solving optimization problems.

2.1. Phase 1: Optimization of geometry of lattice

In general, geometry optimization of trusses with nodal locations as design variables has difficulty due to overlapping nodes [3]. To prevent this difficulty for obtaining various shapes, we use the force density method [4]. The lattice has *n* nodes and *m* members in *x*-*y* plane. The vector of *x*-coordinates of nodes are written as

$$\mathbf{x}^0 = (x_1, x_2, \cdots, x_n)^{\mathrm{T}} \tag{1}$$

The vector $\mathbf{y}^0$ is defined in the same manner, and $\mathbf{x}^0$ and $\mathbf{y}^0$ are divided into fixed nodes $\mathbf{x}_{\mathrm{f}}$, $\mathbf{y}_{\mathrm{f}}$ and free nodes $\mathbf{x}$, $\mathbf{y}$. The vector of force density is expressed as $\boldsymbol{q} = (q_1, q_2, \cdots, q_m)^{\mathrm{T}}$. The equations of self-equilibrium at free nodes can be expressed in the following form:

$$(\mathbf{C}^{\mathrm{T}}\mathbf{QC})\mathbf{x} + (\mathbf{C}^{\mathrm{T}}\mathbf{QC_f})\mathbf{x}_{\mathrm{f}} = \mathbf{0},\ \ (\mathbf{C}^{\mathrm{T}}\mathbf{QC})\mathbf{y} + (\mathbf{C}^{\mathrm{T}}\mathbf{QC_f})\mathbf{y}_{\mathrm{f}} = \mathbf{0} \tag{2}$$

where $\mathbf{C}$ and $\mathbf{C_f}$ are the connectivity matrices with respect to the free and fixed nodes, respectively, and $\mathbf{Q} = \mathrm{diag}(\mathbf{q})$.

For simplicity, we set $\mathbf{D} = \mathbf{C}^{\mathrm{T}}\mathbf{QC}$ and $\mathbf{D_f} = \mathbf{C}^{\mathrm{T}}\mathbf{QC_f}$. Then $\mathbf{x}$ and $\mathbf{y}$ can be obtained from

$$\mathbf{x} = -\mathbf{D}^{-1}\,\mathbf{D_f}\mathbf{x}_{\mathrm{f}},\ \ \mathbf{y} = -\mathbf{D}^{-1}\mathbf{D_f}\mathbf{y}_{\mathrm{f}} \tag{3}$$

It is remarked that by using force density method, the geometry can be modified without modifying topology. Note that the force density is used as an auxiliary parameter for defining the geometry; i.e. it does not have any relation to the axial forces of lattice members for specified deformation.

Optimization problem is formulated as follows:

$$\begin{aligned} &\text{Maximize} && R(\mathbf{q}) \\ &\text{Subject to} && V(\mathbf{q}) \leq V_0 \\ &&& 0.05 \leq q_i \leq 1, \qquad (i = 1, \dots, m) \end{aligned} \tag{4}$$

where $R(\mathbf{q})$ is the lateral reaction force for specified inter-story drift angle (= 0.01 rad), $V(\mathbf{q})$ and V_0 are the total volume of lattice members and its upper bound, respectively.

2.2. Phase 2: Size optimization for lattice members

In Phase 2, the widths of lattice members $\mathbf{d} = (d_1, \dots, d_m)$ are adopted as design variables. Optimization problem is formulated as follows:

$$\begin{aligned} &\text{Maximize} && R(\mathbf{d}) \\ &\text{Subject to} && V(\mathbf{d}) \leq V_0 \\ &&& d_i^{\mathrm{L}} \leq d_i \leq d_i^{\mathrm{U}}, \qquad (i = 1, \dots, m) \end{aligned} \tag{5}$$

where d_i^{U} and d_i^{L} are the upper and lower bounds of d_i , respectively. After solving this problem, the members with small widths are removed to change the topology before returning to Phase 1.

3. Numerical example

Numerical example is a rectangular-shaped shear wall applied to existing frame which is pin-supported at the bottom of each column. Cross-sections of the frame are listed in Table 1. The shear wall consists of 2 × 2 latticed blocks which has 4000 mm width and 2000 mm height. The initial shape is shown in Figure 1, where the width and depth of lattice member are 100 mm and 60 mm, respectively. Materials of frame and lattice members are steel and FRP, respectively, and their properties are listed in Table.2. The frame and lattice members are discretized into plane stress shell elements, and geometrically non-linear analysis is carried out using Abaqus Ver.6.16. Each block is connected to frame by contact at nodes. The specified inter-story drift angle is 1/100 rad, the upper and lower bound of widths are 5 mm and 200 mm, respectively, and the threshold widths for removal member is 30 mm. Three values of initial temperature T = 0.0, 0.2, 1.0 are used for three iterative steps of optimization by SA.

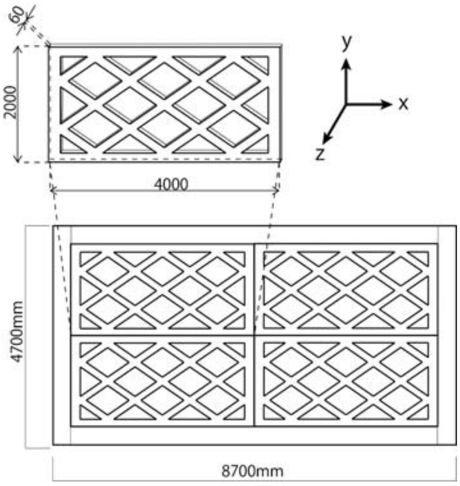

Figure 1: Initial shape of shear wall

Table 1: Cross-sections of the frame

	Width (mm)	Depth (mm)
Beam	350	350
Column	200	350

Table 2: Material properties

Material	Tensile Yield Stress	Comp. Yield Stress	Young's modulus	Poisson ratio
	(N/mm^2)			
Steel	325	325	2.0x10^5	0.3
FRP	335	319	2.0x10^4	0.2

The total horizontal reaction force at supports are shown in Table 3.The shapes of shear wall obtained by this proposed method are drawn in Figure 2. It can be confirmed that the shear forces of optimal solutions are 1.09-1.34 times as large as that of the initial shape. It can be observed from Figure 2 that distinct diagonal configuration which acts as compression strut has been obtained in the shear wall through a few times of iterative optimization steps.

Table 3 Total horizontal reaction force at inter-story drift angle of 1/100 of optimal solutions

		Reaction force (kN)		
		T=0.0	T=0.2	T=1.0
Optimal solution	1st	2469	2489	2416
	2nd	2638	2716	2465
	3rd	2829	2983	2432
Initial shape		2223		
Without shear wall		879		

4. Conclusion

This paper represents a new method of shape optimization of a shear wall consisting of latticed blocks. The conclusions obtained in this paper are summarized as follows;

(1) In shape optimization of latticed shear wall, force density method is useful for obtaining the various geometry while fixing the topology.

(2) By using proposed method, optimal solutions which can resist the shear force 1.09-1.34 times as much as the force of initial shape has been obtained.

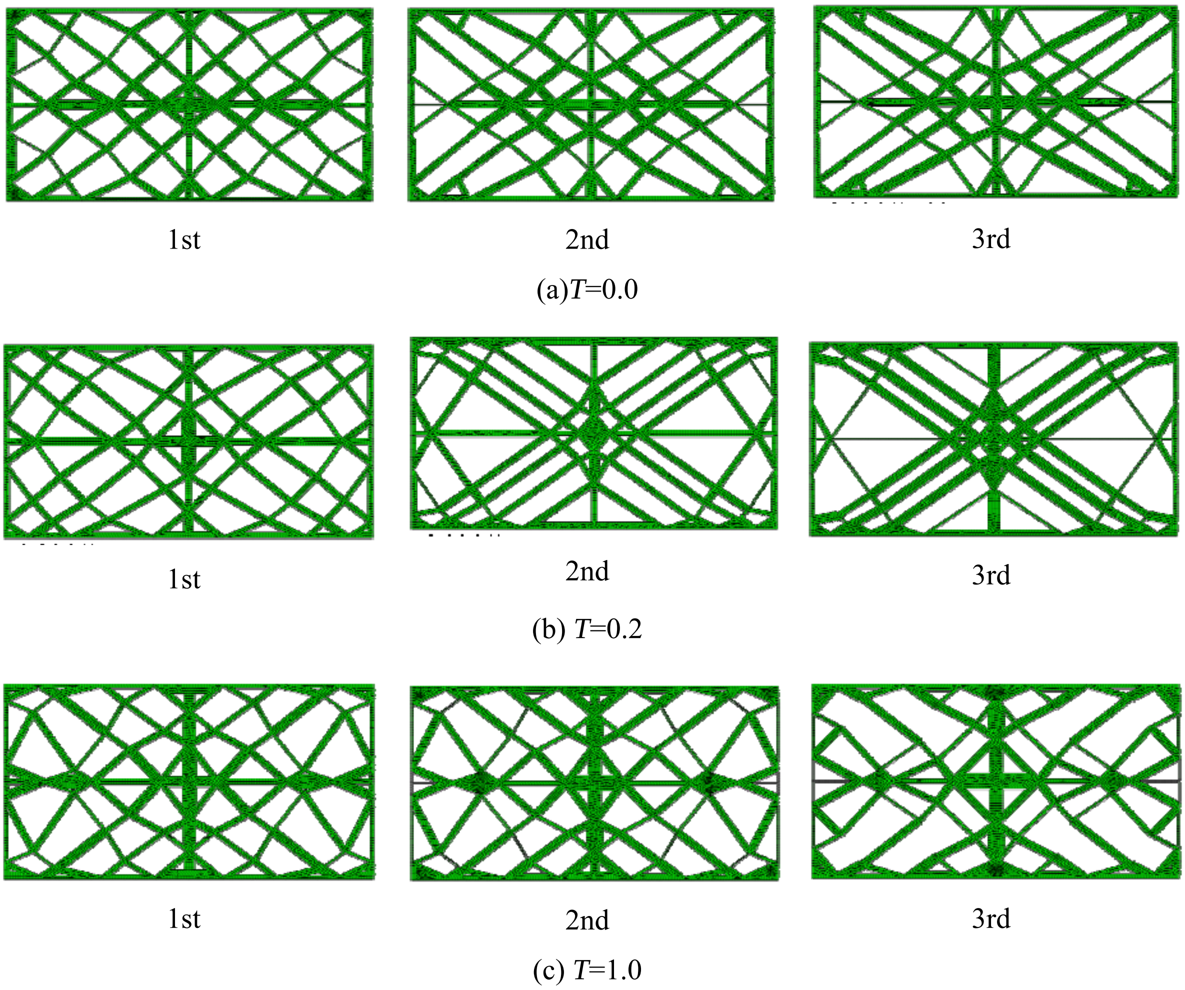

Figure 2: Optimization results corresponded to various SA parameter values

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