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TOPOLOGY OPTIMIZATION OF LATTICED STEEL WALL WITH CONTACT TO EXISTING BEAMS AND COLUMNS OF RC FRAME

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Abstract

In the process of installing steel braces for seismic retrofit of RC frames, braces should be fixed to the beams and/or beam-column joints so that tensile, compressive, and shear forces can be transmitted between the frame members and the braces. However, installation of steel members to RC frame needs substantial cost, time, and effort, and operation of the building as, e.g., office and residence, should be terminated during the retrofit process. Therefore, it is preferable in view of business continuity and reduction of cost if the braces are attached to the frame by contact, without complex anchoring and/or welding, so that the story shear forces are transmitted by compressive forces of the braces. Another difficulty in attachment of braces to an RC frame is that buckling and/or yielding occurs in the braces before the frame exhibits expected story shear deformation.

In this study, we improve the latticed shear wall model in Ref. [1] by considering material nonlinearity of RC frame and optimizing the topology of the lattice under stress constraints. The lattice members are modeled using elastic beam elements. The beams and columns of a single-span single-story frame are modeled using beam element with hinges defined by fiber section of concrete and reinforcement bars. OpenSees is used for geometrically nonlinear analysis subjected to forced shear deformation. A node-to-node contact is used between a node of the lattice and a node on a beam or a column with large stiffness for penetration and small stiffness for shear. A small stiffness is also given for separation to stabilize analysis. Objective function of the optimization problem is the story shear force at the specified interstory drift angle that is to be maximized. Constraints are given for the total structural volume and maximum stress due to the axial force of the lattice members. The existing lattice members have the same cross-section, and the stress constraints are not considered for the removed members for which a small cross-sectional area is assigned for stabilizing the analysis process. Simulated annealing is used for solving the optimization problem with 0-1 integer variables for indicating existence/nonexistence of members.

Numerical examples are presented to demonstrate effectiveness of the proposed model. The interstory drift angle is specified at 1/100. The standard ground structure approach is used for defining the topology of the latticed wall consisting of a 4×4 grid. It is confirmed that various kinds of optimal topology are obtained, and lattice members are located so that the maximum stress is successfully reduced while maintaining the lateral stiffness against the story shear force. The degrading property of story shear force with respect to the interstory drift angle is improved by placing the latticed wall, while keeping the stress of the lattice members within the elastic range. It is confirmed that the shear force is transmitted mainly through compressive forces in lattice members without tensile forces between the lattice members and frame members. The results show possibility of upgrading seismic performance of an RC frame with small constructional cost and short construction period.

Keywords: steel brace, latticed shear wall, seismic retrofit, topology optimization, simulated annealing

1. Introduction

There have been many studies on seismic retrofit using steel braces. Strength of the frame can be upgraded by attaching the X- or K-braces in the external wall; however, the strength of steel brace is too large compared to that of the existing frame members. Therefore, energy dissipating devices such as buckling restrained braces are preferred in view of reducing the effect on the existing frame members allowing large deformation to dissipate seismic energy. However, installation of steel members to RC frame needs substantial cost, time, and effort, and operation of the building as, e.g., office and residence, should be terminated during the retrofit process. Furthermore, these braces are not efficient in aesthetic point of view, and various types of latticed walls have been developed. To alleviate these difficulties, some types of shear walls with blocks have been developed [2, 3].

The first and second authors developed an optimization approach to design of shear walls consisting of latticed blocks. Various types of blocks are combined to optimize the load paths in the wall so that the shear force is transmitted to the frame members mainly by compressive forces of the lattice members [4]. The lattice members as well as beams and columns are modeled using beam elements. The validity of using the beam elements has been confirmed by finite element analysis of the optimized latticed wall [5].

In this study, we develop a new type of latticed steel wall for seismic retrofit of RC frame. The lattice members are attached to the RC beams and columns by contact; thus, the story shear force is transmitted to the frame mainly by the compressive force of lattice members. The lattice and frame members are modeled using beam elements. An optimization approach is presented using a heuristic approach called simulated annealing (SA) [6].

2. Latticed wall model

We consider a latticed shear wall as shown in Fig. 1 for seismic retrofit of RC building frames. A wall consists of steel beams with solid rectangular section. The span and height of the frame are 6.6 m and 3.9 m, respectively. The wall is assumed to regist the story shear force mainly through compressive forces, which are transmitted to the beams and columns through contact forces. The beams and columns are modelled using beam elements; therefore, the effect of sizes of frame members is neglected. Both bottom-side ends, marked by ▲ in Fig. 1, of the existing frame are supported by pin, and the horizontal displacements at upper-beam ends have the same value. A frame analysis program called OpenSees [7] is used for static response analysis.

The width of column is 700×700 (mm), and the height and width of beam is 700 mm and 450 mm, respectively. Both of beam and column are modelled using fiber sections that have reinforcing bars with the cross-sectional area 700 mm^2. The number of bars are six for a beam and eight for a column. For the concrete material, the maximum compressive stress is 30 MPa at strain 0.002, and the fracture stress is 24 MPa at strain 0.004. For the steel material of reinforcement bar, the yield stress is 325 MPa, the maximum stress is 490 MPa, Young's modulus is 200 GPa, and the kinematic hardening coefficient is 2 GPa. The beams and columns of the RC frame with possible plastic hinges are modelled using the forceBeamColumn element of OpenSees.

The out-of-plane width of the lattice member is 75 mm, and the in-plane thickness of each member is considered as design variable, which has the value 25 mm for an existing member. A small value 0.25 mm is given for a non-existing member to stabilize the analysis process. The latticed beams are modelled using elasticBeamColumn element, because the stresses are constrained within the elastic range in the following optimization problem. The zeroLengthContact2D element is placed between the nodes along the boundary of latticed wall, where the penalty parameters for penetration and tangential dislocation are 1.0×10^9 kN/mm and 1.0×10^6 kN/mm, respectively, and the friction coefficient is 0.5.

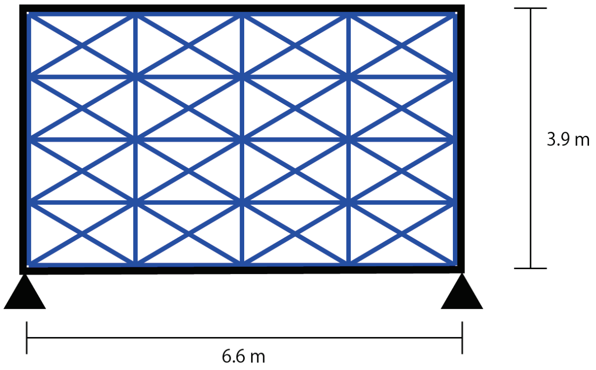

Fig. 1 – Basic configuration of computational model of latticed wall

The frame is subjected to the forced displacement at the top nodes of columns corresponding to inter-story drift angle R = 1/100, and the stiffness of the wall is evaluated from the total horizontal reaction force at the supports. Figure 2 shows the force-displacement relation of the frame without latticed wall. It is seen from Fig. 2 that yielding occurs when the displacement reaches around 0.02 m, which corresponds to about 1/200 of interstory drift angle. The tangent stiffness after yielding is much smaller than the initial stiffness.

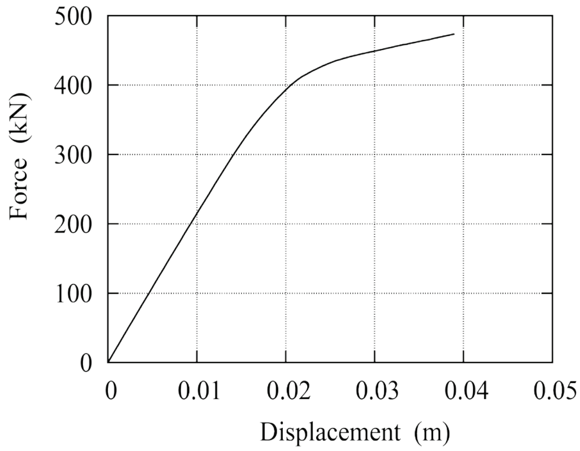

Fig. 2 – Force-displacement relation of frame without latticed wall.

3. Problem formulation and results of optimization

SA is used for optimization, where integer values 1 and 0 are assigned for existing and non-existing lattice members, respectively. Considering symmetry of the grid with respect to the center vertical line, the number of variables is 54 including 12 for vertical, 10 for horizontal, and 32 for diagonal members. The number of steps of SA is 1000, and five variables are randomly modified to generate 10 neighborhood solutions, from which the best solution is selected as the candidate solution for the next step. The cooling rate is 0.995, and the objective function is scaled so that acceptance ratio for the 10% increase of the objective function is 0.5 at the initial step with the temperature equal to 1.

Optimization is carried out four times from different random seeds, which are denoted by Cases 1–4. The values of reaction forces at R = 1/100 and total volume of lattice members are shown in Table 1. In Table 1, 'Original' means the optimal solution that may have obviously unnecessary members as shown in Figs. 3 (a)–(d). The volumes of all cases have slightly smaller values than the upper bound 0.1 m^3, and Case 3 has the largest shear force.

Table 1 – Shear forces and volumes of optimal solutions.

		Case 1	Case 2	Case 3	Case 4
Original	Shear force (kN)	986.48	981.57	1061.30	1007.30
	Volume (m^3)	0.099847	0.099909	0.099971	0.098981
Revised	Shear force (kN)	965.10	967.56	1046.50	942.64
	Volume (m^3)	0.098037	0.096351	0.096413	0.091866

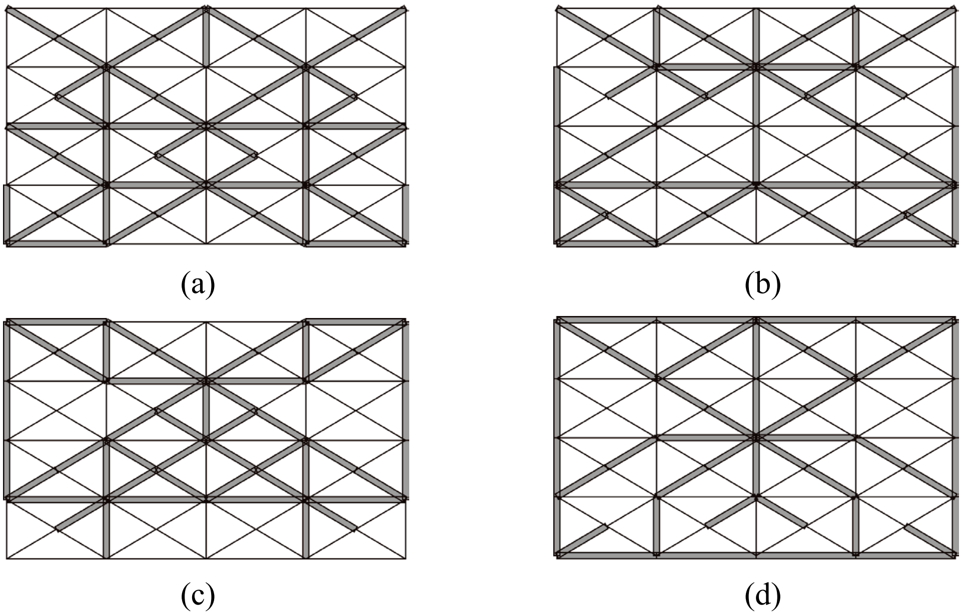

Fig. 3 – Locations of brace members of original optimal solutions;
(a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4.

Unnecessary lattice members are removed from the original optimal solution to obtain the ‘Revised’ optimal solutions as shown in Figs. 4 (a)–(d). The shear forces and the volumes of brace members are listed in Table 1. As seen from the table, the force and volume of each revised optimal solution have slightly smaller values than those of the original optimal solution. Note that the maximum stress of Case 3 is 360.32 MPa, which slightly violates the stress constraint with the upper bound 360 MPa.

The deformed shapes of the revised optimal solutions are shown in Figs. 5 (a)–(d), where the displacements are magnified by the factor 10. The axial forces are plotted in Figs. 6 (a)–(d), where gray and white members indicate compressive and tensile state, respectively. It is seen from Figs 5 and 6 that the braces deform keeping contact to beams and columns in the upper left and lower right parts so that shear forces are transmitted to the frame mainly by the compressive axial forces in the diagonal direction.

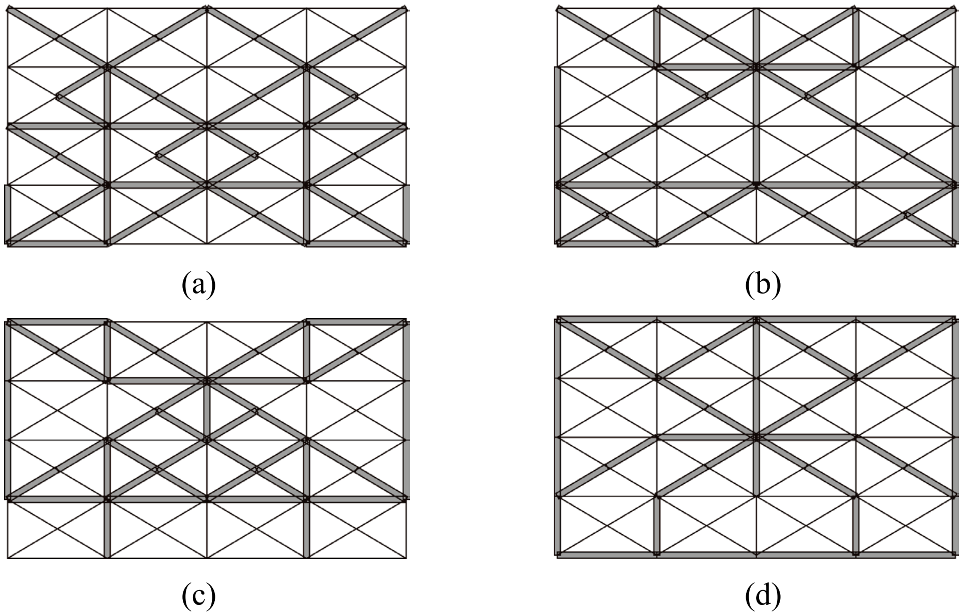

Fig. 4 – Locations of brace members of revised optimal solutions;
(a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4.

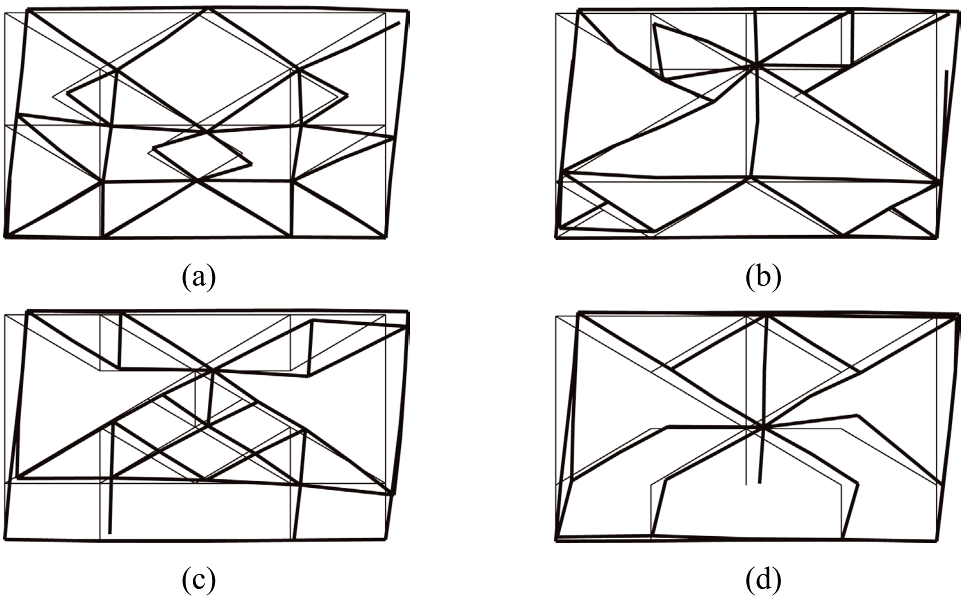

Fig. 5 – Deformation of revised optimal solution at R= 1/100 (magnification factor = 10);
(a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4.

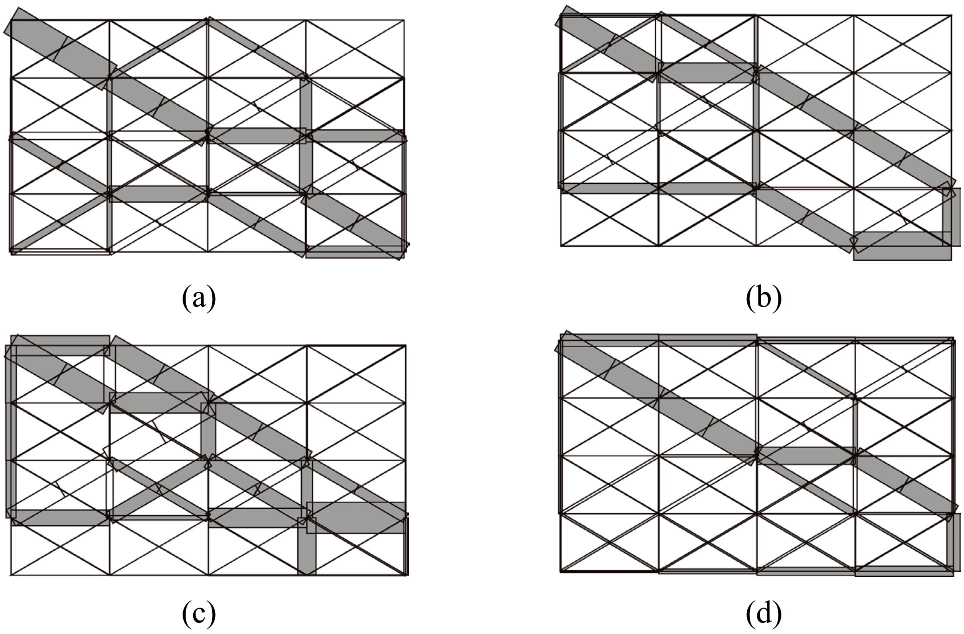

Fig. 6 – Axial forces of revised optimal solution (gray: compression, white: tension); (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4.

Relations between the shear forces and displacements of Cases 1–4 are plotted in Fig. 7. As seen from Figs. 2 and 7, the shear forces at the final state of R = 1/100 of the optimal solutions have the values about twice of that of the frame without braces in Fig. 2. Cases 1, 2, and 4 have almost the same force-displacement relation, while yielding occurs a little earlier in Case 3. However, Case 3 has a larger initial stiffness than the other cases, because all edge members exist in Case 3 as shown in Fig. 4(d).

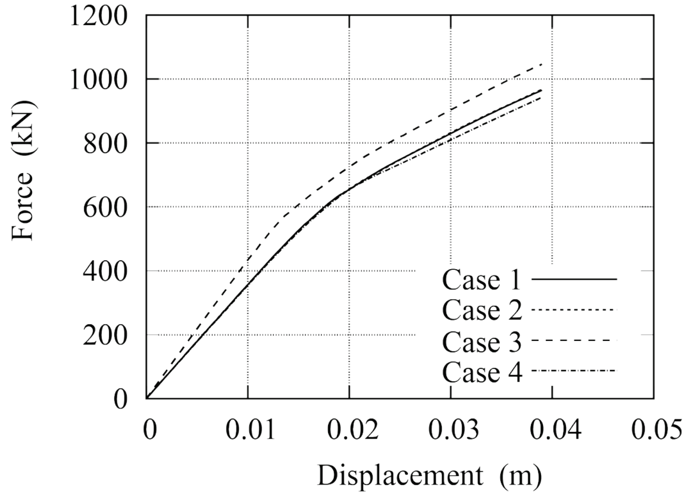

Fig. 7 – Force-displacement relations of revised optimal solutions.

4. Conclusions

Optimal topologies have been found for steel latticed wall for seismic retrofit of RC frames. The wall is connected to the frame by contact, and the story shear force is transmitted mainly through compressive force in diagonal direction of the wall.

It has been confirmed in the numerical examples that the latticed wall is in elastic range up to the interstory drift angle of 1/100. The shear force at 1/100 drift angle has been increased to twice by attaching the latticed wall.

Acknowledgements

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