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Structural Optimization Method for 3D Reinforced Concrete Building Structure with Shear Wall

H. Nikzad, S. Yoshitomi

Abstract**—**In this paper, an optimization procedure is applied for 3D Reinforced concrete building structure with shear wall. In the optimization problem, cross sections of beams, columns and shear wall dimensions are considered as design variables and the optimal cross sections can be derived to minimize the total cost of the structure. As for final design application, the most suitable sections are selected to satisfy ACI 318-14 code provision based on static linear analysis. The validity of the method is examined through numerical example of 15 storied 3D RC building with shear wall. This optimization method is expected to assist in providing a useful reference in design early stage, and to be an effective and powerful tool for structural design of RC shear wall structures.

Keywords**—**Structural optimization, linear static analysis, ETABS, MATLAB, RC moment frame, RC shear wall structures.

I. INTRODUCTION

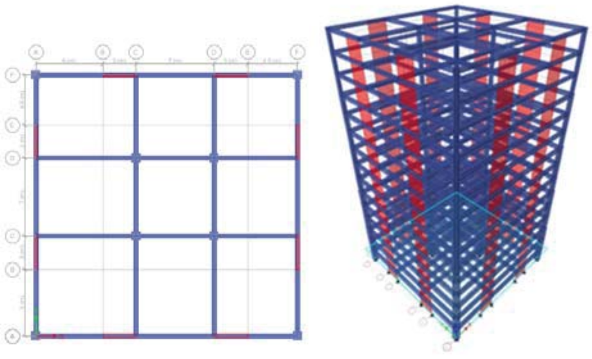
REINFORCED concrete shear wall structures are widely used in many tall, super-tall and high-rise buildings for its excellent seismic behavior. Seismic design of these structures, however, leading expensive structure. Therefore structural optimization is required to minimize the total cost of the structure considering design criteria. The objective of the structural optimization is to design the structure in such a way to minimize the total cost of the structure by obtaining optimal cross-sections such as beam, column and shear wall whereas satisfying related design code provision. Here, cost of the structure refers to weight or material consumption of the structure.

This paper proposes structural optimization method of shear wall-frame structures dual-system, considering minimum cost and displacement of the structures. Dual-system is a series of shear wall with a set of moment resisting frames that tolerate both gravity load and lateral load [1]. There are some studies on optimal design of RC shear wall structures concerning cost of the structure. One such study considering total cost of the structure is optimization method of tall residential building with RC shear wall [2]. The objective of design was to find a suitable scheme by controlling the material consumption to a minimum magnitude. Cost optimization of three-dimensional beamless reinforced concrete shear-wall system by genetic algorithm has been done, considering optimum dimensions of shear wall to minimize cost of the structure [3]. A computer-based the optimal criteria method for optimization of three-dimensional reinforced concrete frameworks with shear walls, considering section dimensions and reinforcement specifications based on ACI code has been proposed [4]. Computer programs called ADS and COMB for the optimization of shear wall systems have been developed using the folded plate theory [5]. Various formulations have been used for the optimum solution of shear wall system. Optimal seismic design of reinforced concrete dual system (shear-wall frame) structures was studied [6]. In this study, databases for beam, column, and shear wall cross sections are generated using *OpenSees* and *MATLAB* software. Member sizes are considered as design variable to minimize the cost, and drift of the structure is concerned as objective function to satisfy the code provisions. Some of these studies however, consider members dimension as design variable, the stresses of beam, column and shear wall, and displacement of the structure are not considered as part of their studies. This study concerns structural optimization method for 3D RC building structure with shear wall. *ETABS* program is used for analysis and design of structural model, and *MATLAB* programing is utilized as optimizer solution. The thickness of the shear walls, cross sections of beams and columns are taken as design variable. As for the final design application, the optimal cross sections are selected to minimize the total cost of the structure whereas satisfying ACI 318-14 design code provision.

II. TARGET MODEL SHEAR WALL-FRAME STRUCTURE

A. Section Definition

Fig. 1 illustrates plan and 3D view of target model shear wall-frame structure for optimization.



(a) Plan (b) 3D view

Fig. 1 Plan and 3D view of shear wall-frame model

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In this paper, a seismic design optimization procedure is applied for 15 storied shear wall-frame structure with 3 spans with length of 9m, 7.5m and 7m in each horizontal direction, and with typical height of 3m. Beams and columns have rectangular shape. Walls are placed between beams. The section sizes of beams and columns, and the thickness of walls are design variable.

B. *Loads of the Structure and Load Combinations*

In this paper, the assumed dead and live loads on slab for each floor are 7.5 KN/m^2 and 5.5KN/m^2 respectively. The assumed dead load on each frame of the floor is 12.5 KN/m. The compressive strength of Concrete is 27 MPa and yield strength for reinforcement is 414 MPa for all section sizes. The lateral loads are calculated based on ASCE7-05 code, by assuming that the site class of the structure is D, response modification factor R=6, and ss and s1 are 1.28 and 0.22, respectively [7]. Following load cases are used for strength design based on ACI 318-14 [1]:

U= 1.2 Dead + 1.6 Live (1)
U= 1.3 Dead + 1 Live ± 1 E (2)
U= 0.8Dead ± 1 E (3)

where U is the required strength of a member for resisting factored loads based on load combination.

C. *Analysis of the Structure*

To obtain displacement, story lateral forces, stresses and moments in the members, linear static analysis is performed using *ETABS* program. Design code of ACI 318-14 recommends the following relationship in order to consider the effect of cracking in RC frames [1].

Ibeam = 0.35Ig ACI(6.6.3.1.1a) (4)
Icolumn = 0.7Ig ACI(6.6.3.1.1a) (5)
I wall=0.7Ig (uncracked) ACI(6.6.3.1.1a) (6)
I wall=0.35Ig (cracked) ACI(6.6.3.1.1a) (7)
Abeam = Ag ACI(6.6.3.1.1a) (8)
Acolumn = Ag ACI(6.6.3.1.1a) (9)

where Ig is gross moment of beam, column or shear wall, and Ag is gross section of the beam, column or shear wall

III. CONSTRAINTS FOR RC SHEAR WALL-FRAME STRUCTURE

In this chapter, constraints for shear wall, columns and beams from ACI code are explained. The followings are the common character definitions:

f_y : specified yield strength for reinforcement in Mpa.
f_c' : specified compressive strength of concrete in MPa,
A_g :gross area of concrete section, mm^2
N_u :factored axial force normal to cross section, N
M_u :factored moment at section, N-mm
V_u is the factored shear force of shear wall, N,
V_c : nominal shear strength provided by concrete, N
V_s : nominal shear strength provided by shear reinforcement, N
s : center to center spacing of items, such as longitudinal reinforcement or transvers reinforcement, mm
ϕ =strength reduction factor.

A. *Special Shear Walls Design Formulation*

Some of the necessary constraints for shear wall to satisfy ACI 318-14 design code provision are included as follows:

1) Reinforcement Limits

ρ_h =horizontal distributed web reinforcement ratio, ρ_v =vertical distributed web reinforcement ratios. The requirements for ρ_h and ρ_v are as follows:

$$\rho_{\min} \le \rho \qquad \text{ACI(11.6.2a)} \quad (10)$$

$$\rho_{\min} = 0.0025 \qquad \text{ACI(11.6.2b)} \quad (11)$$

Reinforcement spacing each way in structural wall shall not exceed 450mm.

2) Shear Strength Limits

Shear force V_u should not exceed the shear strength.

$$V_u \le \phi V_n \qquad \text{ACI(11.5.4.3)} \quad (12)$$

Nominal shear strength, V_n, of the wall with uniformly distributed reinforcement and opening shall not exceed as following:

$$V_n \le V_{n,\max} = 0.66\sqrt{f_c'}\,t_w d \qquad \text{ACI(18.10.4.4)} \quad (13)$$

$$V_n = V_c + V_s \qquad \text{ACI(11.5.4.4b)} \quad (14)$$

$$V_s = \frac{A_h f_y d}{s} = \rho_h t_w d f_y \qquad \text{ACI(11.5.4.8)} \quad (15)$$

$$V_c = \min(V_{c1}, V_{c2})$$

$$V_{c1} = \alpha_c \lambda \sqrt{f_c'}\,t_w d \qquad \text{ACI(18.10.4.1)} \quad (16)$$

$$\alpha_c = \begin{cases} 0.25(h_w/l_w \le 1.5) \\ 0.25 - 0.16(h_w/l_w - 1.5)(1.5 < h_w/l_w \le 2.0) \\ 0.17(2.0 < h_w/l_w) \end{cases} \qquad \text{ACI(18.10.4.1)(17)}$$

$$V_{c2} = \left[0.05\sqrt{f_c'} + \frac{l_w(0.1\lambda\sqrt{f_c'} + 0.2\frac{N_u}{l_w t_w})}{\frac{M_u}{V_u} - \frac{l_w}{2}} \right] t_w d \qquad \text{ACI(11.5.4.6e)(18)}$$

where h_w and l_w refer to height and length of entire wall, respectively. $\lambda = 1$ for normal weight concrete. A_{cw} =area of concrete section of an individual pier or horizontal wall segment, mm^2 ; V_n =nominal shear strength, N; V_c =nominal shear strength provided by concrete, N; V_s =nominal shear strength provided by shear reinforcement, N; s=center to center spacing of items, such as longitudinal reinforcement, transvers reinforcement, mm; N_u =factored axial force normal to cross section, N; M_u =factored moment at section, N-mm; A_v =area of shear reinforcement within spacing s, mm^2.

3) Boundary Elements Requirement

For seismic design of special shear wall, ACI 318-14 illustrates the following constraints for evaluating detailing requirements at wall boundaries:

$$c \geq \frac{l_w}{600(1.5\delta_w / h_w)} \quad \rho_{\min} = 0.0025 \qquad \text{ACI(18.10.6.2a)} \quad (19)$$

$$\delta_w / h_w \geq 0.005 \qquad \text{ACI(18.10.6.2b)} \quad (20)$$

$$\delta_w = 0.007 \qquad \text{ASCE 7-10 (12.12.1)} \quad (21)$$

where c=compression region length of the wall section, δ_w =design displacement. More details about requirements for boundary element is shown below in Fig. 2.

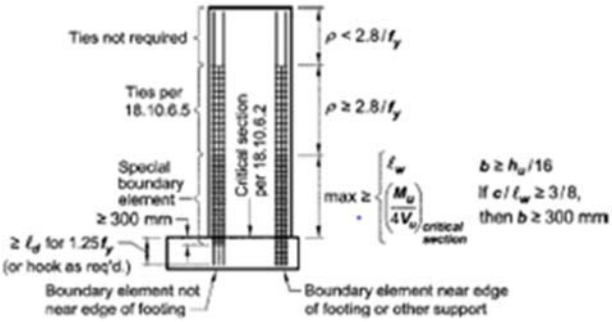


Fig. 2 Summary of boundary element requirements for special shear wall

B. Column Constraints

1) Reinforcement Ratio

The minimum and maximum longitudinal reinforcement ratio shall be the following limitation:

$$\rho_{\min} = 0.01\ A_g \qquad \text{ACI(10.6.1.1a)} \quad (22)$$

$$\rho_{\max} = 0.08\ A_g \qquad \text{ACI(10.6.1.1b)} \quad (23)$$

Based on ACI 318-14 design code provision, the minimum transvers reinforcement of column for rectangular hoops shall be at least the maximum of $\max(\rho_{\min 1}, \rho_{\min 2})$.

$$\rho_{\min} = 0.09 \frac{f'_c}{f_y} \qquad \text{ACI18.7.5.4a)} \quad (24)$$

$$\rho_{\min} = 0.3(\frac{A_g}{A_{ch}} - 1)\frac{f'_c}{f_y} \qquad \text{ACI18.7.5.4b)} \quad (25)$$

For spiral or circular hoops:

$$\rho_{\min} = 0.12 \frac{f'_c}{f_y} \qquad \text{ACI18.7.5.4c)} \quad (26)$$

$$\rho_{\min} = 0.45(\frac{A_g}{A_{ch}} - 1)\frac{f'_c}{f_y} \qquad \text{ACI18.7.5.4d)} \quad (27)$$

where A_g =gross area of concrete section, mm^2; A_{ch} =cross-sectional area of a member measured to the outside edge of transvers reinforcement, mm^2.

2) Column Axial Strength

The Nominal axial compressive strength should be:

$$p_n \leq p_{n,\max} \qquad \text{ACI(22.42.4e)} \quad (28)$$

For transverse reinforcement of non-prestressed members with ties,

$$p_{n,\max} = 0.80\, p_o \qquad \text{ACI(22.42.4a)} \quad (29)$$

For transverse reinforcement of non-prestressed members with spirals,

$$p_{n,\max} = 0.85\, p_o \qquad \text{ACI(22.42.4e)} \quad (30)$$

Nominal axial strength, p_o can be calculated with the following equation:

$$p_o = 0.85 f'_c (A_g - A_{st}) + f_y A_{st} \qquad \text{ACI(22.4.2.2)} \quad (31)$$

where p_n =nominal axial compressive strength of member, N, $p_{n,\max}$ =maximum nominal axial compressive strength of member, N, p_o =nominal axial compressive strength at zero eccentricity, N, A_{st} =total area of non-prestressed longitudinal reinforcement, mm^2.

3) Column Shear Strength

Cross-sectional dimension of column shall satisfy:

$$V_u \leq \phi(V_c + 0.66\sqrt{f'_c}\, b_w d) \qquad \text{ACI(22.5.1)} \quad (32)$$

For non-prestressed member with axial compression,

$$V_c = 0.17(1 + \frac{N_u}{14 A_g})\lambda\sqrt{f'_c}\, b_w d \qquad \text{ACI(22.5.6.1a)} \quad (33)$$

For member with axial tension,

$$V_c = 0.17(1 + \frac{N_u}{3.5 A_g})\lambda\sqrt{f'_c}\, b_w d \qquad \text{ACI(22.5.7.1b)} \quad (34)$$

For member with axial compression force, V_c must be the following limitation:

$$V_{c1} \le \left(0.16\lambda\sqrt{f'_c} + 17\rho_w \frac{V_u d}{M_u - N_u \frac{4D-d}{8}} \right) b_w d \quad \text{ACI(22.5.6.1a)(35)}$$

$$V_{c2} \le 0.29\lambda\sqrt{f'_c}\, b_w d \sqrt{1+0.29 N_u / A_g} \qquad \text{ACI(22.5.6.1b)} \quad (36)$$

$$\rho_w = \frac{A_s}{b_w d} \qquad \text{ACI(22.5.5.1R)} \quad (37)$$

C. Beam Constraints

1) Reinforcement Ratio

The reinforcement ratio can be calculated using the following equations:

$$\rho = \frac{0.85 f_c}{f_y}\left(1 - \sqrt{1 - \frac{2R_n}{0.85 f_c}}\right) \qquad \text{ACI(7.4)} \quad (38)$$

$$R_n = \frac{M_n}{bd^2} \qquad \text{ACI(7.5)} \quad (39)$$

$$\frac{2R_n}{0.85 f_c'} \le 1 \qquad (40)$$

where M_n =nominal moment strength at cross section, N-m. Minimum area of flexural reinforcement, shall be the $\max(A_{s,\min 1}, A_{s,\min 2})$:

$$A_{s,\min 1} = \frac{0.25\sqrt{f_c}}{f_y}\, b_w d \qquad \text{ACI(9.6.12a)} \quad (41)$$

$$A_{s,\min 2} = \frac{1.4}{f_y}\, b_w d \qquad \text{ACI(9.6.12b)} \quad (42)$$

The minimum shear reinforcement should be provided in accordance with, $\max(\rho_{\min 1}, \rho_{\min 2})$.

$$\rho_{\min} = 0.062\sqrt{f'_c}\, \frac{b_w s}{f_y} \qquad \text{ACI(10.6.2.2a)} \quad (43)$$

$$\rho_{\min} = 0.35\frac{b_w s}{f_y} \qquad \text{ACI(10.6.2.2b)} \quad (44)$$

2) Shear Strength of Beam

As for shear strength of beam the same equations with, (14), (16) and the last equation of (18) for wall can be used by replacing b_w for t_w and ρ_s for ρ_h.

IV. OPTIMIZATION PROCEDURES FOR 3D RC BUILDING STRUCTURE WITH SHEAR WALL

A. Cost Optimization Problem

Optimization problem can be defined as follows:

Find $X = (\mathbf{b}_b, \mathbf{d}_b, \mathbf{b}_c, \mathbf{d}_c, \mathbf{t}_w, \mathbf{L}_w)$ (45)

To minimize $f(X) = C_c V_c + C_s V_s$ (46)

Subject to $g(X) \le 0$. Design variable X indicates section sizes of beams ,i.e. $\mathbf{b}_b = (b_{b1},\ldots,b_{bN_b})$, $\mathbf{d}_b = (d_{b1},\ldots,d_{bN_b})$, columns, i.e. $\mathbf{b}_c = (b_{c1},\ldots,b_{cN_c})$, $\mathbf{d}_c = (d_{c1},\ldots,d_{cN_c})$ and walls, i.e. $\mathbf{t}_w = (t_{w1},\ldots,t_{wN_w})$. N_b, N_c, N_w are number of beams, columns and walls. Area of steel bars are not independent design variable but dependent variable of section sizes. As for the reinforcement for shear force of beams, columns and walls, reinforcement ratio has only lower limit. Therefore, the required reinforcement ratios are determined as minimum values. As for the reinforcement for bending moment of beams and columns, required reinforcement ratios are determined as balanced reinforcement ratio.

Various objective functions can be used to find the optimum solution. In this paper, objective function to be minimized is defined as the total cost of reinforcement concrete considering the difference of the cost of concrete and steel bar.

$$V_c = \sum_{i=l}^{N_w} Vc_{wi} + \sum_{i=l}^{N_b} Vc_{bi} + \sum_{i=l}^{N_c} Vc_{ci} \qquad (47)$$

$$V_s = \sum_{i=l}^{N_w} Vs_{wi} + \sum_{i=l}^{N_b} Vs_{bi} + \sum_{i=l}^{N_c} Vs_{ci} \qquad (48)$$

where C_c and C_s are set as 0.6 and 60, respectively [4].

As for the constraint functions, only formulations related to the upper bound of reinforcement ratio and story drift in the previous chapter are considered during optimization by translating them into constraint functions as follows. As for the section sizes both upper and lower limits are applied.

$$g(X) = R(X) - R_{\max} \le 0 \qquad (49)$$

$$g(X) = R_{\min} - R(X) \le 0 \qquad (50)$$

V. NUMERICAL EXAMPLES FOR 15 STORIED MODEL

A. Optimization Setting

In this example, as for the wall, lengths are fixed to 300cm and only thicknesses are design variable. The section sizes for beam and column, and thickness sizes for shear walls are predetermined as 5 sizes for every three stories. The number of design variables are 10 for beam sections, 10 for column sections and 5 for wall sections. The lower limits of section sizes are set to 10cm. The upper limits of width and height are set to 100cm for beams and columns. The upper limits of thickness of walls are set to 60cm.

As explained before 4 types of load combinations are considered. As for the load combination (3) and (4), 4 cases, i.e. +X, -X,+Y and –Y are considered, respectively.

B. Optimization Result

The optimization results are shown in the following Figs. 3-5. Fig. 3 shows the cost function. Figs. 4 and 5 show the cross-section sizes of shear walls, beams, and columns respectively.

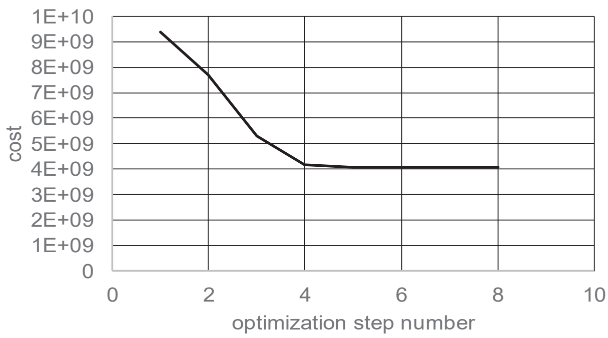


Fig. 3 Total cost of the structure

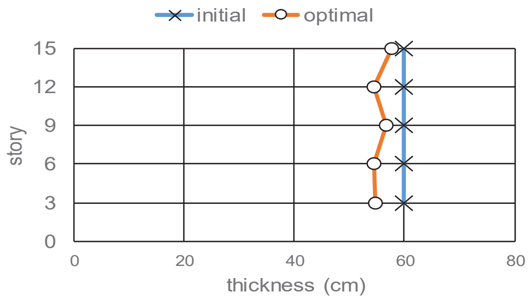


Fig. 4 Thickness of wall

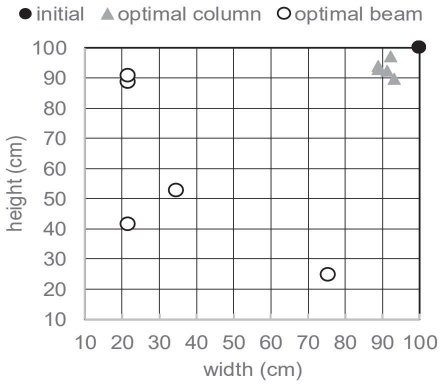
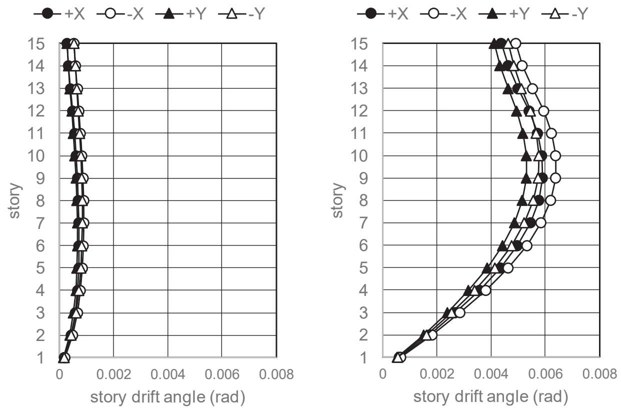


Fig. 5 Section size of columns and beams

Fig. 6 shows the maximum story drift of initial and optimal solutions. Figs. 7-12 show the reinforcement ratio of beams, columns and shear walls of initial and optimal solutions. Figs. 13 and 14 show $2R_n/(0.85 f_c)$ in (40) of beams and columns. Figs. 15 and 16 show the sufficiency ratio of shear strength $V_u/V_{n,\max}$ of shear walls and columns in (13) and (32). From these figures, it can be understood that although this solution is one of local solutions, optimal section sizes of 3D moment resisting shear wall-frame model can be obtained. In this model shear strength of shear wall is the most critical constraint. In order to obtain more practical solutions, further investigation is required.



(a) Initial (b) Optimal

Fig. 6 Story drift angle

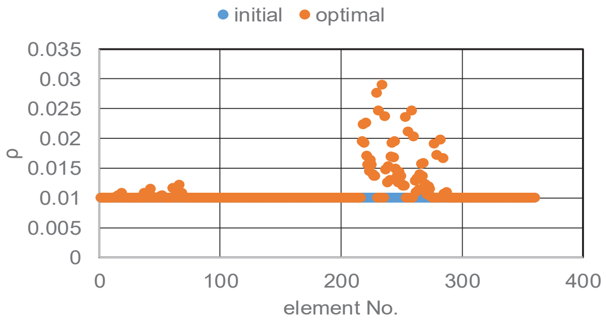


Fig. 7 ρ for bending of beam

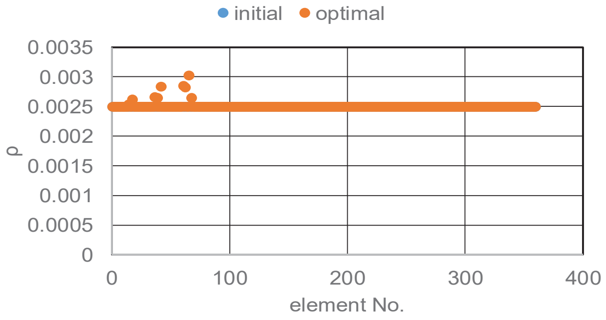


Fig. 8 ρ for shear of beam

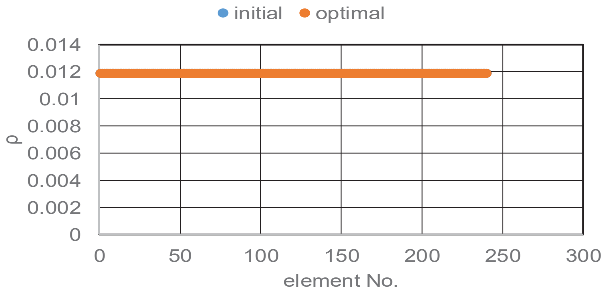


Fig. 9 ρ for bending of column

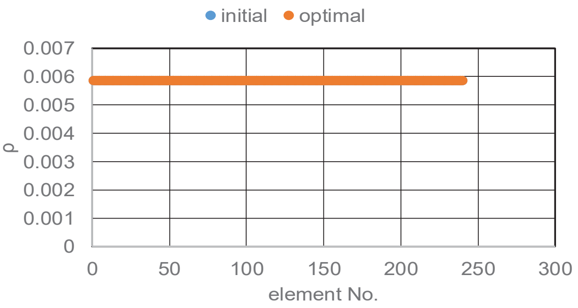


Fig. 10 ρ for shear of column

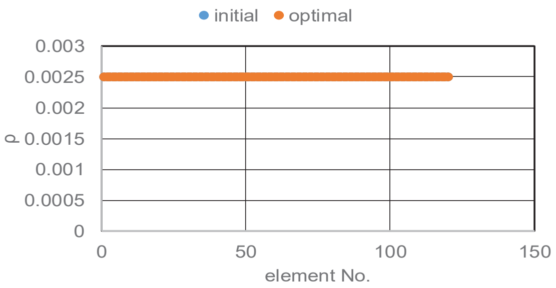


Fig. 11 ρ for shear wall in vertical direction

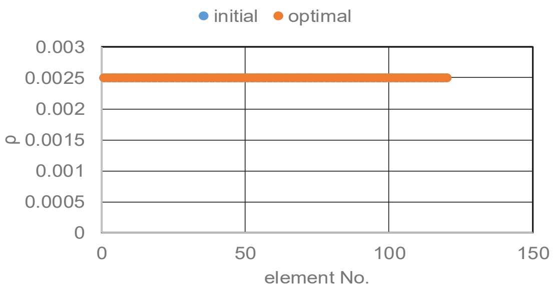


Fig. 12 ρ for shear of wall in horizontal direction

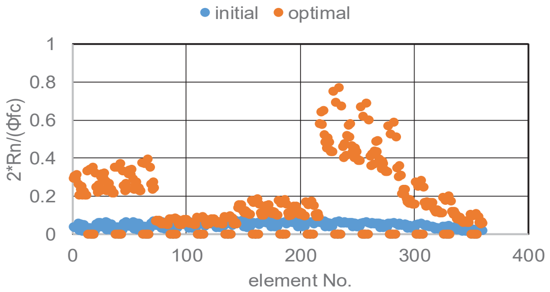


Fig. 13 Constraint of R_n for beams

VI. CONCLUSION

Reinforced concrete structures are very common, and shear walls are widely used in tall, super-tall and high-rise buildings. Seismic design of such structures, however leading expensive structures, the optimization is required to minimize the cost of structures. The structural optimization method for 3D RC dual-system is proposed, and *MATLAB* frame-structure optimizer is utilized as optimization solution. All design formulas are coded in *MATLAB* programming based on ACI 318-14 code provision, and constraints consist of shear force, axial force and reinforcement ratio. Optimal cross-sections of member are generated considering initial sizes, and total cost of the structure is obtained for all steps of optimization.

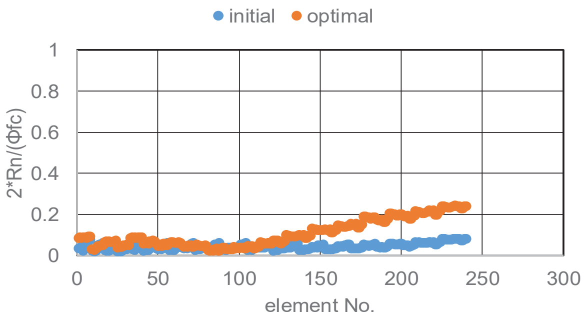


Fig. 14 Constraint of R_n for columns

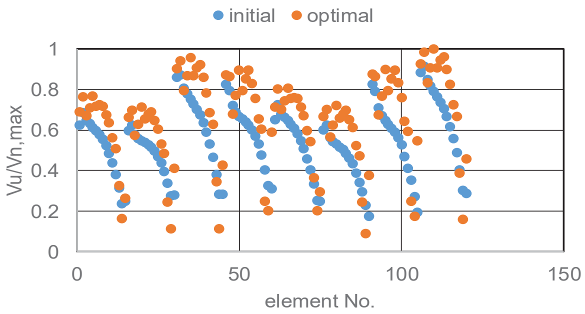


Fig. 15 Constraint of $V_{n,\max}$ for shear wall

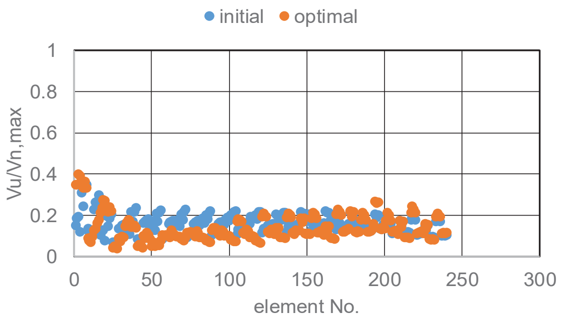


Fig. 16 Constraint of $V_{n,\max}$ for column

The research finding of this method of optimization is expected to provide a useful reference, and can be an effective and powerful tool for structural optimization of RC dual-system structures.

ACKNOWLEDGMENT

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