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Practical Design Procedures of 3D Reinforced Concrete Shear Wall-Frame Structure Based on Structural Optimization Method

H. Nikzad, S. Yoshitomi

***Abstract*—**This study investigates and develops the structural optimization method. The effect of size constraints on practical solution of reinforced concrete (RC) building structure with shear wall is proposed. Cross-sections of beam and column, and thickness of shear wall are considered as design variables. The objective function to be minimized is total cost of the structure by using a simple and efficient automated MATLAB platform structural optimization methodology. With modification of mathematical formulations, the result is compared with optimal solution without size constraints. The most suitable combination of section sizes is selected as for the final design application based on linear static analysis. The findings of this study show that defining higher value of upper bound of sectional sizes significantly affects optimal solution, and defining of size constraints play a vital role in finding of global and practical solution during optimization procedures. The result and effectiveness of proposed method confirm the ability and efficiency of optimal solutions for 3D RC shear wall-frame structure.

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

I. Introduction

EARTHQUAKE is the most sever loading of a structure where it causes unacceptable damages if the structure is not well designed for lateral loads. Shear wall structures as an excellent seismic resistance system however, are widely used in RC building structures to resist gravity and lateral loads. The requirements of related seismic design code of practice, expensive structures are concerned. Therefore, the optimal solution concerning total cost of the structure, known as structural optimization is presented in which suitable dimensions of beams, columns and shear walls can be obtained to minimize the total cost of the structure. Basically, optimization of RC structures used to be done by traditional trial and error processes which are not only time consuming, but also the safe and economical design of structure could not be satisfied. Recently, by developing structural analysis software and other tools, an automatic process of optimization techniques has been introduced with the capability of high performance, both, in terms of cost and time. In the optimization procedures, different objective functions can be defined and a large number of design variables can be utilized in order to find the optimal and practical solution. In all these processes, the minimal cost of the structure is concerned, whereas conforming to the related design code requirements.

In this paper, structural optimization method for RC building shear wall-frame structure is done, and the effect of sectional sizes on optimal and practical solutions of seismic design of RC shear wall-frame is proposed, focusing on the minimal cost of the structure. Extensive studies and evolutions on the optimal design of RC structures concerning cost of the structure have been proposed. Computer-based, design optimization of 3D RC frameworks with shear wall was investigated [1]. In their study, section sizes and reinforcement area were considered as design variables concerning minimum cost of the structure. A novel optimization algorithm for a minimum cost solution of multi-bay portal frame and multistory RC structure, integrating optimal stiffness correlation among members was proposed [2]. Performance-based design criteria for the optimum seismic design of RC structure has been done based on non-linear time history analysis conforming to European design code [3]. The real valued model of Particle Swarm Optimization for the optimum design of RC frames was proposed, whereas design constraints conforming ACI and 2800 codes [4]. Review of optimization approaches, using nature-inspired heuristic algorithm for high-rise building RC structure was done [5]. In their study, optimization of floor and roof structures, 2D high-rise frame structures were also evaluated. Seismic design optimization of RC dual-systems and moment resisting frames was proposed using meta-heuristic optimizer [6]. In their study, databases were constructed for generating optimal cross-sections of beams, column and shear walls to minimize the total cost of the structure. Optimal seismic design of RC structures using hybrid of particle swarm optimization algorithm and intelligent regression model under several time history earthquake loads was investigated considering different sets of constraints for obtaining minimum cost of the structure [7]. Design optimization for RC plane frame structure was proposed by adopting Artificial Neural Network computational model through the neuroShell-2software program [8]. In their study, member sizes and the area of longitudinal reinforcement were considered as design variables to obtain the optimal design cross sections conforming to the ACI code criteria. The optimum seismic design of RC frames was compared and investigated based on EC8 and MC2010 [9]. Genetic algorithm was employed in order to derive the optimal solution for RC

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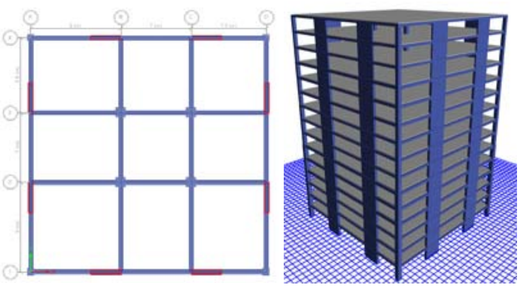
frame structure by MC2010, and the obtained optimal solution was compared with the seismic design performance of RC frames by Euro codes. Optimization of real-world 3D RC frames using multi-criterion decision making and particle swarm optimization algorithm was proposed to minimize the cost of RC frames, whereas satisfying ACI design code provision [10].

Structural optimization method for 3D RC building structure with shear wall was proposed [11]. The objective of their study was to minimize the total cost of the structures by the optimal solution of section sizes of beam, column and shear wall. In this study, the structural optimization method proposed in the previous paper is developed. Moreover, the practical section sizes of elements are obtained for the numerical example of a 15 storied shear wall-frame structure considering mathematical optimization problems with and without size constraints. The most suitable combination of section sizes is selected, considering the total minimum cost of the structure and practical section sizes, comparing the result of both optimization problems as for the final design application based on linear static analysis. Here, cost of the structure refers to materials such as the steel and concrete used in the structure. ETABS structural analysis software is utilized for the analysis and design of structure, and the constraints of the optimization conforming ACI 318-14 design code.

II. Numerical Example of 15 Storied RC Building Shear Wall-Frame Structure Model Shear Wall-Frame Structure

A. Modeling Procedures

In this study, a 15 storied RC building shear wall-frame structures is selected as optimization problem [11]. The structure has three pans with length of 9 m, 7.5 m and 7 m in each horizontal direction, respectively. Predetermined section sizes are considered for beams, columns and shear walls for every three floors where the column has a square shape, and beam and shear wall have rectangular shapes. The compressive strength of concrete is 27 MPa and yield strength of reinforcement is 420 MPa for all member sizes. Fig. 1 shows plan and 3D view of numerical example model.



(a) Plan (b) 3D view

Fig. 1 Plan and 3D view of numerical model

B. Loadings and Load Combinations

In this paper, lateral loads are calculated based on ASCE 7-10, where the site class of the structure is D, response modification factor R=6, and S_1 and S_s are 0.51 and 1.28, respectively [12]. The dead load for frame is calculated 7.5 KN/m and calculated dead and live loads for slab are 5 KN/m^2, respectively. For this example, however, the wind load is neglected. Only gravity and lateral loads are considered during optimization procedures based on automatic load combination of ETABS 2015 V.2.2 as follows [13]:

$$U= 0.9\ \text{Dead} \quad (1)$$

$$U= 1.2\ \text{Dead} + 1.6\ \text{Live} \quad (2)$$

$$U= 1.3\ \text{Dead} + 1\ \text{Live} \pm 1\ E \quad (3)$$

$$U= 0.8\text{Dead} \pm 1\ E \quad (4)$$

In these equations, U corresponds to the required strength of members' resisting factored loads in a load combination, and E stands for earthquake load.

C. Analysis of the Structure

For validity of proposed method, linear static analysis is performed. The contents of this section are explained in [11]. Based on recommendation of ACI 318-14, moment of inertia in RC frame shall be calculated for the cross-sectional area of beam, column and shear walls as follows [14]:

$$I\ \text{beam} = 0.35Ig,\ \text{ACI}(6.6.3.1.1a) \quad (5)$$

$$I\ \text{column} = 0.7Ig,\ \text{ACI}(6.6.3.1.1a) \quad (6)$$

$$I\ \text{wall}=0.7Ig\ (\text{un-cracked}),\ \text{ACI}(6.6.3.1.1a) \quad (7)$$

$$I\ \text{wall}=0.35Ig\ (\text{cracked}),\ \text{ACI}(6.6.3.1.1a) \quad (8)$$

$$A\ \text{beam} = Ag,\ \text{ACI}(6.6.3.1.1a) \quad (9)$$

$$A\ \text{column} = Ag,\ \text{ACI}(6.6.3.1.1a) \quad (10)$$

In these equations, Ig is gross moment of beam, column or shear wall, and Ag is the gross section of beam, column or shear wall.

III. Constraints for the Seismic Design Requirement of RC Shear Wall-Frame Structure

Building structure with lateral load-resisting system should fully comply with all gravity and lateral loads. To withstand the design ground motion within the prescribed limits of deformation and strength demand, the system shall be capable of providing adequate strength and stiffness [12]. All cross sections for applicable factored load combination shall satisfy the following design strength:

$$\phi P_n \geq P_u\ ,\ \text{ACI}(11.5.1.1a) \quad (11)$$

$$\phi M_n \geq M_u\ \ \text{ACI}(11.5.1.1b) \quad (12)$$

$$\phi V_n \geq V_u\ \ \text{ACI}(11.5.1.1c) \quad (13)$$

Each of the above constraints is explained separately in the next sections. Some of the necessary characters of constraints for seismic requirements of the structure are determined in a previous paper as the following [11]:

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 transverse reinforcement, mm

ϕ =strength reduction factor shall be in accordance with ACI (21.2.1)

δ_w =design displacement

p_o =nominal axial compressive strength at zero eccentricity, N,

p_n =nominal axial compressive strength of member, N,

A_{st} =total area of non-prestressed longitudinal reinforcement, mm^2.

In general, the design constraints can be classified as follows [15]:

1. Allowable section and element conditions, as well as practical structural configuration.
2. Capacity criteria and seismic provisions for combinations of static loads, and consideration of allowable story drift.
3. Capacity criteria and seismic provisions for combinations of gravity and earthquake loads.

The next sections discuss the constraints in detail.

A. Column Constraints

1) Reinforcement Constraint

The ratio of reinforcement shall be the $(\rho_{\min} \le \rho \le \rho_{\max})$

$$\rho_{\min} = 0.01\ A_g \text{, ACI(10.6.1.1a)} \quad (14)$$

$$\rho_{\max} = 0.08\ A_g \text{, ACI(10.6.1.1b)} \quad (15)$$

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

For rectangular hoops:

$$\rho_{\min 1} = 0.09 \frac{f'_c}{f_y} \text{, ACI18.7.5.4a)} \quad (16)$$

$$\rho_{\min 2} = 0.3(\frac{A_g}{A_{ch}} - 1)\frac{f'_c}{f_y} \text{ , ACI18.7.5.4b)} \quad (17)$$

For spiral or circular hoops:

$$\rho_{\min 1} = 0.12 \frac{f'_c}{f_y} \text{, ACI18.7.5.4c)} \quad (18)$$

$$\rho_{\min 2} = 0.45(\frac{A_g}{A_{ch}} - 1)\frac{f'_c}{f_y} \text{ , ACI18.7.5.4d)} \quad (19)$$

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

2) Column Axial Strength Constraint

The Nominal axial compressive strength should be:

$$p_n \le p_{n,\max} \text{, ACI(22.42.4e)} \quad (20)$$

For transverse reinforcement of non-prestressed members with ties,

$$p_{n,\max} = 0.80 p_o \text{, ACI(22.42.4a)} \quad (21)$$

For transverse reinforcement of non-prestressed members with spirals,

$$p_{n,\max} = 0.85 p_o \text{, ACI(22.42.4e)} \quad (22)$$

Nominal axial strength, p_o can be calculated with:

$$p_o = 0.85 f'_c (A_g - A_{st}) + f_y A_{st} \text{, ACI(22.4.2.2)} \quad (23)$$

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:

$$V_u \le \phi(V_c + 0.66\sqrt{f'_c} b_w d) \text{, ACI (22.5.1)} \quad (24)$$

For non-prestressed member with axial compression,

$$V_c = 0.17(1 + \frac{N_u}{14 A_g})\lambda\sqrt{f'_c} b_w d \text{, ACI(22.5.6.1a)} \quad (25)$$

For member with axial tension,

$$V_c = 0.17(1+\frac{N_u}{3.5A_g})\lambda\sqrt{f'_c}b_w d \text{ , ACI(22.5.7.1b)} \quad (26)$$

For member with axial compression force, $V_c = \max(V_{c1}, V_{c2})$, where,

$$V_{c1} \le \left(0.16\lambda\sqrt{f'_c}+17\rho_w \frac{V_u d}{M_u - N_u\frac{4D-d}{8}}\right)b_w d \text{ ACI(22.5.6.1a)} \quad (27)$$

$$V_{c2} \le 0.29\lambda\sqrt{f'_c}b_w d\sqrt{1+0.29N_u/A_g} \text{ , ACI(22.5.6.1b)} \quad (28)$$

In this equation, $\rho_w = \frac{A_s}{b_w d}$, ACI(22.5.5.1R) (29)

B. Beam Constraints

1) Size Constraint

Based on recommendation of ACI, over all beam depth h, shall satisfy the following:

TABLE I
LIMITATION ON BEAM DEPTH

Minimum depth of beams ACI 9.3.11				
Support condition	Simply supported	One-end continuous	Both-ends continuous	Cantilever
h	$l/16$	$l/18.5$	$l/21$	$l/8$

2) Reinforcement Ratio

The reinforcement ratio can be calculated using the following equations:

$$\rho = \frac{0.85 f_c}{f_y}\left(1-\sqrt{1-\frac{2R_n}{0.85 f_c}}\right) \text{, ACI (7.4)} \quad (30)$$

$$R_n = \frac{M_n}{bd^2} \text{ , ACI (7.5)} \quad (31)$$

$$\frac{2R_n}{0.85 f_c'} \le 1 \quad (32)$$

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

$$A_{s,\min 1} = \frac{0.25\sqrt{f_c}}{f_y} b_w d \text{ , ACI(9.6.12a)} \quad (33)$$

$$A_{s,\min 2} = \frac{1.4}{f_y} b_w d \text{ , ACI(9.6.12b)} \quad (34)$$

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

$$\rho_{\min} = 0.062\sqrt{f'_c}\frac{b_w s}{f_y} \text{ , ACI(10.6.2.2a)} \quad (35)$$

$$\rho_{\min} = 0.35\frac{b_w s}{f_y} \text{ , ACI(10.6.2.2b)} \quad (36)$$

3) Shear Strength of Beam

As for the shear strength of beam the same equations with, (40), (43), and the last equation of (45) for a wall can be used by replacing b_w for t_w and ρ_s for ρ_h.

C. Special Shear Wall Design Constraints

However, some of the formulations for the optimum design of shear wall have been explained, flexural strength, boundary requirements, and other constraints for designing of shear wall are not considered [11]. In this paper, formulation for optimal designing of shear wall is proposed and developed. In this section, besides the formulation from the ACI 318-14, special provisions for walls, of the ACI building code (ACI 318-71) [16]-[18] are utilized for the optimum design of shear walls. For this model, rectangular structural walls are placed between beams with uniform distribution of bars. Shear wall constraints are discussed in the next sections.

1) Size Constraint

The minimum thickness of wall designed by empirical method with rectangular cross-section shall be the following:

TABLE II
LIMITATION ON WALL THICKNESS

Wall type		Minimum thickness, t, ACI 11.3.1.1
Bearing	≥	100 mm $1/25$ of unsupported length and unsupported height
Nonbearing	≥	100mm $1/30$ the lesser of unsupported length and unsupported height
Exterior basement and foundation		190 mm

Considering analysis method, the thickness of walls with rectangular cross-section shall be limited to the absolute minimum of $1/20$ (preferably $1/15$) of the unsupported height of the wall for the sake of better placement of concrete [18].

2) Reinforcement Constraint

Ratio of ρ_h horizontal shear reinforcement area to gross concrete area shall not be less than the following [11]:

$$\rho_{\min} \le \rho, \ \rho_{\min} = 0.0025 \text{, ACI(11.6.2a)} \quad (37)$$

Ratio of ρ_V vertical shear reinforcement shall not be less than:

$$\rho_v = 0.0025+0.5(2.5-h_w/l_w)(\rho_h - 0.0025) \ge 0.0025 \text{ , ACI(11.6.2b)} \quad (38)$$

ρ_h =horizontal distributed web reinforcement ratio, ρ_v =vertical distributed web reinforcement ratios.

Reinforcement spacing each way in structural wall shall not exceed $l_w/3$, 3h or 450 mm.

3) Shear Strength Constraint

Structural walls subjected to horizontal shear forces, should be capable of resisting total design shear forces. The nominal shear force V_u should not exceed the shear strength:

$$V_u \le \phi V_n \text{, ACI (11.5.4.3)} \quad (39)$$

The constraints for nominal shear strength, V_n of wall with uniformly distributed reinforcement and opening shall not exceed as the following:

$$V_n = V_c + V_s \text{, ACI(11.5.4.4b)} \quad (40)$$

In no case shear strength, V_n shall be taken greater than:

$$V_n \le V_{n,\max} \text{, ACI (18.10.4.4)} \quad (41)$$

where,

$$0.83\sqrt{f_c'}t_w d \ge V_{n,\max} \ge 0.66\sqrt{f_c'}t_w d \text{, ACI (18.10.4.4)} \quad (42)$$

The constraint, V_c for shear wall subjected to axial compression, shall satisfy the following:

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

$$V_{c1} = \alpha_c \lambda \sqrt{f_c'} t_w d \text{, ACI (18.10.4.1)} \quad (43)$$

$$\alpha_c = \begin{cases} 0.25(h_w/l_w \le 1.5) \\ 0.25 - 0.16(h_w/l_w - 1.5)(1.5 < h_w/l_w \le 2.0) \\ 0.17(2.0 < h_w/l_w) \end{cases} \text{ ACI (18.10.4.1)} \quad (44)$$

$$V_{c2} = \left[0.05\sqrt{f_c'} + \frac{l_w(0.1\lambda\sqrt{f_c'} + 0.2\frac{N_u}{l_w t_w})}{\frac{M_u}{V_u} - \frac{l_w}{2}} \right] t_w d \text{ ACI(11.5.4.6e)} \quad (45)$$

For wall resisting factored shear force exceeding ϕV_c, the constraints for V_s shall satisfy:

$$V_s \ge \left(\frac{V_u}{\phi} - V_c\right)$$

where V_s shall be calculated with the following equation:

$$V_s = \frac{A_h f_y d}{s} = \rho_h t_w d f_y \quad \text{ACI (11.5.4.8)} \quad (46)$$

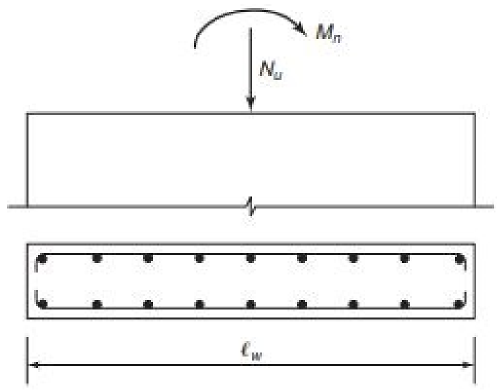
where h_w and l_w refer to height and length of entire wall, respectively. $\lambda = 1$ for normal weight concrete. A_{cw} =area of concrete section of an individual pier or horizontal wall segment, mm^2; V_n =nominal shear strength, N; V_c =nominal shear strength provided by concrete, N; V_s =nominal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

4) Flexural Strength Constraint

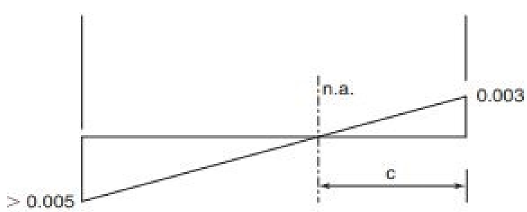
In designing of a shear wall in high-rise building, in seismic region however, the minimum amount of horizontal reinforcement, 0.0025, is sufficient for the flexural strength of shear wall. Based on this assumption, wall shall be designed to resist bending moment and axial forces produced by vertical loads or wall weight.

The flexural strength of rectangular walls with h_w/l_w equal or greater than 1.0 subjected to factored axial loads, shall be calculated with the following equation [16], [18]:

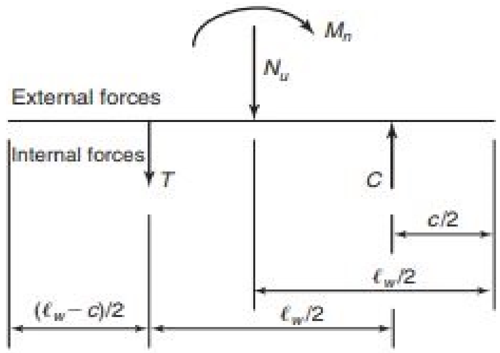
$$M_u = 0.5 A_s f_y l_w \left(1 + \frac{N_u}{A_s f_y}\right)\left(1 - \frac{c}{l_w}\right) \text{ ACI(318-71-1)} \quad (47)$$



(a) Typical wall section



(b) Assumed strain distribution



(c) Resultant external and internal forces acting on wall section

Fig. 2 Wall with uniform distribution of vertical reinforcement subjected to axial load and bending

Based on assumption of [16] and [18], and considering nominal strength conditions for shear wall sections of Fig. 2, the following approaches have been derived:

1. All reinforcing bars in tension zone yield in tension.
2. All reinforcing in compression zone yield in compression.
3. The tension force acts at mid-depth of the tension zone.
4. The summation of concrete and steel compression forces, acts at mid-depth of compression zone.

From Fig. 2, the following approaches have been made for deriving flexure strength calculation based on assumption of [16], [18].

The amount of tension stress sustained by tension bar and the amount of compression stress sustained by the compression concrete and reinforcing proportion to length of wall are calculated as following:

$$T = A_s f_y \left(\frac{l_w - c}{l_w}\right) \tag{48}$$

$$C = C_s + C_c \tag{49}$$

$$C_c = 0.85 f'_c * t * a \tag{50}$$

$$C_s = A_s f_y \left(\frac{c}{l_w}\right) \tag{51}$$

$$N_u = C_c + C_s - T \tag{52}$$

Considering the equilibrium equation and its progress result in:

$$N_u = 0.85 f'_c h \beta_1 c + A_s f_y \left(\frac{c}{l_w}\right) - A_s f_y \left(\frac{l_w - c}{l_w}\right) \tag{53}$$

where C, is compressive force in cross section, with the subscript of s=steel and c=concrete, N.

By processing the formulas proposed by [16] and [18], the concrete compression block can be derived as follows:

$$c = \frac{N_u + A_s f_y}{\left\{0.85 f'_c * t * \beta + 2\left(\frac{A_s f_y}{l_w}\right)\right\}} \tag{54}$$

Considering the above equations, and from Fig. 2, the nominal moment strength of shear wall can be calculated with the following equation:

$$M_n = T\left(\frac{l_w}{2}\right) + N_u\left(\frac{l_w - c}{2}\right) \tag{55}$$

5) Boundary Element Constraint

The critical zones of a shear wall are located close to the edges or next to the wall opening, strengthened by longitudinal and transverse reinforcement due to high compressive demand, resulting from combined lateral and gravity loads. There are two approaches for the requirements of boundary zones, displacement-based design and nominal compressive strength with $\sigma \geq 0.2 f'_c$ based on ACI design code. As for the first approach, confinement reinforcement is required if:

$$c \geq \frac{l_w}{600(1.5\delta_w / h_w)}, \text{ ACI(18.10.6.2a)} \tag{56}$$

$$\delta_w / h_w \geq 0.005, \text{ ACI(18.10.6.2b)} \tag{57}$$

where c=compression region length of wall section, δ_w =design displacement.

The ratio of transverse reinforcements for special boundary elements shall not be less then, $\max(\rho_{\min 1}, \rho_{\min 2})$

For transverse reinforcement with a rectangular hoop,

$$\rho_{\min 1} \geq 0.3\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f'_c}{f_y}, \text{ ACI(18.10.6.4a)} \tag{58}$$

$$\rho_{\min 2} \geq 0.09\frac{f'_c}{f_y}, \text{ ACI(18.10.6.4b)} \tag{59}$$

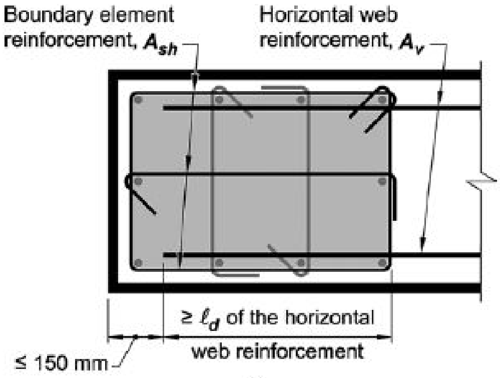
For transverse reinforcement with a spiral or circular hoop,

$$\rho_{\min 1} \geq 0.45\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f'_c}{f_y}, \text{ ACI(18.10.6.4c)} \tag{60}$$

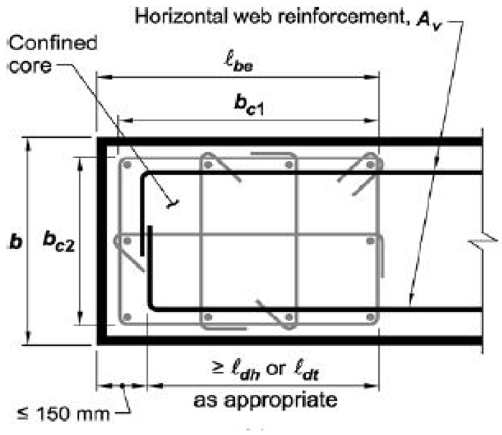
$$\rho_{\min 2} \geq 0.12\frac{f'_c}{f_y}, \text{ ACI(18.10.6.4d)} \tag{61}$$

where $A_g = l_{be} b$ and $A_{ch} = b_{c1} b_{c2}$.

The dimension of l_{be}, b, b_{c1}, and b_{c2} are illustrated in Fig. 3. The spacing of transverse reinforcements shall be in accordance with ACI (18.7.5.3)



(a) Option with standard hook reinforcement



(b) Option with straight developed reinforcement

Fig. 3 Development of wall horizontal reinforcement in confined boundary element

D.Size Constraint

Within the height direction of the structure, different classes of beam, column and shear wall exist.

In order to obtain solutions with practical section sizes, some size constraints are considered.

As for the shape of beam section, upper limit about a ratio of width to depth of every beam is considered.

$$\frac{b_b}{D_b} \le \overline{r} \tag{62}$$

As for the relationship between beam width and wall thickness or beam width and column width, the following constraints are considered at every connection in the i-th floor.

$$t_{wi} \le b_{bi} \tag{63}$$

$$b_{bi} \le D_{ci} \tag{64}$$

As for the relationship between members in i-th and i+1th story, the constraints for column depth and wall thickness are considered.

$$D_{c(i+1)} \le D_{ci} \tag{65}$$

$$t_{w(i+1)} \le t_{wi} \tag{66}$$

IV. Optimization Procedures for a 3D RC Building Structure with Shear Wall

A. Cost Optimization Problem

To solve the structural optimization, the objective functions, design variables and other constraints have been defined. As for the practical section sizes, the constraints of (62)-(66) have been considered. In addition, the seismic provision for shear force, bending moment and axial force for beam, column and shear wall shall satisfy design code requirement during optimization procedures.

Mathematically, optimization problem can be defined as:

$$\text{Find } X = (\mathbf{b}_b, \mathbf{d}_b, \mathbf{b}_c, \mathbf{d}_c, \mathbf{t}_w, \mathbf{L}_w) \tag{67}$$

$$\text{to minimize } f(X) = C_c V_c + C_s V_s \tag{68}$$

subjected to $g(X) \le 0$, where design variable X indicates section sizes of beams, i.e. $\mathbf{b}_b = (b_{b1},...,b_{bN_b})$, $\mathbf{d}_b = (d_{b1},...,d_{bN_b})$, columns, i.e. $\mathbf{b}_c = (b_{c1},...,b_{cN_c})$, $\mathbf{d}_c = (d_{c1},...,d_{cN_c})$ and walls, i.e. $\mathbf{t}_w = (t_{w1},...,t_{wN_w})$. N_b , N_c , N_w are number of beams, columns and walls, respectively. C_c and V_c indicate cost per unit weight of concrete and volume of concrete, and C_s and V_s , cost per unit weight of steel bar and volume of steel bar respectively. The area of steel bars is not an 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 a lower limit. Therefore, the required reinforcement ratios are determined as minimum values. As for the reinforcement for the bending moment of beams and columns, the required reinforcement ratios are determined as balanced reinforcement ratios.

B. Objective Function

Various objective functions can be used to find the optimum solution. In this paper, the objective function to be minimized is total cost of the structure, defined as to what extent the size constraints affect the total cost of the structure considering the difference of the cost of concrete and steel bar. Here, the objective function is taken as the initial cost of the structure defined as the total cost of steel bar and concrete used in the structure, concerning optimal practical section sizes as follows:

$$V_c = \sum_{i=l}^{N_w} Vc_{wi} + \sum_{i=l}^{N_b} Vc_{bi} + \sum_{i=l}^{N_c} Vc_{ci} \tag{69}$$

$$V_s = \sum_{i=l}^{N_w} Vs_{wi} + \sum_{i=l}^{N_b} Vs_{bi} + \sum_{i=l}^{N_c} Vs_{ci} \tag{70}$$

where C_c is given 60\$/m^3 and C_s is set as 0.6 \$/kg, respectively.

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.

$$g(X) = R(X) - R_{max} \leq 0 \tag{71}$$

$$g(X) = R_{min} - R(X) \leq 0 \tag{72}$$

V. Numerical Examples for 15 Storied Model

A. Mathematical Formulations of Structural Optimization

Before starting the optimization process, pre-defined section database is made in Excel 2016. The database includes width and depth of beams and columns, and thickness of shear wall ranging 75-130 cm for column, 50-80 cm for beam and 35-70 cm for shear wall, respectively. The lower bounds for the section sizes are considered to be constant, and only the upper bound varies based on initial values.

During optimization procedures, the optimal solution is considered corresponding to section sizes with size constraints and without size constraints. Therefore, the analysis is performed for both cases separately in order to obtain the most practical solution.

Table III shows design variable constraints for the model. In this example, only section sizes for beams, columns and shear walls are considered as design variables. Section sizes for beam and column, and thickness sizes for shear walls are predetermined as five sizes for every three stories. Here, the focus is on practical section sizes, while the optimal minimum cost is expected to be obtained as for the final solution. This optimization problem has high dependency on initial section sizes. Therefore, the most optimal initial values of section size among several variations are selected depending on the most practical solution case as follow:

TABLE III
Optimal Selected Design Variable Constraints

Design Variable Constraints			
Element Name	Number of Design Variables	Upper Bound (cm)	Lower Bound (cm)
Beam	20	70	25
Column	10	100	35
Shear Wall	5	50	15
Total Number of Design Variables	35		

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

B. Optimization Result

Following optimization procedures, the optimum solution for 15-storied shear wall-frame is obtained. The optimum result includes practical section sizes, minimum total cost of the structure considering cost of concrete and steel bar for the beam, column and shear wall. As explained above, various cases with different initial section sizes are carried out and the optimum results of cross-sectional sizes for numerical example with size constraints and without size constraints are summarized in Figs. 4 and 5, and Table IV. Figs. 4 and 5 show cost of the concrete and steel bars for beams, columns and shear walls, respectively.

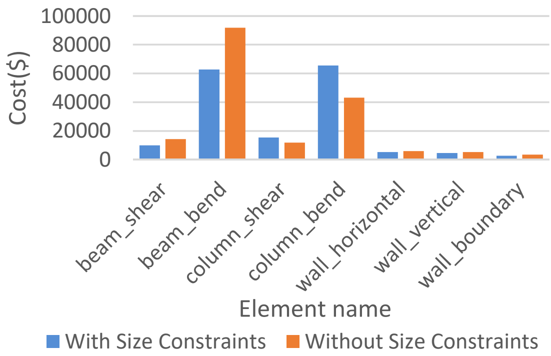


Fig. 4 Cost ratio of steel bar of each element

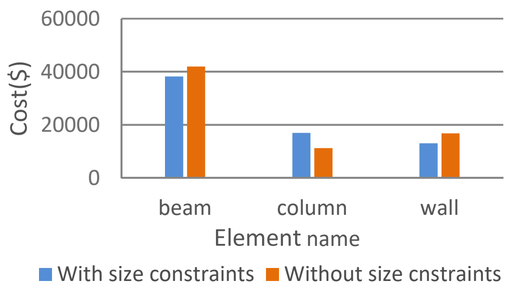


Fig. 5 Cost ratio of concrete of each element

TABLE IV
Optimal Selected Design Variable Constraints

Element type	Story Number	Optimal result (Section sizes)			
		With size constraints hxb (cm)		Without size constraints hxb (cm)	
		Central	Edge	Central	Edge
Column	1-3	95x95	72x72	35x35	74x74
	4-6	83x83	59x59	36x36	50x50
	7-9	83x83	51x51	49x49	48x48
	10-12	81x81	46x46	35x35	54x54
	13-15	69x69	39x39	35x35	42x42
		Inside	Outside	Inside	Outside
Beam	1-3	58x27	65x29	34x25	48x25
	4-6	63x34	64x42	53x36	59x58
	7-9	65x41	64x42	51x48	65x65
	10-12	65x38	64x43	39x65	64x65
	13-15	58x26	64x34	48x25	41x65
Shear wall	1-3	26		37	
	4-6	23		27	
	7-9	20		21	
	10-12	18		30	
	13-15	15		15	
Optimal structural cost (\$)		234123		245397	

From Table IV and Figs. 4 and 5, it can be understood that two optimal solutions show different tendency with respect to the allocation of element type. The optimal solution with size constraint has a larger column, smaller beam and smaller wall than that without size constraint. Table IV implies that for a model with size constraint, the section sizes of the elements seem to be more practical than the model without size constraints.

Contrary to general predictions, the optimal solution with size constraint has 4.6% lower cost than that without size constraints. From this result, it can be noted that this problem has multimodal solution space and strong dependency on initial sectional sizes, and that in these cases, the size constraint is effective to find solutions with both practical sectional size and low cost.

VI. Conclusion

This paper proposes a computer-based automated optimization methodology, focusing on effect of size constraints on optimal solution of RC shear wall-frame structures. Cross-section of beam, column and shear wall are considered as design variables, and the most suitable combination of section sizes are obtained conforming ACI 318-14 design criteria based on linear static analysis. Various cases of analysis with different upper bounds of section sizes have been carried out considering optimization problems with size constraints and without size constraints.

Based on numerical example of optimization solution, it can be concluded that size constraints plays a vital role in optimization problem to obtain practical section sizes. In addition to the upper bound for sectional sizes, having vast experience in designing of RC structures is crucial to decide the most suitable section sizes for the final design application.

As for future research, more critical design constraints related to earthquake and gravity loads can be included, besides the constraints on cross-sections of the elements, in order to find global solution for optimization problem.

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