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CO_2 Emission and Cost Optimization of Reinforced Concrete Frame Designed by Performance Based Design Approach

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***Abstract*—**As greenhouse effect has been recognized as serious environmental problem of the world, interests in carbon dioxide (CO_2) emission which comprises major part of greenhouse gas (GHG) emissions have been increased recently. Since construction industry takes a relatively large portion of total CO_2 emissions of the world, extensive studies about reducing CO_2 emissions in construction and operation of building have been carried out after the 2000s. Also, performance based design (PBD) methodology based on nonlinear analysis has been robustly developed after Northridge Earthquake in 1994 to assure and assess seismic performance of building more exactly because structural engineers recognized that prescriptive code based design approach cannot address inelastic earthquake responses directly and assure performance of building exactly. Although CO_2 emissions and PBD approach are recent rising issues on construction industry and structural engineering, there were few or no researches considering these two issues simultaneously. Thus, the objective of this study is to minimize the CO_2 emissions and cost of building designed by PBD approach in structural design stage considering structural materials. 4 story and 4 span reinforced concrete building optimally designed to minimize CO_2 emissions and cost of building and to satisfy specific seismic performance (collapse prevention in maximum considered earthquake) of building satisfying prescriptive code regulations using non-dominated sorting genetic algorithm-II (NSGA-II). Optimized design result showed that minimized CO_2 emissions and cost of building were acquired satisfying specific seismic performance. Therefore, the methodology proposed in this paper can be used to reduce both CO_2 emissions and cost of building designed by PBD approach.

***Keywords*—**CO_2 emissions, performance based design, optimization, sustainable design.

I. INTRODUCTION

SINCE global warming has been recognized as a critical problem of the world, interests in GHGs have been rapidly improved. As CO_2 emissions account for about 80% of total GHG emissions among various type of GHGs emitted, people have focused on especially CO_2 emissions. Thus, Kyoto Protocol was adopted in 1997 and recently, Paris Agreement was adopted in 2015 by consensus of total 195 nations. According to International Energy Agency (IEA), CO_2 emissions due to energy consumed in buildings comprise approximately 24% of total CO_2 emissions. [1] In Europe, CO_2 emissions of building sector comprise approximately 36% of total CO_2 emissions. [2] 54% and 40% of total energy consumption are indirectly or directly related to construction industry in United States and South Korea, respectively. [3] As mentioned above, CO_2 emissions of construction industry or building sector comprise relatively large portion of total CO_2 emissions. Therefore extensive studies about reducing CO_2 emissions in construction and operation of building have been carried out after the 2000s. [4]-[7] On the other side, after Northridge Earthquake in 1994, PBD methodology based on nonlinear analysis have been robustly researched and developed by structural engineers since prescriptive code based design method turns out that it cannot exactly address inelastic response of structure encountered earthquake and reliably assure intended structural performance of prescriptive code. Thus, recently, Extensive researches on optimized design of building applying PBD approach have been carried out. [8]-[10]

Although aforementioned CO_2 emissions and PBD approach are rising and critical issues on construction industry and structural engineering, there were quite few studies considering these two areas at the same time until now. Especially in terms of optimized design problem, there were no researches. Therefore, this paper presents CO_2 emission and cost optimization method for reinforced concrete building designed by PBD approach. Proposed optimization method is applied to 4 story and 4 span reinforced concrete frame and simultaneously minimizes three objective functions that are CO_2 emission, cost and coefficient of variation (COV) of interstory drift ratio acquired by nonlinear pushover analysis, while satisfying the constraints on strength of sections, constructability, minimum and maximum reinforcement ratio, strong column weak beam (SCWB) requirement and interstory drift ratio. As an optimization tool, NSGA-II [11] is used.

II. ANALYSIS MODEL DESCRIPTION

A. Elastic Analysis (Equivalent Static Analysis)

To meet code regulations, elastic analysis is performed. Linear elastic analysis model is used and OpenSees is used as analysis tool. Load combinations applied to the structures are considered as 1.4D, 1.2D+1.6L, and 1.4D+1.0L+1.0E presented in ASCE 7-10.

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B. Nonlinear Static Pushover Analysis

To assure designated performance objective from PBD approach, analysis result of nonlinear static pushover analysis is used. With an assumption that inelastic deformation is concentrated over specified hinge lengths at the element ends, fiber sections representing inelastic deformation of element are located along the end of element with a half-length of depth of elements as shown Fig. 1. Concrete material model used in fiber is assumed that stress-strain curve is perfectly plastic after yielding and Steel material model used in fiber is assumed that stress-strain curve is bilinear having 3% of hardening ratio after yielding. To perform nonlinear static pushover analysis, OpenSees is used as analysis tool and FEMA 356 is referred.

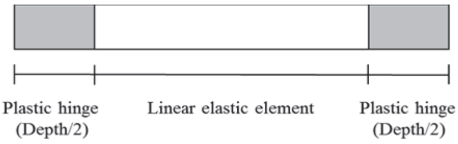


Fig. 1 Nonlinear element model

III. CO$_2$ EMISSION AND COST OPTIMIZATION METHODOLOGY FOR REINFORCED CONCRETE FRAME DESIGNED BY PBD

Three objective functions, i.e., CO$_2$ emissions (tonf), total material cost (USD), COV of interstory drift ratio (%) are minimized while satisfying the constraints on strength of sections, constructability, minimum and maximum reinforcement ratio, SCWB requirement and interstory drift ratio. The amounts of concrete and steel of reinforced concrete frame is determined minimizing objective functions and satisfying constraint conditions by NSGA-II.

A. Objective Functions

First two objective functions minimize CO$_2$ emissions and total material cost:

$$\text{Minimize } f_1 = V_C \rho_C E_C + V_S \rho_S E_S \quad (1)$$

$$\text{Minimize } f_2 = V_C \rho_C C_C + V_S \rho_S C_S \quad (2)$$

where V and ρ are volume and density of structural material, respectively. E and C are the unit CO$_2$ emissions [6], [7] and cost [5] of structural material, respectively. Subscripts s and c represent steel reinforcement and concrete, respectively. Unit CO$_2$ emissions and cost of structural material varies according to strength of material and LCA database are obtained from other related researches. [5]-[7]

Third objective function minimizes COV of interstory drift ratio:

$$\text{Minimize } f_3 = \text{Standard deviation}(IR_n) / \text{Average}(IR_n) * 100 \quad (3)$$

where IR is interstory drift ratio acquired by nonlinear static pushover analysis and Subscripts n is 1 to number of stories. This objective function is added to assure more performance ability of structure. It is because when structure is experienced earthquake, if seismic response of interstory drift ratio is not uniform, weak story is occurred and structure could have more damages.

B. Constraint Conditions

Total 9 constraint conditions are considered as below. 8 constraint conditions are to satisfy code regulation according to IBC 2012, ASCE 7-10 and ACI 318-11 and one constraint condition (c_5) is to satisfy designated performance objective from PBD approach (FEMA 356). Shear strength condition is optimized manually to reduce optimization time while considering prevention of brittle shear failure of element.

$$c_1 = Mu_b{}^i / Mn_b{}^i \leq 1.0 \quad (4)$$

where $Mu_b{}^i$ and $Mn_b{}^i$ is factored moment and flexural strength of i th beam, respectively.

$$c_2 = PMu_c{}^i / PMn_c{}^i \leq 1.0 \quad (5)$$

where $PMu_c{}^i$ is factored axial load and moment interaction and $PMn_c{}^i$ is axial and flexural strength interaction of i th column.

$$c_3 = D_C{}^{upper} / D_C{}^{lower} \leq 1.0 \quad (6)$$

where $D_C{}^{upper}$ and $D_C{}^{lower}$ are depth of upper and lower column, respectively.

$$c_4 = A_{sb,\min}{}^i / A_{sb}{}^i \leq 1.0 \quad (7)$$

where $A_{sb,\min}{}^i$ and $A_{sb}{}^i$ are minimum steel reinforcement area and steel reinforcement area for i th beam, respectively.

$$c_5 = \Delta_{\max,nonlinear} / \Delta_{a,nonlinear} \leq 1.0 \quad (8)$$

where $\Delta_{\max,nonlinear}$ and $\Delta_{a,nonlinear}$ are maximum interstory drift ratio and allowable interstory drift ratio to assure designated performance objective when nonlinear static analysis is performed.

$$c_6 = \Delta_{\max,linear} / \Delta_{a,linear} \leq 1.0 \quad (9)$$

where $\Delta_{\max,linear}$ and $\Delta_{a,linear}$ are maximum interstory drift ratio and allowable interstory drift ratio to consider intended performance of prescriptive code when elastic analysis is performed.

$$c_7 = A_{sb}{}^i / A_{sb,\max}{}^i \leq 1.0 \quad (10)$$

where $A_{sb,\max}{}^i$ and $A_{sb}{}^i$ are maximum steel reinforcement area and steel reinforcement area for i th beam, respectively.

$$c_8 = A_{sc,\min}{}^i / A_{sc}{}^i \le 1.0 \tag{11}$$

where $A_{sc,\min}{}^i$ and $A_{sc}{}^i$ are minimum steel reinforcement area and steel reinforcement area for i th column, respectively. Maximum steel reinforcement area is not considered since all of steel reinforcement area is less than limit when optimization result is acquired.

$$c_9 = [1.2 * \sum Mn_b]^i / [\sum Mn_c]^i \le 1.0 \tag{12}$$

where $\sum Mn_b$ and $\sum Mn_c$ are the sum of flexural strength of beams and columns at i th joint, respectively. This constraint condition is for SCWB requirement according to ACI 318-11.

C. Optimal Design Procedure

Fig. 2 shows a flow chart of the proposed optimal design method using NSGA-II. After setting parameters as design variables, such as concrete dimension and steel reinforcement diameter, values of individual (building) for first population is randomly initialized. Then elastic analysis and nonlinear static analysis are performed for individuals. The reason why elastic analysis is performed to satisfy code regulation is that prescriptive code is a law. However as mentioned earlier, prescriptive code based design cannot certainly assure intended performance objective. Performance objective of ASCE 7-10 is collapse prevention for earthquake having 2% probability of exceedance in 50 years. Therefore, PBD approach having same performance objective is applied by nonlinear static analysis and design result will be more reliable for intended performance of building. Various performance objectives different with code can be applied by proposed method as needed. After analyses are completed, objective functions and constraint conditions are calculated. When all individuals of current generation are evaluated, rank and crowding distance of all individuals are calculated. If generation number is not met up to designated number, individuals for current population is modified by selection, crossover, mutation operators.

TABLE I
DESIGN VARIABLES OF REINFORCED CONCRETE FRAME

No.	Design variable	Range	Remark
1	Width of column	300-800 mm	Increment 50 mm
2	Size of column reinforcement	D22,D25, D29,D32	
3	Number of column reinforcement	8,12,16 EA	
4	Width of beam	300-500 mm	Increment 50 mm
5	Depth of beam	1.5 to 2.5 times of width of beam	
6	Size of beam reinforcement	D19,D22,D25	
7	Number of tension reinforcement of beam	3-12 EA	Increment 1 EA
8	Strength of concrete	24,27,30,35,40,50 MPa	
9	Strength of steel reinforcement	300,400,500 MPa	

[a] Section of column is square.

[b] Number of compression reinforcement of beam is half of tension reinforcement

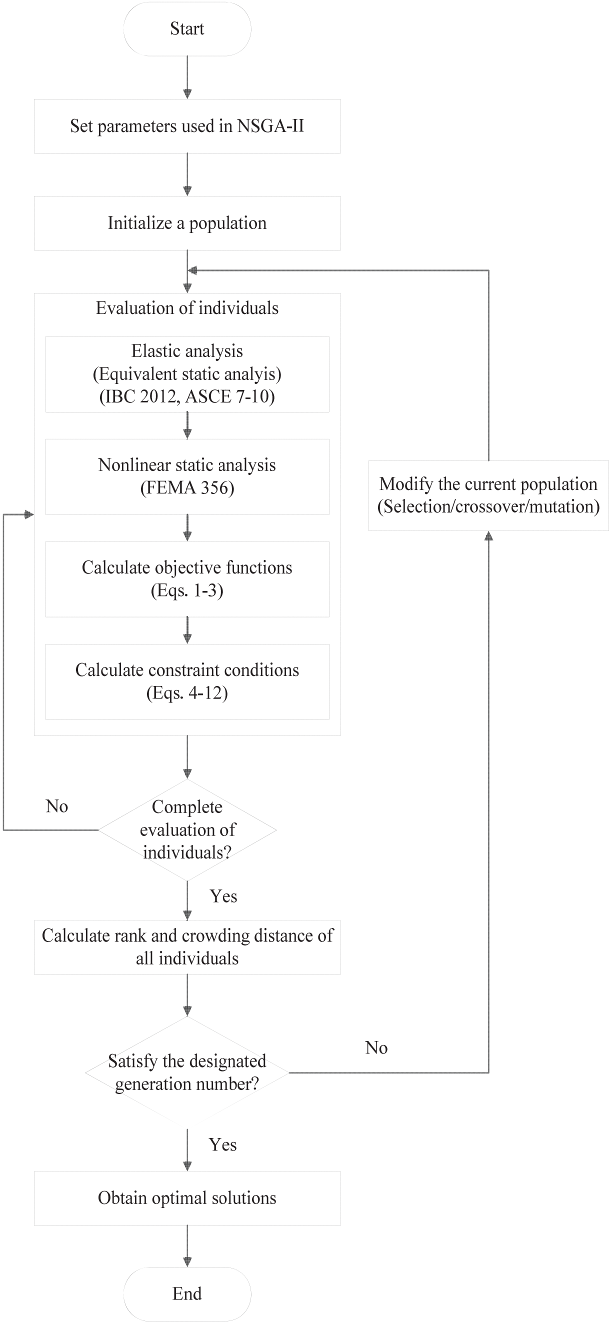


Fig. 2 Flow chart of the proposed optimal design method

IV. APPLICATION

A. Example Structure and Target Performance Objective

Proposed optimal design method is applied to 4 story and 4 span reinforced concrete frame as shown Fig. 3. Columns are grouped symmetrically and beams are grouped for each story. It is assumed that example structure located Los Angeles which is posed to strong earthquake. 0.2 second spectral acceleration, 1 second spectral acceleration and site class are assumed to 1.62g, 0.62g and D, respectively. As per the ASCE 7-10, building is classified to special moment frame system.

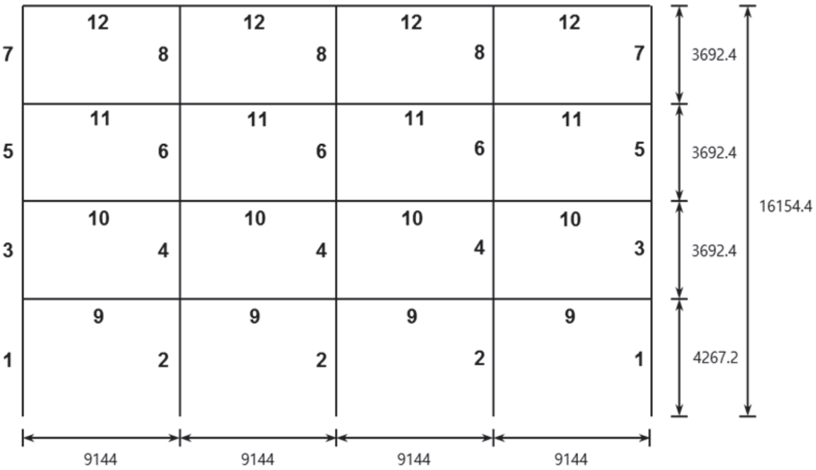


Fig. 3 Example 4 story and 4 span reinforced concrete frame (Unit: mm)

Performance objective for PBD approach is designated as same performance objective that ASCE 7-10 intended. (Collapse prevention for earthquake having 2% probability of exceedance in 50 years.) Maximum interstory drift ratio is 2.5% for elastic analysis as per the ASCE 7-10 and 4% for nonlinear pushover analysis according to the FEMA 356.

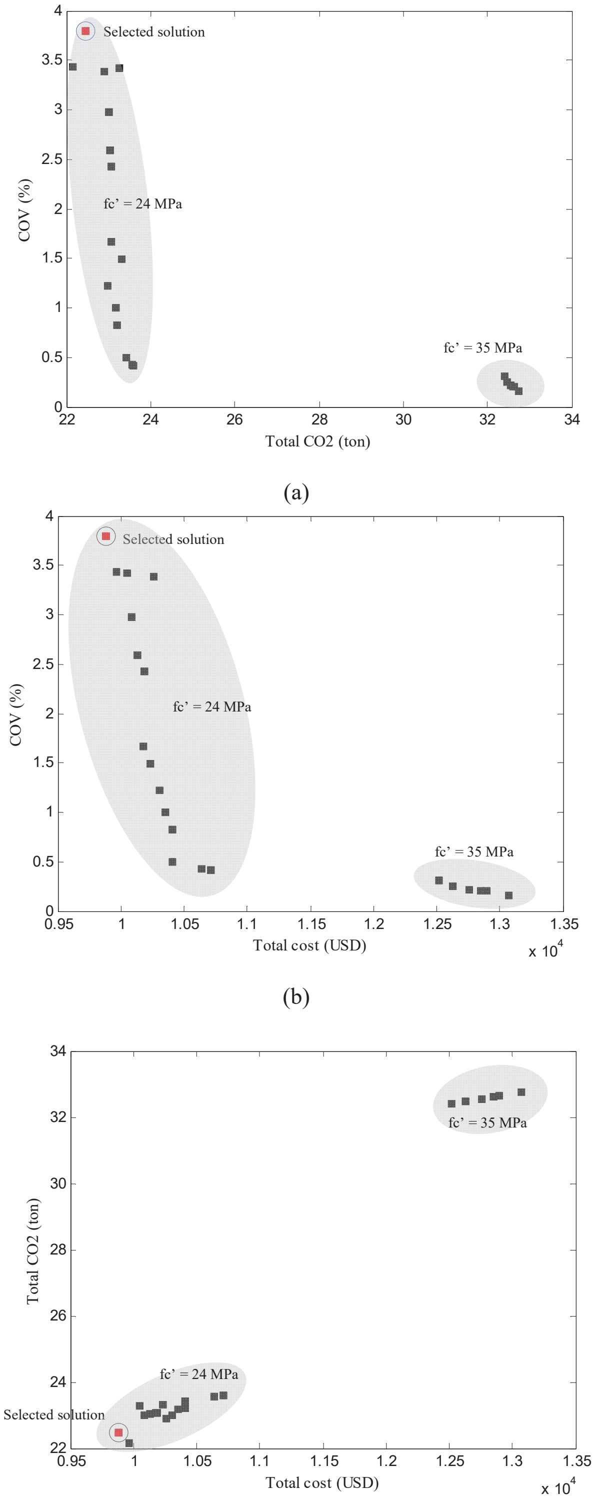
B. Application of Proposed Optimization Method

Element group's design variables used to optimization of example structure are set as shown Table I. Shear reinforcements of steel for beams are assumed to be arranged at intervals of 100 mm from joint face to 1500 mm and intervals of 300 mm for the rest. Shear reinforcements of steel for columns are assumed to be arranged at intervals of 100mm throughout the length of column. Diameter of all steel reinforcement for shear is assumed to 13 mm bar (D13). Steel reinforcement for shear is optimized manually in separate manner. Objective functions and constraint conditions are set as Section III. Generation and population sizes are set to 200 and 32, respectively. Fig. 4 shows the pareto front of optimization result. Since number of objective functions are three, three 2-dimensional graphs are obtained. As COV of interstory drift ratio is decreased, CO_2 emissions, total material cost and strength of concrete tend to increase. However, strength of concrete is not increased up to maximum design variable. On the contrary to this, as COV of interstory drift ratio is increased, CO_2 emissions, total material cost and strength of concrete tend to decreased. Strength of concrete have smallest value when CO_2 emissions and total material cost are relatively small. Also, as CO_2 emissions is increased, total material cost tend to increase. All individuals' strength of steel reinforcement is 500MPa. Among optimized solutions, solution having relatively small CO_2 emissions and total material cost is selected to analyze since CO_2 emissions and total material cost are major interests for engineers, owner and related people and COV of interstory drift ratio of selected solution is not that large (3.79%).

Table II represents optimized design variables for selected solution. Selected solution's total CO_2 emissions, total cost and COV of interstory drift ratio are 22.47 tonf, 9882 US dollars and 3.79%, respectively. Fig. 5 represents constraint condition ratios of all constraint conditions except third constraint condition (c3) for constructability. These results show that constraint conditions for flexural strength (c1), interstory drift ratio from elastic analysis (c6), minimum steel reinforcement area (c8) and SCWB requirement (c9) are over 0.95. These imply that code based design is slightly more conservative than PBD approach for assuring same performance objective and flexural strength condition is critical due to SCWB requirement. As concrete dimension of column is determined by flexural strength condition and SCWB requirement, even though columns' minimum steel reinforcement ratios are almost near minimum limit there is some margin for columns' axial and flexural strength. (c2)

TABLE II
DESIGN VARIABLES OF OPTIMIZED RESULT

GroupNo.	Width of section	Depth of section	Size of steel reinforcement	Number of steel reinforcement
1	550 mm	550 mm	D22	8
2	700 mm	700 mm	D25	16
3	550 mm	550 mm	D25	12
4	650 mm	650 mm	D32	8
5	550 mm	550 mm	D29	12
6	600 mm	600 mm	D29	12
7	300 mm	300 mm	D25	12
8	550 mm	550 mm	D22	8
9	400 mm	650 mm	D25	6
10	350 mm	750 mm	D22	6
11	350 mm	550 mm	D22	7
12	300 mm	700 mm	D19	8



(a)

(b)

(c)

Fig. 4 Distribution of the optimal solutions

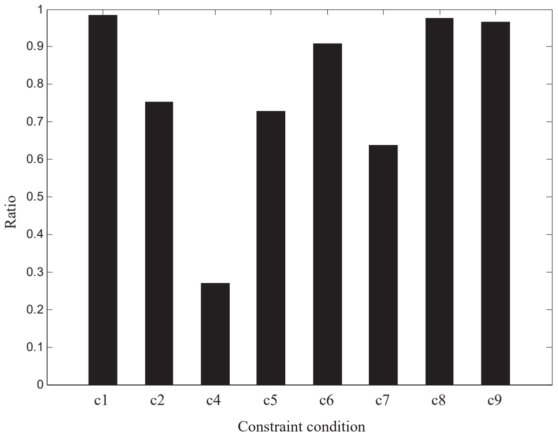


Fig. 5 Constraint condition ratios

V. CONCLUSION

In this study, CO_2 emission and cost optimization method of reinforced concrete frame designed by PBD approach is proposed. 4 story and 4 span reinforced concrete frame was optimized by proposed method. Optimized results show that strength of concrete has smallest value and strength of steel reinforcement has largest value to extremely minimize CO_2 emission and total material cost and prescriptive code is slightly more conservative than PBD approach in terms of assuring same performance objective. However, these results are especially for strong earthquake area and low-rise building. Thus, result for weak or medium earthquake area or high-rise building may be different from results of this paper.

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