A TRIAL DESIGN OF STEEL FRAMED OFFICE BUILDING BASED ON AN OPTIMUM DESIGN METHOD

M. Keii[1], K. Ikago[2], Y. Lee[3] and K. Uetani[4]

[1] *General Manager, Dept. of Structural Engineering, NIKKEN SEKKEI, Tokyo Japan*
[2] *Associate Professor, Graduate School of Engineering, Tohoku University, Sendai Japan*
[3] *Researcher, Graduate School of Engineering, Kyoto University, Kyoto Japan*
[4] *Professor, Graduate School of Engineering, Kyoto University, Kyoto Japan*
Email: ikago@archi.tohoku.ac.jp

ABSTRACT :

Until now, many researches on optimum design of building structures have been made, and improving performance of computers enabled us to solve large and complicated optimum design problems numerically. However, the optimum designs given by conventional optimum design methods don't necessarily provide directly acceptable optimum solutions for practical structural design at the present time.
In this paper, we clarify the point to build an optimum design system which is to give optimum designs suitable for practical structural design by showing an example using an optimum design method considering constraints required by actual design in practice within the framework of the Building Standard Law of Japan.

KEYWORDS: Optimum design, Discrete-variable optimization, Gradient projection method, Design support tool

1. INTRODUCTION

Until now, many researches on optimum design of building structures have been made, and improving performance of computers enabled us to solve large and complicated optimum design problems numerically. However, the optimum designs given by conventional optimum design methods don't necessarily provide directly acceptable optimum solutions for practical structural design at the present time.

Many case studies are required to obtain an acceptable and desirable design which satisfies various constraints required by architectural planning, building code, standards or guidelines provided by architectural societies. Purposes of optimum design programs vary depending on the design stages; a preliminary design stage in which structural designers study efficient layouts of structural members, a basic design stage in which they choose materials and structural form, and final design stage in which structural designers decide the sizes of each members. And each design stage requires many case studies for decision-making.

Despite of requirements for many case studies, many structural designers would like to cope with such problems depending on their experience without making any case study, because they can't afford the time and cost to make such many case studies.
While conventional optimum design methods can't meet the aforementioned requirements, we show in this paper that an acceptable and desirable design can be obtained performing many case studies using a practical optimum design program which takes various practical constraints into account. A trial design of a steel framed office building shown in this paper shows that we can easily perform comparative case studies on requirements quantitatively for decision-making at a detail design stage.

Although many problems must be solved to put this optimum design system—a structural design support tool—to practical use, we expect that we can establish a new design method by which structural engineers don't need to depend on their intuition derived from their experiences when they design building structure any more.

2. FORMULATION OF AN OPTIMUM DESIGN PROBLEM

In this paper we formulate an optimum design problem for a realistic steel framed structure whose; design variables are sizes of structural members; constraints consist of inequalities on performance which design solutions should satisfy; objective function, which is closely related to cost of the structure, is total weight of the steel given by the design variables. The formulation of the problem ODPSF (Optimum Design Problem for a Steel Frame) is shown below.

ODPSF	find	$\mathbf{x} = \{x_i\}$
	to minimize	$W(\mathbf{x})$
	subject to	$\mathbf{g}(\mathbf{x}) = \{g_j\} \le 0$

Where x_i (unit: mm) denotes a size of a steel member, *i.e.*, depth or width of the steel member, or thickness of steel plate. $W(\mathbf{x})$ is total mass (unit: ton) of the structure and is function of $\mathbf{x}$. The inequality $\mathbf{g}(\mathbf{x}) \le 0$ stands for constraints that design variable $\mathbf{x}$ have to satisfy.
Detailed explanation for those variables and functions are described below.

2.1. Objective function, design variables and constraints

2.1.2. Design variables

A design variable $\mathbf{x}$ is a vector whose *i*-th component x_i (unit: mm) stands for depth or width of a steel member, or thickness of a steel plate. Each component of the design variable $\mathbf{x}$ has to be discrete, because sizes of steel members used for buildings have discrete value. For example, depth or width of the member may have such discrete values as; 100, 125, 150, 175, $\cdots$, and thickness of steel plates may have such discrete values as; 6, 9, 12, 16, $\cdots$. At the first step the design variable is handled as a continuous variable to relax the discrete optimization problem into a continuous one, which is easier to solve, to obtain an initial design to be inputted to the discrete optimization problem next step.

2.1.2. Objective function

In the practical structural design, engineers usually grasp and control the total mass of the steel they use to design a building frame. So, the total mass of the steel is very important index to evaluate the design.
Let area and length of a *k*-th steel member — column, girder or brace — be $A_k(\mathbf{x})$ and l_k respectively, the objective function $W(\mathbf{x})$ may be expressed as follows:

$$W(\mathbf{x}) = \sum \rho A_k(\mathbf{x}) l_k \tag{1}$$

Where ρ is density of steel (=7.8ton/m^3).

2.1.2. Inequality constraints

Requirements in practical structural design can be expressed as inequalities as follows.

$$g_j(\mathbf{x}) \le 0 \tag{2}$$

For example, let *j*-th design requirement be a constraint of a member stress $\sigma_k(\mathbf{x})$ which is to be smaller than allowable stress σ_A, following inequality holds.

$$g_j(\mathbf{x}) = \sigma_k(\mathbf{x}) - \sigma_A \le 0 \tag{3}$$

Thus, we can also express other design requirements as inequalities, and can define a constraint vector $\mathbf{g}(\mathbf{x})$.

3. OPTIMIZATION METHODS

Yoshitomi et.al.[2] proposed a solution method which divide a discrete optimum design problem into two problems, continuous (relaxed) optimum design problem whose continuous design variable approximate the distribution of the standard sections, and discrete optimum design problem using the solution obtained from the former problem as an initial design. We herein employ this method to solve the optimum design problem.

The proposed method features in using a continuous optimization in seeking discrete sections. At first, as shown in Figure 1, we solve a continuous optimization problem and obtain candidate sections, whose sizes are discrete, near the continuous solution. Sequentially, we perform another optimization to seek another set of candidates until the design doesn't improve the objective function any more.

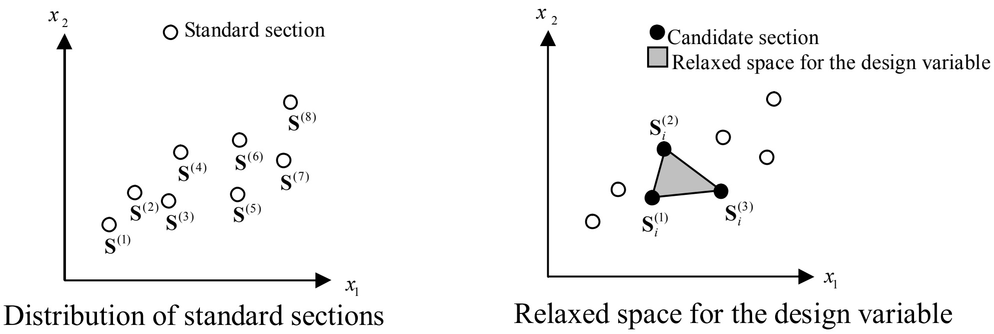

Figure 1 Relaxation of the discrete optimum design problem

If the constraint functions have strong non-linearity, the sensitivities of the objective function are effective only in the close area around the present design. Gradient projection method [3] we employ herein is very effective to solve such problems.

As illustrated in Figure 2, an optimum design is sought repeating a set of modifications of present design;
(1) a modification based on "projection move vector" $\Delta\mathbf{X}_{\text{proj}}$, which is projection of the steepest descent vector of objective function $-\nabla W$ to the equality constraint plane and, (2) another modification based on "restoration move vector" $\Delta\mathbf{X}_{\text{resto}}$ which is to compensate the error caused by the non-linearity of the constraint function.

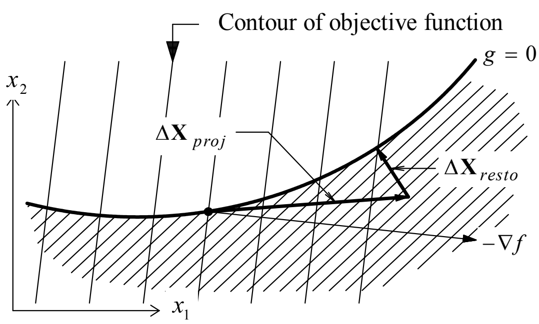

Figure 2 Gradient Projection Method

4. Example

4.1. Analysis model for a trial design

A design problem for 14-storey steel framed office building model is employed to discuss points on practical usage of the optimization method. As Figure 4 shows, this model has typical plan as an office building: elevator shafts and stair-cases are located on one side of the plan, and the other side is located 16-m spanned office space. Storey-height of the first storey is 6 m and those of typical floors (2nd to 14th floor) are 4m.

4.2. Design requirements and assumptions

Design requirements and assumptions we made to create the design example model are listed below.

(1)Steel of 490 N/mm^2 tensile class is employed for columns and girders. Shapes used for column sections are built-up wide-flange sections (for external columns) and built-up steel box sections (for internal columns). Only built-up wide-flange sections are selected for girders.

(2)Design of each section member is based on the allowable stress concept, that is, each section member is designed in such a manner that member stresses caused by permanent loads and combinations of permanent and temporary loads are to be smaller than allowable stresses. When we calculate long-term stress at each end of the members, we use bending moments at joints. Stresses derived from member face moment by temporary loads (X and Y-directional, forward and backward horizontal loads) are added to long-term stresses to obtain short-term stresses.

(3)Composite effect of steel girder united with reinforced concrete slab is taken into account and girder stiffness is augmented.

(4)Design of foundation girder is given (reinforced concrete section whose width is 900mm and depth is 1500mm), so sizes of foundation girders are not design variables. We assume that the given section of the foundation girders have enough strength so that they won't yield even if the structure is subjected to horizontal forces.

(5)Design of piles is also given. Piles are modeled as foundation springs which have characteristics as illustrated in Figure 3. Axial forces of piles caused by moderate earthquakes are constrained to be smaller than 2/3 of the ultimate strength—which is defined short-term allowable strength for piles—for compression and tension respectively, while no constraint is introduced for severe earthquakes.

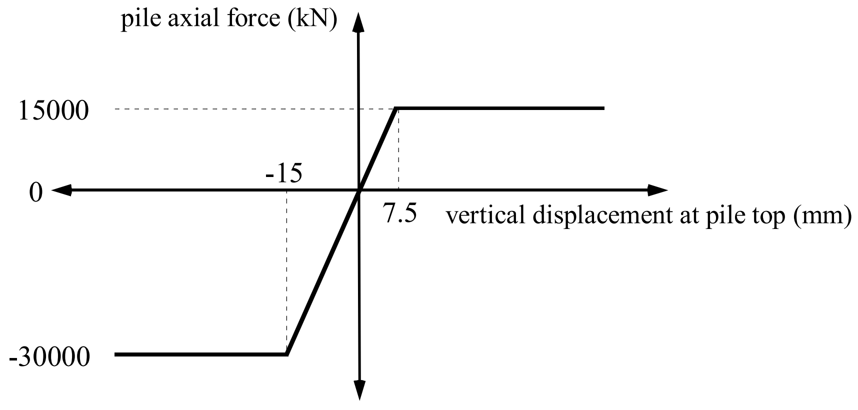

Figure 3. Restoring force model of piles

(6)Permanent load and seismic load are set as shown in Table 1. External girders bear 10kN/m of exterior wall weight distributed along them.
Design seismic load is determined according to Building Standard Law of Japan.

4.3. Member sizes and design variables

In concrete, design variables we have already explained in section 2.1. may be set as follows.

(1)Design variables for columns: Sizes of a wide-flange section, depth, width, web thickness and flange thickness are set as variables independent of each other. For a box section, depth and plate thickness are set as independent variables.

(2)Design variables for girders: Sizes of a wide-flange section, depth, width, web thickness and flange thickness are set as independent variables.

(3)Design variables for braces: Brace area is set as a design variable.

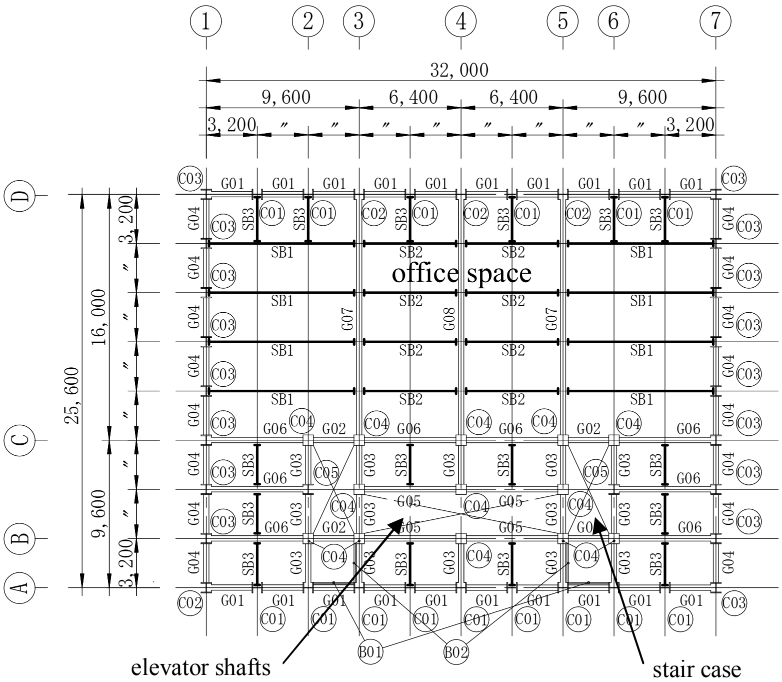

Figure 4. Plan of the example model

Table.1 Design Load [Unit:N/m²]

Office	・concrete slab	t=145mm	3,480N/m²
	・deck plate		200N/m²
	・finish (free access floor)	t=100	1,000 N/m²
	total		4,680 N/m²
Roof	・concrete slab	t=145mm	3,480N/m²
	・deck plate		200N/m²
	・finish (asphalt water proof)	t=100	2,600 N/m²
	total		6,280 N/m²
Stair case	steel stair case		2,500 N/m²

A. Dead Load

room	for floor design	for frame design	for seismic design
office	2,900	1,800	800
stair case, corridor	1,800	1,300	600
roof	1,800	1,300	600

B. Live Load

4.4. Constraints

Until now, few researches have aimed at broad practical usage of optimum design method, because most of conventional researches on optimum design have confined their interest to individual structural problems. Some of them are hard to apply to practical design problems directly because their interest is far from practical interest. We herein aim at considering most of the constraints which is required within the framework of

Building Standard Law of Japan and can be expressed by inequalities.
Constraints we employ in the example are listed in Table 2.

Table 2. Constraints

bounds of sizes (side constraints)	girders	Constraints on girder depth *H*. $300mm \le H \le 750mm$ (G01-G06) $300mm \le H \le 900mm$ (G07,G08) Constraints on girder width *B*. $150mm \le B \le 400mm$ (G01-G06) $200mm \le B \le 500mm$ (G07,G08) Constraints on plate thickness. t_w :web thickness, t_f :flange thickness $6mm \le t_w \le 16mm$, $9mm \le t_w \le 36mm$ (G01-G06); $6mm \le t_f \le 19mm$, $9mm \le t_f \le 32mm$ (G07-G09)
	columns	$300mm \le H \le 600mm$, $300mm \le B \le 600mm$ $9mm \le t_w \le 30mm$, $9mm \le t_f \le 70mm$ (Wide-flange) $200mm \le D \le 800mm$, $16mm \le t \le 40mm$ (Box section)
	braces	Constraint on brace area *A*. $5cm^2 \le A \le 100cm^2$
constraints on width-thickness ratio	girders columns	$2t_f / B \le 7.7$, $t_w /(H - 2t_f) \le 51.0$ $2t_f / B \le 8.1$, $t_w /(H - 2t_f) \le 36.6$ (Wide-flange) $t / D = 28.1$ (Box section)
stress constraints for moderate earthquakes	girders columns	$\left\|\frac{M_y}{f_b Z_y}\right\| + \left\|\frac{M_z}{f_t Z_z}\right\| + \left\|\frac{N}{f_c A}\right\| \le 1.0$ M_y : bending moment around strong axis M_z : bending moment around weak axis N : axial force f_b : allowable bending stress f_t : allowable tensile stress f_c : allowable compressive stress
constraints on inter-storey drift	for each storey	$\delta_i / h_i \le 1/200$ δ_i : inter-storey of *i*-th floor, h_i : *i*-th storey height
constraints on pile axial forces	at pile top	$-30000\text{kN} \le R \le 15000\text{kN}$ R : pile axial force
constraints on column-girder strength ratio	for each storey	$1.5\sum M_B \le \sum M_{CL} + \sum M_{CU}$ $1.3\sum M_{PP} \le \sum M_{CL} + \sum M_{CU}$ M_B : plastic bending moment of girder M_{CL} :plastic bending moment at bottom of column M_{CU} :plastic bending moment at top of column
constraints on horizontal resistant forces	for each storey	$Q_{UN} \le Q_U$ Q_{UN} :required horizontal resistant strength Q_U :ultimate horizontal resistant force of the structure

5.Result of the optimization

Table 3. shows the optimum design obtained from the proposed method. In case A.Ⓓ ends of the long spanned girders (G07,G08) are pin connected while in case B they are rigidly connected. Obviously, the condition of the connections at girder end affects the result of column sizes connected to the long spanned girders.

Table 3. Result of optimization

Case A. Ⓓ end of long spanned girders (G07,G08) are pin connected.

STORY	List of Girder	H(mm)	B(mm)	tw(mm)	tf(mm)	STORY	List of Column	H(mm)	B(mm)	tw(mm)	tf(mm)	STORY	List of Brace	Area(cm^2)
2 F ~ 4 F	G01	H−600	× 200	× 14	× 16	1 F ~ 2 F	C01	H−550	× 550	× 16	× 36	1 F	B01	65
	G02	H−600	× 300	× 14	× 22		C02	H−550	× 550	× 16	× 36		B02	65
	G03	H−600	× 250	× 12	× 19		C03	□−400	× 400	× 16	× 16	2 F	B01	65
	G04	H−600	× 250	× 12	× 19		C04	H−550	× 550	× 16	× 36		B02	65
	G05	H−600	× 300	× 14	× 22		C05	H−550	× 550	× 16	× 40	3 F	B01	65
	G06	H−600	× 250	× 12	× 19								B02	65
	G07	H−800	× 300	× 16	× 22							4 F	B01	65
	G08	H−800	× 350	× 19	× 25								B02	65
5 F ~ 7 F	G01	H−600	× 200	× 12	× 16	3 F ~ 5 F	C01	H−550	× 550	× 14	× 36	5 F	B01	65
	G02	H−600	× 300	× 14	× 22		C02	H−550	× 550	× 16	× 36		B02	65
	G03	H−600	× 250	× 12	× 19		C03	□−400	× 400	× 16	× 16	6 F	B01	65
	G04	H−600	× 200	× 12	× 16		C04	H−550	× 550	× 16	× 36		B02	65
	G05	H−600	× 250	× 14	× 19		C05	H−550	× 550	× 16	× 36	7 F	B01	65
	G06	H−600	× 250	× 12	× 19								B02	65
	G07	H−800	× 250	× 16	× 19							8 F	B01	65
	G08	H−800	× 350	× 19	× 25								B02	65
8 F ~ 10 F	G01	H−600	× 200	× 12	× 14	6 F ~ 8 F	C01	H−550	× 550	× 16	× 36	9 F	B01	65
	G02	H−600	× 300	× 14	× 22		C02	H−550	× 550	× 19	× 36		B02	65
	G03	H−600	× 250	× 12	× 19		C03	□−400	× 400	× 16	× 16	10 F	B01	65
	G04	H−600	× 200	× 12	× 16		C04	H−550	× 550	× 16	× 36		B02	65
	G05	H−600	× 300	× 14	× 22		C05	H−550	× 550	× 16	× 36	11 F	B01	65
	G06	H−600	× 250	× 12	× 19								B02	65
	G07	H−800	× 300	× 16	× 19							12 F	B01	65
	G08	H−800	× 350	× 19	× 25								B02	65
11 F ~ 14 F	G01	H−550	× 175	× 12	× 14	9 F ~ 11 F	C01	H−550	× 550	× 19	× 36	13 F	B01	65
	G02	H−550	× 300	× 14	× 25		C02	H−550	× 550	× 16	× 36		B02	65
	G03	H−550	× 200	× 12	× 16		C03	□−400	× 400	× 16	× 16	14 F	B01	65
	G04	H−550	× 200	× 12	× 16		C04	H−550	× 550	× 16	× 40		B02	65
	G05	H−550	× 250	× 14	× 22		C05	H−550	× 550	× 19	× 36			
	G06	H−550	× 250	× 12	× 19									
	G07	H−800	× 250	× 16	× 19									
	G08	H−800	× 350	× 19	× 25									
Roof	G01	H−650	× 300	× 14	× 22	12 F ~ 14 F	C01	H−550	× 550	× 16	× 36			
	G02	H−650	× 350	× 14	× 25		C02	H−550	× 550	× 16	× 36			
	G03	H−650	× 300	× 14	× 22		C03	□−400	× 400	× 16	× 16			
	G04	H−650	× 350	× 14	× 25		C04	H−550	× 550	× 22	× 36			
	G05	H−650	× 350	× 14	× 25		C05	H−550	× 550	× 16	× 36			
	G06	H−650	× 300	× 14	× 22									
	G07	H−850	× 350	× 19	× 25									
	G08	H−850	× 400	× 19	× 25									

Case B. Ⓓ end of long spanned girders (G07,G08) are rigidly connected.

STORY	List of Girder	H(mm)	B(mm)	tw(mm)	tf(mm)	STORY	List of Column	H(mm)	B(mm)	tw(mm)	tf(mm)	STORY	List of Brace	Area(cm^2)
2 F ~ 4 F	G01	H−600	×200	×12	×12	1 F ~ 2 F	C01	H−550	×550	×16	×36	1 F	B01	20
	G02	H−600	×200	×12	×14		C02	H−550	×550	×16	×65		B02	45
	G03	H−600	×300	×12	×22		C03	H−550	×550	×16	×36	2 F	B01	40
	G04	H−600	×150	×12	×12		C04	□−650	×650	×25	×25		B02	55
	G05	H−600	×150	×12	×12		C05	H−550	×550	×16	×32	3 F	B01	45
	G06	H−600	×175	×12	×12								B02	35
	G07	H−900	×300	×19	×25							4 F	B01	45
	G08	H−900	×250	×19	×22								B02	35
5 F ~ 7 F	G01	H−550	×175	×12	×16	3 F ~ 5 F	C01	H−550	×550	×16	×32	5 F	B01	40
	G02	H−550	×175	×12	×12		C02	H−550	×550	×16	×55		B02	40
	G03	H−550	×200	×12	×16		C03	H−550	×550	×16	×32	6 F	B01	40
	G04	H−550	×200	×12	×14		C04	□−600	×600	×22	×22		B02	45
	G05	H−550	×150	×12	×12		C05	H−550	×550	×16	×32	7 F	B01	35
	G06	H−550	×175	×12	×12								B02	45
	G07	H−900	×300	×19	×22							8 F	B01	35
	G08	H−900	×250	×19	×22								B02	35
8 F ~ 10 F	G01	H−550	×175	×12	×12	6 F ~ 8 F	C01	H−550	×550	×16	×32	9 F	B01	30
	G02	H−550	×175	×12	×12		C02	H−550	×550	×16	×50		B02	30
	G03	H−550	×200	×12	×14		C03	H−550	×550	×16	×36	10 F	B01	45
	G04	H−550	×200	×12	×14		C04	□−550	×550	×25	×25		B02	45
	G05	H−550	×150	×12	×12		C05	H−550	×550	×16	×36	11 F	B01	45
	G06	H−550	×175	×12	×12								B02	55
	G07	H−900	×350	×19	×25							12 F	B01	35
	G08	H−900	×250	×19	×19								B02	35
11 F ~ 14 F	G01	H−400	×175	×9	×14	9 F ~ 11 F	C01	H−550	×550	×16	×32	13 F	B01	30
	G02	H−400	×150	×9	×9		C02	H−550	×550	×16	×40		B02	30
	G03	H−400	×175	×9	×12		C03	H−550	×550	×16	×36	14 F	B01	35
	G04	H−400	×150	×9	×12		C04	□−500	×500	×22	×22		B02	45
	G05	H−400	×150	×9	×12		C05	H−550	×550	×16	×32			
	G06	H−400	×175	×9	×12									
	G07	H−900	×350	×19	×22									
	G08	H−900	×300	×19	×19									
Roof	G01	H−500	×150	×12	×12	12 F ~ 14 F	C01	H−550	×550	×16	×36			
	G02	H−500	×250	×12	×19		C02	H−550	×550	×16	×55			
	G03	H−500	×300	×12	×25		C03	H−550	×550	×16	×36			
	G04	H−500	×175	×12	×14		C04	□−450	×450	×19	×19			
	G05	H−500	×200	×12	×14		C05	H−550	×550	×16	×36			
	G06	H−500	×150	×12	×12									
	G07	H−900	×400	×19	×32									
	G08	H−900	×300	×19	×22									

The discrete optimum design obtained from present method directly satisfies the requirements of practical design. And structural engineers in practice can refer to and use the optimum designs obtained from present method when they conduct a final design of buildings.

What we realized through the example is noted as follows.

(1)Some trials are needed for us to obtain the final solution shown in Table 3. For example, it took a lot of time to solve and we obtained a "checkerboard pattern" solution—the section given by the solution vary extremely between adjoining members—when we assigned independent variables to each member. In practical design, checkerboard pattern solution is unacceptable because it is common that members which have similar lengths or areas are grouped together and given same section.

(2)If a design variable has small effect to reduce the objective function, the design variable won't also be reduced. Therefore unacceptably large section may be obtained as an optimum design if we assign an independent design variable to a member size. This means grouping of design variables is important.

To avoid such problems noted above and to obtain a reasonable and practical design solution, we need to find out effective constraints and groupings of design variables. Control of constraints and groupings which determine quality of the solution is the point structural designers have to be involved. In the present example, we obtained the good practical design solution through the member grouping shown in Figure 3. which is derived from some trial optimizations.

Further studies which we think have to be done are listed below.

(1)While different sections are used for end part and central part of a girder member in common practical design, the girder member in the present example has unified section. So, independent design variable should be introduced to end and central part of a girder member.

(2)Check of panel zone strength at beam-column joint should be taken into account.

(3)Effective member grouping and effective constraints to obtain reasonable design solution should be proposed by conducting many optimizations using present method.

6.Conclusions

Most of conventional researches on optimum design have confined their interest to individual structural problems. Some of them are hard to apply to practical design problems directly because their interest is far from practical interest. We proposed an optimization method considering most of the constraints which is required within the framework of Building Standard Law of Japan and can be expressed by inequalities. It is shown by an example using a realistic building model that we can directly obtain a practical design consisting of discrete member sizes. We pointed out that appropriate member grouping and control of constraints are key factor to obtain a desirable solution. Especially, constraints have close relationship to performance of a building structure such as safety factor of members and deformation of structures. Therefore, control of constraints means control of performance

We are going to take more detailed constraints into account and widen the coverage of present method. It is expected that this optimization program is widely used in practical structural design.

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