REFERENCES

1. B. Bedenik, "SET-Structural Engineering Tool", Ellis-Horwood Ltd, Chichester, 1986.

Three-Dimensional Analysis and Optimum Design of Building Structures

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KEYWORDS

3-D Analysis, Construction sequence, Optimum design, Discrete solutions

ABSTRACT

This paper concentrates on the practical application of optimum design technique for building structures and on the techniques of three-dimensional analysis of building structures. Two unique features of structural analysis in this paper are; 1) the use of rectangular plate element with cut-outs, and 2) the consideration of the effects of construction sequence in structural analysis. The benifits of this improved analysis is materialized by the optimum design of the structure. The structural optimization is carried out in two different stages. The discrete optimum solution for the members in the structure is obtained from the pseudo continuous solution with the stress constraints. Then, the total building structure may be optimized with displacement constraints through the repeated reanalysis and redesign. These analysis and design techniques of building structure is integrated into BUILDS system.

L'Analyse de la Troisième Dimension et le Dessein Optimal des Structures du Bâtiment

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MOTS-CLÉFS:

Analyse basee sur les trois Dimensions, Sequence de Construction, Dessin Optimal, Solutions Discretes

Sommaire:

Cette these consacre aux applications pratiques de la technique du déssin optimal des structures de l'immeuble, et aux techniques de l'analyse basée sur les trois dimensions des structures de l'immeuble. Cette thèse est composée de deux figures uniques de l'analyse structurale; 1) Utilisation des éléments plats et rectangles découpés 2) Consideration des éffets de la séquence de la construction basée sur l'analyse structurale. Les bénéfices de cette analyse développée sont matérielisés par le déssin optimal de la structure. Le processus structural est procédé en deux étapes différentes. La solution discrète et optimale pour les membres de la structure est obtenue de la pseudo-solution continuelle avec les contraintes de préssion. La structure totale de l'immeuble serait optimisee par le déplacement des contraintes par réanalyse èt radessin répétés. Ces analyse et techniques du déssin de la structure de l'immeuble s'intégrent dans le system BUILDS.

INTRODUCTION

This paper emphasizes the translation of the current research in the area of optimum design of building structures into the practical application. Two techniques were introduced for that purpose. The first is the three-dimensional analysis of building structures in which the special characteristics of building structures are utilized. The second technique is the application of optimum design theory to practical structural design with discrete elements. The more sophisticated optimization model that represent the real system more accurately requires so many variables and complicated descriptive functions that only small simple structures may be treated at a reasonable expenses. The computational efforts required to solve the problems of practical size severely limit its practical applications of the optimum design techniques.

By splitting the subjected constraints into two categories, i.e., the constraints related to the member design and those related to whole structure, and having them satisfied at the different stages of design process, a effective technique that is applicable to the structural optimization of practical size is developed. These two techniques discussed in this paper are integrated into the BUILDS(integrated building design system) as subsystems (BUILDS-A and BUILDS-S) for practical use.[1]

STRUCTURAL ANALYSIS

The building is modeled as an assemblage of planar frames in arbitray directions interconnected with rigid slabs at each floor level. The followings are two unique features incorporated into the structural analysis method in this study.

Plate Element with Cut-Outs

Due to the functional requirements, such as windows, doors and other openings, a shear wall in a building frequently contains many cut-outs. It is of particular interest to structural engineers to model the shear walls with openings in buildings with a single element per story, i.e., a plane stress element which has four corner nodes and cut-outs of arbitrary shapes in it.

The stiffness matrix of a plate element with cut-outs is formed by subtracting the appropriate values of the stiffness of the portions occupied by the cutouts from the corresponding values of the stiffness of the whole element.[2]

Sequential Dead Load

The exterior column in a building is loaded roughly one-half of the dead load to which the interior column is subjected. In many design practices, however, there is a tendency that the exterior columns are designed to have nearly equal cross-sectional areas to the interior ones. Therefore, there exists a substantial inequality between the ratio of applied dead load to the cross-sectional area of an exterior column and that of an interior one. This inequality may cause a differential shortening in the exterior and interior columns of the frame. These are incorrect in reality.

In order to cope with the aforementioned problem, a progressive nature of the analysis with "one floor (or a substructure) at a time" approach, i.e. from top down to the bottom of the building, may be employed along with the concepts of "active", "inactive" and "deactived" floors. This corresponds to taking the construction sequence into account in the structural analysis. This analysis model can adequately represent the actual condition on which the structure is placed and can produce more accurate solutions.[3]

CHARACTERISTIC OF OPTIMUM DESIGN OF BUILDING STRUCTURE

In many optimization problems, the fundamental assumption used is that the design variables are continuous.[4] In reality, however, the design of building structure is mainly involved in the selection of members of discrete sizes. Therefore, optimization for such structures should be also discrete types. The design of a steel building frame is one of the typical examples.[5] Thus, the problem may be defined as finding a design variable vector b that minimizes a objective weight function as following form in general

$$\Psi_0(b) = \sum_{i=1}^{NE} W_i L_i B_i(b) \tag{1}$$

satisfying the equilibrium equations (state equations)

$$h(b,z) = k(b)Z - P(b) = 0 \tag{2}$$

and subject to the constraints

$$\Psi^c(b,z) \leq 0 \tag{3}$$

$$\Psi^s(z) \leq 0 \tag{4}$$

and

$$\Psi^d(b) \leq 0 \tag{5}$$

where b = design variable vector (moment of inertia in this paper), NE = total element number, W_i, L_i, and B_i = weight density, length, and cross sectional area of i-th element, respectively, z = state variable vector of n nodal displacements, K = n by n structural stiffness matrix. P = vector of n nodal loads, Ψ^c = critical stress constraints, Ψ^s = constraints on the nodal displacements, and Ψ^d = design variable constraints.

In this paper, the optimum solution is obtained in the pseudo continuous variables first and the discrete optimum solution is obtained later by taking discrete sizes near the optimum solutions in continuous variables.

TRANSFORMATION OF DISCRETE VARIABLES

In order that the continuous optimum solution may be obtainable, the objective function, constraints and stiffness matrices are required to be continuous and differentiable with repect to the design variables. Therefore, the discrete design variables of roled H-sections have to be transformed into the continuous variables.

In Figs. 1 and 2, the cross sectional area, and modulus of section, respectively, are plotted with the major axis moment of inertia of H-sections. The

relationships between moment of inertia and those other variables can be established by regression and some of the typical ones are given in Table I.

Instead of a single regression curve [6], two different curves are obtained in this paper based on the characteristics of section properties, i.e., the curve that represent the sections suitable for columns (HC) because of the similar dimensions of width and depth and the other curve that are suitable for beams (HB) which have larger values of moment of inertia than columns with same cross sectional areas. These distinguished two curves are clearly shown in Figs. 1 and 2.

STRUCTURAL OPTIMIZATION THROUGH ELEMENT OPTIMIZATION

The optimization of total structure with all the constraints considered at once requires a lot of computational efforts and this may limit the application of optimization in the practical problems. For an instance, the Gradient Projection Method[4] requires that all the stress constraints in the design specifications in engineering practice must be differentiable with respect to design variable. It is, however, virtually impossible to establish all such relationships with design variable. In order to avoid this difficulty, the subjected constraints are divided into two categories, i.e., 1) the constraints to be considered in the first stage optimization (element design) such as stress constraints and local member deflections and 2) the constraints to be considered in the second stage optimization (whole structure design) such as structural displacements and natural frequencies and, accordingly, the optimization of total structure is carried out in two separate stages.

Element Design Optimization -- First Stage Solutions

At the first step, the optimum solution is obtained at the individual member level with the stress constraints and the limitation of local member deflections. The variables in constraints, such as cross sectional area, modulus of section and radius of gyration, are transformed into the major axis moment of inertia by using the appropriate relationships in Table I. The moment of inertia now becomes the primary design variable. Thus, with the given loads, the continuous optimum solution can be obtained in terms of moment of inertia in accordance with fully stressed design concept.[4] Using the continuous solution as the starting point, the search technique is used to find the discrete optimum solutions, assuming that there is one near the continuous solution. With the first cycle solution obtained, reanalysis and redesign are repeated until the stop criteria is satisfied.

Structural Optimization -- Second Stage Solutions

Once the element optimization is obtained, the structural displacement and structural dynamic constraints are considered next. If the first stage solution satisfy the displacement and frequency constraints, the first stage solution can be taken as the final value of optimum design. In the case that the displacement constraints are not satisfied, the most sensitive member (or a group of members) should be identified through sensitivity analysis.[7] Then, the member (or a group of members) identified as the most sensitive one that has the largest constraint error correction vector is replaced by the member of next larger variable in the group of tabulated sections. Thus, the new (next) design point is determined. This process continues until the displacement constraints are fully satisfied and the final value of optimum design is determined. The solutions obtained by this procedure should be considered as approximate optima rather than exact ones.

NUMERICAL EXAMPLE

The frame with is elements as shown in Fig. 3 is optimized under the conditions given in the same figure. The optimal design results obtained by the method suggested in this paper are shown in Table II along with the continuous optimum results obtained by the Gradient Projection Method[7] and the discrete optimum solutions obtained by two Phase Method[8].

The computation time or the total number of iterations needed to obtain the optimum solution fȯr this particular problem by the method proposed in this study were roughly one half to one third of that needed for the structural optimization with all the constraints considered at once. It is shown that the final objective function values, i.e., the total weights in Table II are very close to each other.

CONCLUSIONS

In this paper, the optimum design of building structure through the discrete element optimization and the three-dimensional analysis of building structure which uses the special characteristics are presented. The structural optimization through element optimization gives economical solutions comparing with those from other methods. The optimization method suggested in this study was found to be applicable to the practical size problems. It is also shown that the design results obtained by this method well converge to the discrete boundary points.

ACKNOWLEDGMENTS

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REFERENCES

1. C. K. Choi, "User's Manual for Integrated Building Design System-BUILDS", (in preparation)

2. C. K. Choi and M. S. Bang, "A Simplified Plate Element with Rectangular Cutouts for Perforated Shear Wall Analysis", Proceedings of the 4th International Conference on Applied Numerical Modelling, Taiwan, (1984).

3. C. K. Choi and E. D. Kim, "Multistory Frames under Sequential Gravity Loads", J. of Str. Eng., ASCE, 111, pp. 2373-2384, (1985).

4. R. H. Gallagher and O. C. Zienkiewicz, "Optimum Structural Design", John Wiely & Sons, New York, (1978).

5. A. Raymond Toakly, "Optimum Design Using Available Sections", J. of Str. Div., ASCE, 94, pp. 1219-1241, (1978).

6. Y. Nakamura, "Optimal Design of Framed Structures Using Linear Programming", Thesis presented to the Department of Civil Engineering at the Massachusetts Institute of Technology, at Cambridge, Mass. (1966).

7. J. S. Arora and E. J. Haug Jr., "Efficient Optimal Design of Structure by Generalized Steepest Descent Programming", Int. J. for Numerical Methods in Eng., 10, pp. 747-766, (1976).

8. H. S. Lee, "Optimal Design of Structures with Specified Member Sizes", MS thesis, KAIST, Seoul, (1985).

Table I. Relationships between variables

Group	Description	Interval (cm) (Moment of Inertia)	Relationships	Coefficient of Determination
HC	Cross Sectional Area (cm^2)	$2880 \le I \le 737000$	$A=0.035\ I^{.79}+27.7$	0.99
	Modulus of Section (cm^3)		$Z=0.500\ I^{.80}-76.5$	0.99
	Radius of Gyration (cm)		$R=-84.713\ I^{-.14}+34.3$	0.98
HB	Cross Sectional Area (cm^2)	$187 \le I \le 498000$	$A=0.945\ I^{.45}+1.3$	0.97
	Modulus of Section (cm^3)		$Z=1.099\ I^{.70}-28.8$	0.99
	Radius of Gyration (cm)		$R=1.102\ I^{.27}-0.4$	0.99

Table II. Comparison of optimum design values

Element Number	Initial Design Values	This Study		Continuous Optimum Design (Ref. 7)		Discrete Optimum Design (Ref. 8)	
		1st Stage Design	2nd Stage Design	Case 1[a]	Case 2[b]	Case 1[a]	Case 2[b]
1	47600	4720	16900	5764	24369	4980	23400
2	47600	8790	28200	12296	28844	11500	28200
3	47600	2880	16900	2880	24402	2880	23400
4	40300	4720	18800	5733	22687	8790	21500
5	40300	4720	20400	6918	22974	6530	21500
6	40300	2880	4720	2880	2880	2880	2880
7	28200	4720	16900	7796	16228	6530	11500
8	28200	2880	9930	2895	12242	2880	11500
9	28200	2880	4720	5139	4002	4980	2880
10	33500	11100	11300	13853	22129	13600	20000
11	33500	20000	21700	24890	22157	23700	21700
12	20000	11100	11300	14665	9191	13600	11100
13	20000	13300	13600	15018	11812	13600	11300
14	11100	11300	13300	10000	9358	11300	13300
15	11100	13300	13600	11517	11509	11300	11300
Total Weight	5735	3257	4296	3330	4230	3525	4492

Units; Design values, Cm^4, Weight values, Kg

a Considers stress constraints only

b Considers displacement constraints additionaly

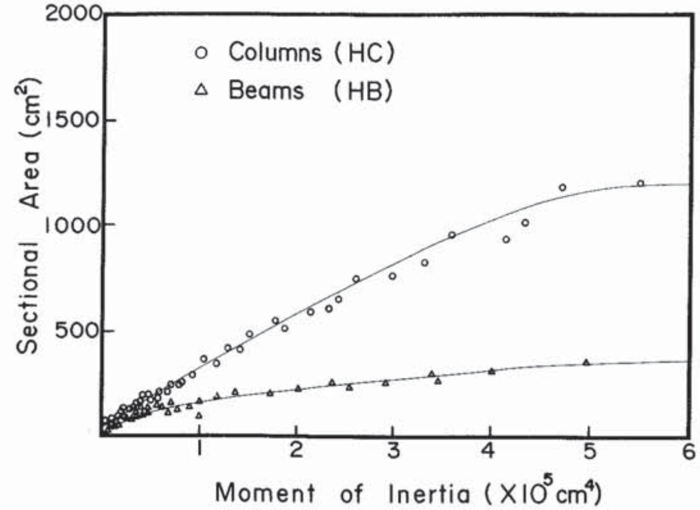

Fig. 1 Relation between cross sectional area and moment of inertia

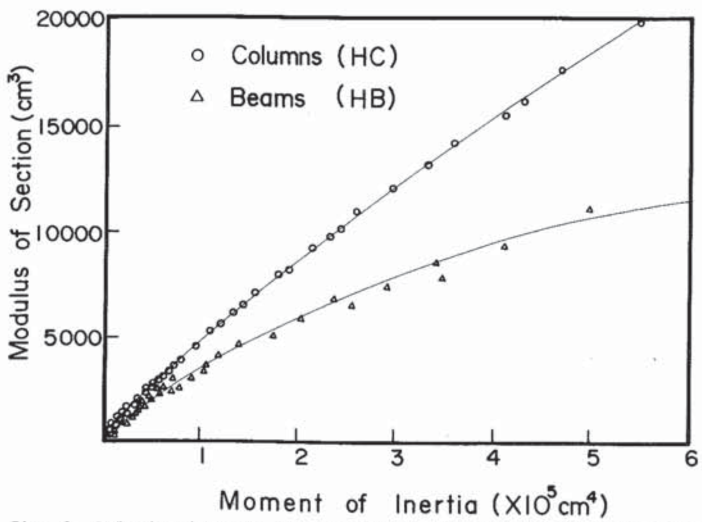

Fig. 2 Relation between modulus of section and moment of inertia

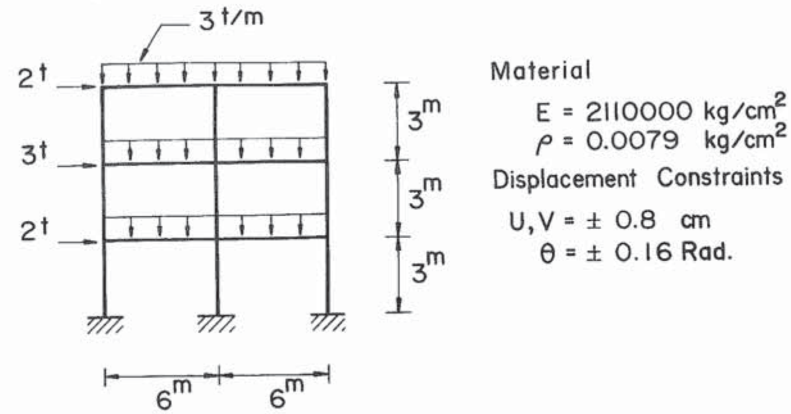

Fig. 3 3-story steel frame