SEISMIC OPTIMUM DESIGN FOR THE HIGH-RISE BUILDING WITH GIRDER TRANSFER FLOOR

Gang Li[1] and Hongchao Ning[2]

[1] *Professor, Dept. of Engineering Mechanics, Dalian University of Technology, Dalian, China*
[2] *Graduate student, Dept. of Engineering Mechanics, Dalian University of Technology, Dalian, China*
Email: ligang@dlut.edu.cn

ABSTRACT :

This paper proposes an integrated seismic optimum design approach for the high-rise buildings with girder transfer floor, including topology optimum design of the transfer floor and size optimum design of beams and columns. First, the girder transfer floor is optimized using the SIMP topology optimization method to obtain the optimum topological form of the transfer floor. Then the size optimum design of beams and columns is performed. The initial cost and life cycle cost are employed as the objective function in the seismic design, respectively. Finally, a numerical example of 23-story high-rise building is calculated, and the results show the optimum design of minimum life cycle cost is more cost-effective.

KEYWORDS: transfer floor, topology optimization, size optimization, seismic design, life cycle cost

1. INTRODUCTION

The concept of performance based seismic design was proposed in the early 1990s, and has been gradually accepted by the earthquake engineering profession recently. (SEAOC 1995; FEMA 1996; ATC 1996; Li and Cheng 2004). The basic thought of PBSD is to design a structure so that it will perform in a specified manner when subjected to various loading scenarios. Cost-effectiveness criterion is one of the most important principles in PBSD, which involves not only engineering analysis but also social, economic, political, cultural, ethical and many other aspects. The aim of cost-effective design is to minimize the life cycle cost of the structure so as to a good balance between the initial cost and the expected loss in the structural life cycle could be obtained. Thus, the central issue of cost-effective design is the proper estimation of the structural life cycle cost. The evaluation of structural life cycle cost, generally including initial cost, the cost of inspection and maintenance and the expected loss, is the key problem in cost-effective design, and the computation of structural failure probability in the evaluation of the expected loss may be very costly and time consuming because the limit state function is usually a highly nonlinear implicit function with respect to the basic design variables, especially for the complex large-scale structures for dynamic and nonlinear analysis.

Transfer floors are increasingly applied in design of high-rise buildings in recent years due to the complex shapes and multi-functions of the buildings (Tang 2002; Li et.al 2003). There are generally four forms of transfer floors, which are girder, plate, truss and box. The girder transfer floors are wide used in high-rise buildings with the advantages of clear load path and simple structure, etc. However, the transfer girder always needs a lot of construction materials (concrete and steel), and the "strong-beam-weak-column" design may occur, which is unfavorable to the seismic design. So this paper tries to solve these problems by optimum design begin with changing the form of transfer floor.

This paper proposes an integrated seismic optimum design approach for the high-rise buildings with girder transfer floor, including topology optimum design of the transfer floor and size optimum design of beams and columns. The initial cost and life cycle cost are employed as the objective function in the seismic design, respectively. An approximate evaluation of life-cycle cost with fuzzy theory is proposed. Finally, a numerical example of 23-story high-rise building is calculated.

2. FORMULATION OF SEISMIC OPTIMUM DESIGN FOR HIGH-RISE BUILDING WITH GIRDER TRANSFER FLOOR

2.1Topology Optimization Formulation of Transfer Floor

Structural topology optimization is to seek the optimum material distribution of structure by designing the number, location and shape of holes in a continuum structure under the given constraints and some specific objectives. Among the three levels of optimization of size, shape and topology, topology optimization is the most difficult with the most potential benefits.

The SIMP (Solid Isotropic Material with Penalization) method was developed from homogenization method, in which the dependence of material properties with design variables is expressed in terms of the material density using a simple ‘power-law’ interpolation to suppress the intermediate values by penalizing the bulk densities (Bendsøe and Sigmund 2003). The material density describing the amount of material in each point of the domain which can assume values between 0 and 1, and the density of 0 is equal to void and 1 is equal to solid material. The topology optimization formulation of transfer floor with SIMP method can be written as

$$\begin{cases} Find \quad X=\{x_1,x_2,\ldots,x_n\}^T \\ Min: \;\; C(X)=U^TKU=\sum_{e=1}^{N}(x^e)^p {u_e}^T k_e u_e \\ s.t.: \;\; \dfrac{V(X)}{V_0}\le f \\ \qquad KU=F \\ \qquad 0<x_{\min}\le x^e\le x_{\max}\le 1 \end{cases} \tag{2.1}$$

where, X is the vector of design variable, representing the material densities; x^e is the design variable of element (e＝1,2,…,N， N is the number of design variables); x_{max}, x_{min} are the upper and lower bounds of design variable (1and 0.001 are taken in this study)；$C(X)$ is the objective function of structural compliance; F is the load vector, U is the displacement matrix, K is the matrix of global stiffness; $V(X)$ is the structural volume with the design variables of X; V_0 is the structural volume with the design variables of 1; f is the percentage of material (0.3 is used in this paper)； u^e and k^e are the element matrix of displacement and stiffness; p is the penalty factor (3 is taken herein).

2.2 Size Optimization Formulation of Beams and Columns

Structural size optimization is to find the size of structural members to optimize the objective function (such as cost, structural properties, life-cycle-cost, etc.) under some constraints, given the structural topology and shape. The size optimization formulation of beams and columns with the minimum initial cost is

$$\begin{aligned} &Find: X=\{x_1,x_2,\ldots,x_n\}^T \\ &Min: \;\; V(X)=\sum_{i=1}^{k}A(x_i)l \\ &S.t. \qquad g_j(X)\le 0 \quad (j=1,2,\ldots,m) \\ &\qquad\qquad X^L\le X\le X^U \end{aligned} \tag{2.2}$$

where, X is the vector of design variable, representing the size of beams and columns; $V(X)$ is the objective function of structural volume; $g_i(X)$ is the constraint, referring to axial compression ratio of columns, story drift, etc. X^L and X^U are the lower and upper bounds of the design variable, respectively.

The size optimization formulation with minimum life cycle cost can be stated as

$$\begin{aligned} &Find: X = \{x_1, x_2, \ldots, x_n\}^T \\ &Min: \quad C_{tot} = C_I + C_F \\ &S.t. \qquad g_j(X) \le 0 \quad (j = 1,2,\ldots,m) \\ &\qquad\qquad X^L \le X \le X^U \end{aligned} \tag{2.3}$$

where, C_I is the initial cost and C_F is the expected loss during the life cycle.

Thus, the sketch flow chart of structural optimization in this paper is shown in Figure 1.

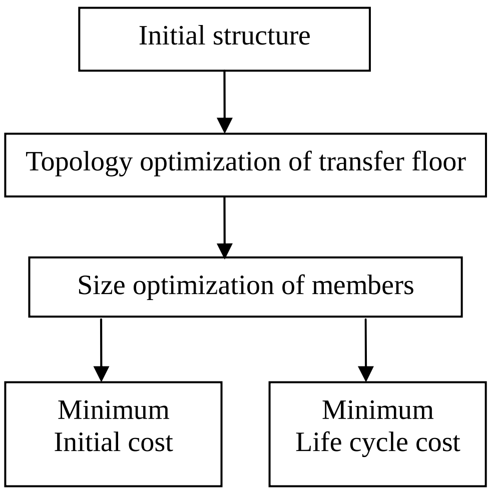

Figure 1 Sketch flow chart of structural optimization

3. EVALUATION OF LIFE CYCLE COST WITH FUZZY THEORY

The structural expected loss during its life cycle under the earthquake with failure probability is expressed as

$$C_{Fp} = \sum_I L_P(I)P(I) = \sum_I [\sum_i C(B_i)P(B_i \mid I)]P(I) \tag{3.1}$$

where I is the earthquake intensity, B is the structural damage level, $P(I)$ is the occurrence probability of the earthquake intensity I; $L_p(I)$ is damage loss caused by the earthquake intensity I, evaluated with probability theory; $P(B_i|I)$is the occurrence probability of damage level B_i caused by earthquake intensity I; $C(B_i)$ is the loss value when damage level B_i occurs, including direct loss and indirect loss.

As pointed out previously, the calculation of $P(B_i|I)$ is always time consuming because the limit state function is usually a highly nonlinear implicit function with respect to the basic design variables for practical problems. Therefore, we proposed to use the fuzzy theory to evaluate the expected loss (Li and Cheng 2004), and the fuzzy set of damage levels are defined as follows

$$\tilde{\mathbf{B}} = \{B_1, B_2, B_3, B_4, B_5\} \tag{3.2}$$

Our task is to determine the membership function of the damage caused by the story-drift ratio to the fuzzy set of damage levels

$$\mu_{\tilde{\mathbf{B}}}(x) = \{\mu_1(x), \mu_2(x), \mu_3(x), \mu_4(x), \mu_5(x)\} \tag{3.3}$$

Therefore, the structural life-cycle expected loss based on the fuzzy theory can be evaluated by

$$C_F = \sum_I L_f(I)P(I) = \sum_I [\sum_i C(B_i)\mu_{\tilde{\mathbf{B}}}(B_i \mid I)]P(I) \tag{3.4}$$

where $L_f(I)$ is the damage loss caused by the earthquake intensity I, evaluated with fuzzy theory; $\mu_{\tilde{\mathbf{B}}}(B_i \mid I)$ is the membership function to the damage level B_i, caused by the story-drift ratio under the earthquake intensity I.

It should be noted that the failure probability $P(B_i|I)$ and the membership function $\mu_{\tilde{\mathbf{B}}}(B_i \mid I)$ are different in concept, although both of them are the real number within the region [0,1]. Probability is a kind of measurement for the stochastic uncertainty, in which the events involved that may occur in the future are well defined. The value of probability from 0 to 1 demonstrates the degree of possibility at which the event may occur. The membership function is a key concept in the fuzzy theory, in which the more-or-less type set rather than the conventional yes-or-no type set is studied. Both of the failure probability and the membership function can describe the degree of damage caused by a specific story-drift ratio from different views. The former gives the occurrence probability of the five damage levels, and the latter gives the degree of membership of the five damage levels, both of which can be employed to evaluate the expected loss.

How to choose a proper membership function is the key problem in the evaluation of the expected loss with fuzzy theory. The power function and normal function are employed as membership functions in this paper.

A method to estimate the damage was proposed (Li and Cheng 2004), in which the story-drift ratio is used to evaluate the structural damage level. Five damage levels are defined, which are roughly intact, slightly damaged, moderately damaged, severely damaged and collapsed. The structures are classified as four types, ST-1, ST-2, ST-3 and ST-4 according to their importance (ST-1 is the most important and ST-4 is the less) (GBJ, 2001).The relations between the damage levels and structural story-drift ratio, direct loss, and the ratio of structural indirect loss to direct loss for different types of buildings, as shown in Table 1 and 2.

Table 1 Relations of story-drift ratio, damage levels and structural direct loss

Damage level	Roughly intact	Slightly damaged	Moderate damaged	Severely damaged	Collapsed
Story-drift ratio	0~0.0.2%	0.0.2%~0.4%	0.4%~0.8%	0.8%~2%	2%~
Direct loss (C_0)	0.02	0.10	0.30	0.70	1.00

Table 2 Ratio of indirect loss to direct loss under different damage levels
for different types of building structures

Damage level	Roughly intact	Slightly damaged	Moderate damaged	Severely damaged	Collapsed
ST-1	0.0	0.0	1.0~10.0	10.0~50.0	50.0~200.0
ST-2	0.0	0.0	0.5~1.0	3.0~6.0	8.0~20.0
ST-3	0.0	0.0	0.5	2.0	6.0
ST-4	0.0	0.0	0.2	1.0	2.0

The earthquake intensity in China has the probability distribution of extreme type III, and three earthquake levels are used in the Chinese seismic design code, minor, moderate and severe earthquakes (GBJ 2001). The intensity of the minor earthquake is defined as the intensity with the exceeding probability of 63.2% for the design period 50 years, the basic intensity with the exceeding probability of 10% and the intensity of severe earthquake with the exceeding probability of 2~3%. In general, the basic intensity is 1.55 degree higher than that of the minor earthquake, and 1 degree lower than that of the severe earthquake. Thus, according to our computational results, the occurrence probability of the intensity of minor, moderate and severe earthquakes for the design period 50 years, $P(I_S), P(I_M), P(I_L)$, can be determined approximately as follows,

$$P(I_S) = 70\%, \quad P(I_M) = 25.5\%, P(I_L) = 4.5\% \tag{3.5}$$

4. NUMERICAL EXAMPLE

A 23-story, 74m high RC frame, with the girder transfer floor of 2m high located above the third story, is optimized, as shown in Fig. 2. For story 1-3, the distance between columns is 10m and the story height is 4m. For other stories, the distance between columns is 5m and the story height is 3m. The member size and material of the structure are listed in Table 3. The site of type II and the intensity of 7 are considered. In the size optimization, the allowable axial compression ratio is 0.8, and the allowable story drift is 1/550. The cost of reinforced concrete is taken as 1300 Yuan/m^3.

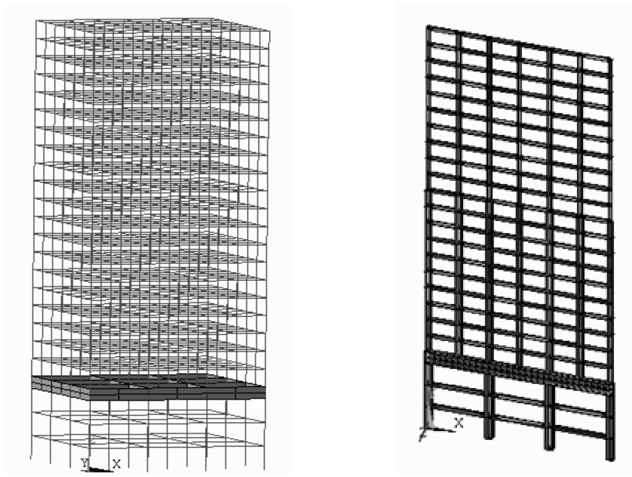

Fig.2 23-story RC frame with girder transfer floor

Table 3 Material and size of the Structure

story	Column		beam	
	Size (mm)	concrete	Size (mm)	concrete
1～3	1400*1400	C40	800*350	C30
4～5	1200*1200	C40	700*250	C30
6～13	700*700	C35	700*250	C30
14～23	500*500	C35	700*250	C30

4.1 Topology Optimization of Transfer Floor

2D model is used to perform the topology optimization of the girder transfer floor. We take 1/3 part of the girder transfer floor for optimization design due to the periodic property of the structure, based on which the optimum topology of the transfer floor can be integrated. Considering the practical situation and construction requirements, the final optimum topology of the transfer floor is converted to truss-type from beam-type, shown in Figure 3.

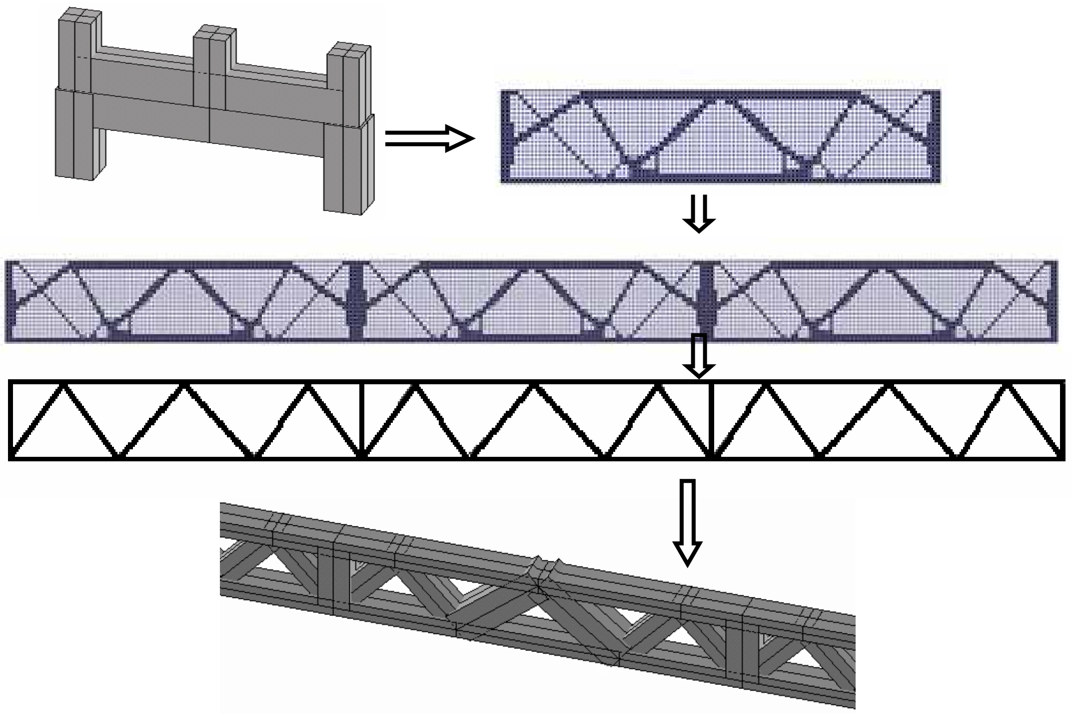

Figure 3 Topology optimization of the girder transfer floor

4.2 Size Optimization of Beams and Columns

Table 4 is the optimum results of some columns. Figure 4 shows the iteration history of size optimization of minimum initial cost and minimum life cycle cost, respectively. Figure 5 shows the comparison of the story drift of the 3D structure, in which curve-A corresponds to the structure of minimum initial cost design, curve-B and curve-C to minimum life cycle cost design with the membership function of power function and normal function respectively. Figure 6 gives the comparison of the life cycle cost of the different optimum designs. The follow observations can be obtained:

1) The optimum results of both minimum initial cost design and minimum life cycle cost design can satisfy the requirements of seismic performance, such as axial compression ratio, story drift, etc.

2) For the initial cost (blue bar in Fig.6 of the RC volume), the optimum design of minimum initial cost can obtain the most benefit, reducing the RC volume of the initial design by 10.98%. The optimum design of minimum life cycle cost can reduce the RC volume of the initial design by 7.21% and 9.08%, with the membership function of power function and normal function, respectively.

3) For the life cycle cost, the optimum design of minimum life cycle cost is more cost-effective. Compared to the minimum initial cost design, the life cycle cost is reduced by 655.8 and 777.8 thousand yuan after the minimum life cycle cost design with the power function and normal function, respectively, covering the percentage of 4.9% and 5.5% of the total lifecycle cost.

Table 4 Optimum results of some columns

	B_1 (mm)	B_2 (mm)	B_7 (mm)	B_8 (mm)	B_9(mm)	B_{10}(mm)
Initial	1400	800	1200	500	700	700
Min. initial cost	1000	800	900	450	700	600
Min. (power) life cycle cost	1300	800	1000	500	700	600
Min. (normal) life cycle cost	1300	800	1000	450	700	550

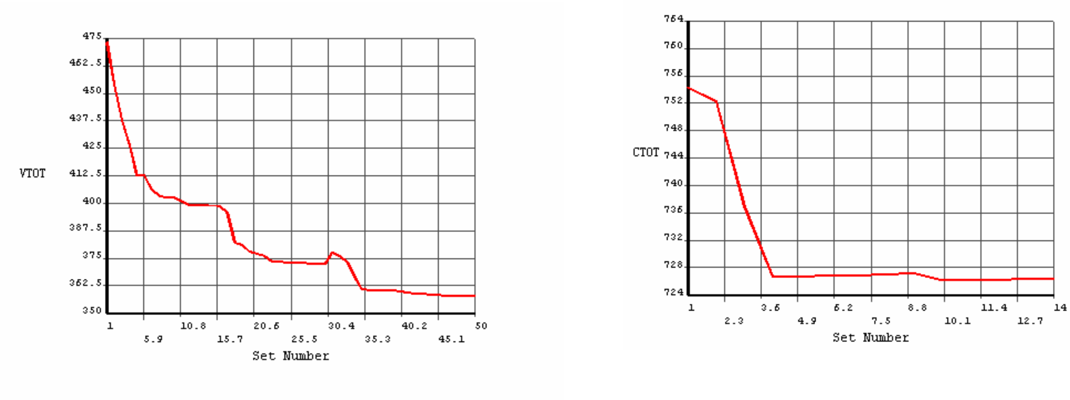

Figure 4 Iteration History of optimization (left: Min. initial cost; right: Min. life cycle cost)

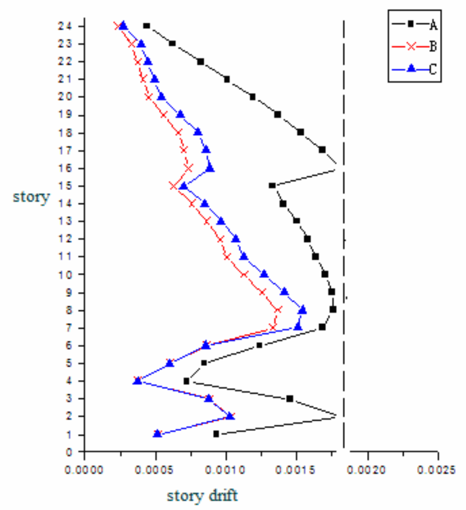

Figure 5 Story drift of Structure

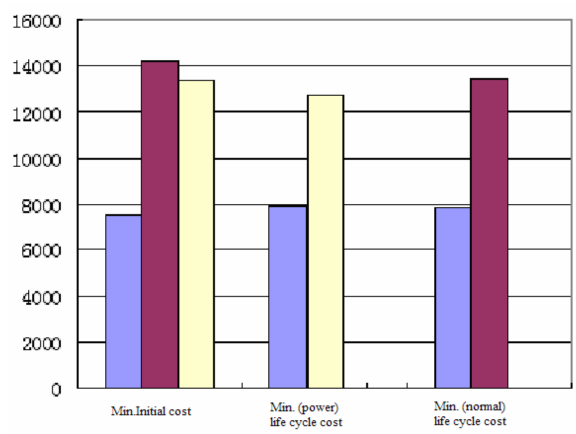

Figure 6 Comparison of life cycle cost

5. CONCLUSION

This paper proposes an integrated seismic optimum design approach for the high-rise buildings with girder transfer floor, including topology optimum design of the transfer floor and size optimum design of beams and columns. The initial cost and life cycle cost are employed as the objective function in the seismic design, respectively. The results show that the optimum design of minimum life cycle cost is more cost-effective.

ACKNOWLEDGEMENTS

The support of the National Natural Science Foundation of China (No.50578028 and No.10721062), the National Basic Research Program of China (973 Program, 2006CB705403) and the Program for New Century Excellent Talents in University are very appreciated.

REFERENCES

ATC (1996). Seismic Evaluation and Retrofit of Existing Concrete Buildings, ATC 40, Applied Technology Council.

Bendsøe, M.P., Sigmund, O. (2003). Topology optimization: Theory, Methods, and Applications, Springer, Berlin Heidelberg, New York

Dai, G.L., Tong, X.D. (2005). Application of laminated vierendeel truss in high-position transfer story structure. *Joumal of Southeast University*, 184-190.

FEMA (1996). NEHRP Guidelines for the Seismic Rehabilitation of Buildings, FEMA 273, Federal Emergency Management Agency.

GBJ (2001). Code for Seismic Design of Buildings (GBJ50011-2001), China Building Industry Press, Beijing.

Li, G., Cheng G.D.(2004). Performance Based Seismic Design of Structures: Theory, Methods and Applications, Beijing Science Press

Li, J.H., Su, R.K.L., Chandler, A.M.(2003). Assessment of low-rise building with transfer beam under seismic forces. *Engineering Structures*, 25:1537-1549.

SEAOC(1995). Performance Based Seismic Engineering of Buildings, SEAOC Vision 2000, Structural Engineers Association of California.

Tang, X.R. (2002). Design and Construction of Transfer Floor Structure of Tall Building, Beijing, China Building Industry Press