Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Optimum design of connecting elements in complex structures and its application to aseismic design of boiler plant structures

E. Nishida
Kure Research Laboratory, Babcock-Hitachi K.K., Hiroshima, Japan

K. Suzuki
Department of Mechanical Engineering, Faculty of Technology, Tokyo Metropolitan University, Japan

T. Yasuda & Y. Ohwa
Structural Design Center, Babcock-Hitachi K.K., Kure, Hiroshima, Japan

ABSTRACT: This paper deals with an optimum design method for connecting elements of adjacent structures which are excited by earthquakes. Considering the expansion of this study to an active or semi-active control of connecting elements, the structures are modeled by block diagram. In order to improve the calculation efficiency, a substructure synthesis method is introduced. Time-domain optimization with inequality constraints is carried out using a non-linear programming technique. A connecting element is modeled by the combination of a spring and a dashpot. Elasto-Plasticity is taken into account using equivalent linearization method. These characteristics of connecting elements are optimized to minimize seismic time-response of the structures, under constraints for relative displacement between these structures. This method is applied to a fundamental lumpedmass model of a boiler plant structure composed of the boiler, its supporting structure and connecting elements between them. An objective function is a total of story shear force of the supporting structure. As a result of this investigation, the proposed optimization method has proven to be effective and practical for aseismic design of adjacent structures with connecting elements.

INTRODUCTION

This paper deals with the aseismic design problem of connecting elements between adjacent structures. We often find the same kind of problems, including the snubber reduction problem in the piping support design for nuclear power plants (1). The same problem exists in the design of connecting elements of boiler plants in thermal power stations, which is the main theme of this study.

Regarding the function of connecting elements, this problem is classified into three types; passive, active and semi-active. In the case of passive type, it is essential to develop the tuning method of the elements' charactristics and arrangement. In the case of active type, actuators are incorporated in the elements and their real-time control is executed (2). In the semi-active type, instead of actuators, the elements' characteristics (spring, or damping constants) are controlled. "Optimum design" and "Vibration control" techniques are fundamental in the design of these type of elements. Besides, recently, certain literature is available on the study of simultaneous optimum design methods for structure and control system (3).

The objective of this study is to develop a practical aseismic design system of connecting elements of adjacent structures, where three types of elements mentioned above can be treated in a unified way. This paper deals with the first stage of the study; the optimum design of the passive type elements. Time-domain optimization is necessary in the aseismic design (4)(5), and this is achieved by the combination of seismic response simulation in the time-domain and non-linear programming technique. Considering future expansion of this study to active, or semi-active problems, block diagram modeling is introduced which easily enables the incorporation of sensing and control systems. The time-domain optimization consumes computation time, so the substructure synthesis method (6) is adopted to achieve computational efficiency. A connecting element is modeled by a pair of a spring and a dashpot. Elasto-Plasticity is taken into account using an equivalent linearization method. These characteristics of connecting elements are optimized to minimize seismic time-response of the structures, under the constraint for relative displacement between these structures.

This method is applied to a fundamental lumped-mass model of a boiler plant structure composed of the boiler, its supporting structure and connecting elements between them. A total of story shear force of the supporting structure is adopted as an objective function. As a result of this study, the proposed optimization method has proven effective and practical for aseismic design of adjacent structures with connecting elements.

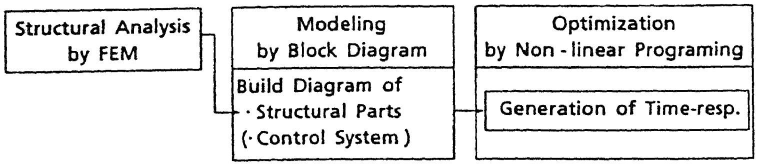


Fig. 1 Connecting Elements Optimum Design System

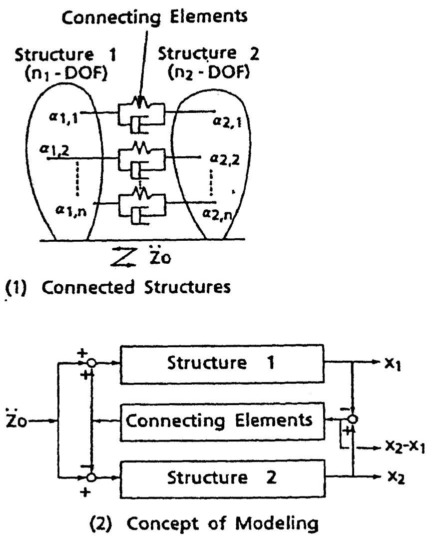


Fig. 2 Block Diagram based on Substructure Synthesis

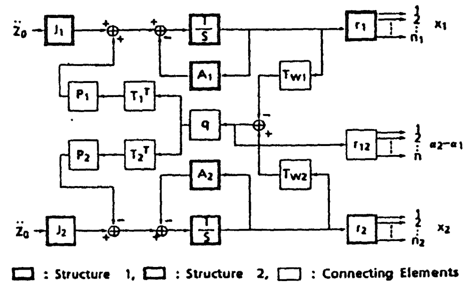


Fig. 3 Block Diagram of Connected Structures

OPTIMUM DESIGN OF CONNECTING ELEMENTS

Optimum design system

Fig. 1 shows the proposed optimum design system. This system is composed of three subsystems; Finite Element Method (FEM) structural analysis, seismic response simulation with the block diagram modeling, and optimization using non-linear programming. At the stage of FEM software, the structure is transformed to the numerical model, and a modal analysis is executed to introduce the modal model. This model is transformed to the equivalent block diagram. The block of design variables (characteristics of connecting elements) are incorporated, too.

The block diagram is transformed to the state equations and seismic response simulation is executed. Nonlinear programming software repeats seismic response simulation renewing the design variables according to the guide of optimization, to lead the optimum solution where the defined objective function takes minimum value. In the above-mentioned system, the part of structural analysis is realized by SAP and the remaining parts consisted of the option software of MATRIXx.

Modeling with block diagram

Fig. 2 shows the concept of block diagram modeling based on the substructure synthesis (6). The structures are composed of three parts; two substructures and a group of connecting elements of which characteristics are modeled by a pair of a spring and a dashpot. The block diagram of these structures (shown in Fig. 2) consists of three parts which correspond to the above-mentioned three structural parts.

Mathematical formulation is as follows. As to the substructure i (i = 1, 2) excited by base acceleration $\ddot{Z}_0$, the equation of motion is:

$$M_i\ddot{x}_i + C_i\dot{x}_i + K_i x_i = - M_i I_i \ddot{Z}_0 \pm F_i \qquad (1)$$

where M_i, C_i and K_i are n_i-by-n_i mass, damping, and stiffness matrices; x_i is n_i-by-1 displacement vector ; F_i is n_i-by-1 force vector generated by the deformation of connecting elements. Here, the substructure synthesis method is introduced to reduce the degree of freedom of the system. Using a n_i-by-l_i modal matrix, U_i, displacement vector x_i is expressed as follows;

$$x_i = U_i y_i \qquad (2)$$

where y_i is l_i-by-1 modal coordinate vector. In general cases of seismic excitation, a few lower modes are dominant, which results in $n_i > l_i$ and the degree of freedom of the system is reduced. Substitution of eq. (2) into eq. (1) and assumption of orthogonality of damping matrix lead to;

$$\ddot{y}_i + D_i\dot{y}_i + W_i y_i = - b_i\ddot{Z}_0 \pm U^T{}_i F_i \qquad (3)$$

$$Di = diag\ (2\xi_\alpha \omega_\alpha),\ (\alpha = 1 \sim \ell_i) \quad (4)$$

$$Wi = diag(\omega_\alpha^2)$$

$$b_i = (U^t{}_i M_i U_i)^{-1}\ U_i{}^T M_i I_i$$

Rewriting eq.(3) by state space expresssion,

$$\dot{Y}_i = A_i Y_i + J_i \ddot{Z}_o \pm P_i F_i \quad (5)$$

$$Y_i = (\dot{y}_i,\ y_i)^T, \quad A_i = \begin{bmatrix} -D_i, & -W_i \\ E_i, & 0 \end{bmatrix} \quad (6)$$

$$J_i = (b_i,\ 0)^T, \quad P_i = (U_i{}^T,\ 0)^T$$

E_i is l_i-by-l_i unit matrix. In the following, the behavior of the connecting elements is described. Let α_i refer to the n-by-1 connecting point coordinate vector in i-th structure. n is the total count of connecting elements. Two coordinate vectors, α_i and x_i, are related as follows;

$$\alpha_i = T_i x_i \quad (7)$$

where T_i is n-by-n_i coordinate transformation matrix. Here, the force vector of connecting elements, F_i, and the state vector in the modal coordinates, Y_i, is related as follows;

$$F_i = T_i{}^T \cdot q(T_{w2}Y_2 - T_{w1}Y_1) \quad (8)$$

where, n-by-2n matrix q is composed of the design variables of j-th connecting elements (j = 1 ~ n); spring constant k_j and damping constant c_j.

$$q = \lfloor diag(c_j),\ diag\ (k_j) \rfloor \quad (9)$$

$T_{wi}(i=1,2)$ is 2n-by-$2l_i$ matrix;

$$T_{wi} = \begin{bmatrix} T_i U_i, & 0 \\ 0, & T_i U_i \end{bmatrix} \quad (10)$$

Fig. 3 shows the block diagram based on this formulation. The symbols in each block correspond to the matrices mentioned above. The blocks r_1, r_2 and r_{12} just before the outputs, are as follows;

$$r_i = [0,\ U_i],\ (i = 1,\ 2)$$

$$r_{12} = [0,\ diag\ (1)] \quad (11)$$

In the optimum design system, this block diagram is converted to the equation of motion in the state space, and seismic response simulation is executed. In this calculation, the variable step Kutta-Merson method is adopted.

Formulation for optimum design

Optimum design problem is defined, in general, as follows;

$$\begin{aligned} &\underset{x}{\text{minimize}}\ f(x) \\ &\text{subject to } h_{min} < h(x) < h_{max} \\ &\qquad \text{(Behavior constraint)} \\ &\qquad x_{min} < x < x_{max} \\ &\qquad \text{(Side constraint)} \end{aligned} \quad (12)$$

x is refered to as the vector of design variables. In this study, x consists of n pairs of (k_i, c_i), where k_i and c_i are spring, and damping constant of i-th connecting element, respectively.

$$x = (c_1,\ \ldots,\ c_n,\ k_1,\ \ldots,\ k_n)^T \quad (13)$$

Here, the connecting elements are numbered in order from top to bottom, and i refers to this number.

f(x) is an scalar value referred to as an objective function, and the representative value of seismic response of the structures is adopted as f(x). h(x) is referred to as the behavior constraint, and the strength of connecting elements, or relative displacement between two substructures are adopted as h(x). For example, the boiler structures have many pipes and ducts which expand between the boiler and its supporting structure, so there are allowable values for relative displacement so as to prevent pipes and ducts from structural damage. Neither f(x) nor h(x) is defined as the explicit function of x, so optimization is executed by the combination of nonlinear programming technique and seismic response simulation in the time-domain.

In the above-mentioned case, the visco-elastic characteristics of connecting elements are supposed and these elements are modeled by a pair of a spring and a dashpot. Here, it is shown that the elasto-plastic characteristics can be optimized by the same model as is used in the visco-elastic elements. This is achieved by the introduction of equivalent linearization method and the addition of a behavior constraint related to elasto-plasticity. Fig. 4 shows the diagram of elasto-plasticity and its linearization method. Elasto-plasticity can be defined by two parameters; stiffness, k, and yield displacement, x_y. Equivalent stiffness, k_e, is

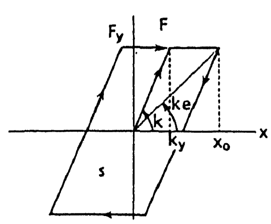


Fig. 4 Equivalent Linearization for Elasto-Plastic Tie

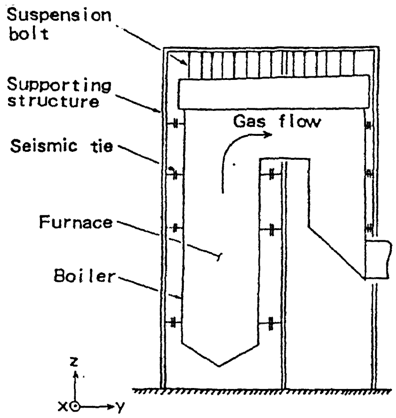


Fig. 5 View of Boiler Structure

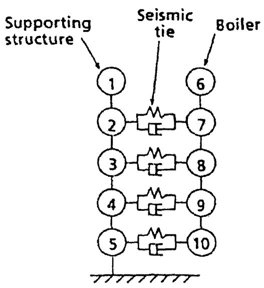


Fig. 6 Lumped Mass Simulation Model

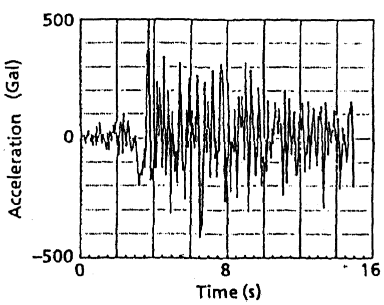


Fig. 7 Input Time-History (Taft, E-W)

Table 1 Conditions for Optimum Calculation

Items	Visco-Elastic Ties	Elasto-Plastic Ties
Design Variables & Side Constraints	$0<k_i<5\times10^9 N/m$ $0<c_i<5\times10^8 N\cdot s/m$	$0<k_i<5\times10^9 N/m$ $1<d_i<20$
Behaviour Constraints	$\overline{\delta x}_{max}<7\times10^{-2}m$	$\overline{\delta x}_{max}<7\times10^{-2}m$ $0<x_{yi}<1\times10^{-2}m$
Objective Function	$\overline{G}=\sum_{i=1}^{5}\overline{G_i}/5$	

easily obtained by the way shown in Fig. 4. Equivalent damping, c_e, is determined based on the equality of kinetic energy dissipation per cycle. This idea is formulated as follows;

$$S = \oint c_e \cdot \dot{x} dx \tag{14}$$

where S is the area of the hysteresis loop in Fig. 4. Based on this formulation, the relation between the elasto-plasticity (k, x_y) and the equivalent visco-elasticity (k_e, c_e) is expressed as follows;

$$k_e = \frac{k}{d}$$

$$c_e = \left(1 - \frac{1}{d}\right) \cdot \frac{2k}{\pi^2 f d} \tag{15}$$

where f is frequency, and d is the ductility factor defined by the ratio of maximum displacement, x_0, to the yield displacement, x_y. In the case of the boiler structure, almost seventy percent of the seismic responses are contributed by the first mode, so the fundamental natural frequency is used as f. We have confirmed the accuracy of this method by comparison of simulated results based on this method, and the method with elasto-plastic model.

Optimization of elasto-plastic elements are executed repeating the transformation based on eq.(15) between elasto-plasticity and visco-elastisity in each iternative calculation. As the design variables, the pair of (k, x_y) seem to be suitable, but the pair of (k, d) is a better selection. In this selection, addition of the side constraint,

$$1 < d < d_{max} \tag{16}$$

where d_{max} is the allowable ductiliy ratio, keeps c_e positive by eq. (15). Therefore divergence in the iteration caused by the negative value of c_e, does not happen.

APPLICATION TO BOILER STRUCTURE

This chapter mentions the efficiency of the proposed method through its application to aseismic design of the boiler structures.

Fig. 5 shows a view of the boiler plant in a thermal power station. In the case of 1000 MW class plant, the structure is over 80 meters high. The boiler itself has an asymmetrical box-type structure and weighs approximately 8,000 tons. It is suspended from the roof girders of its supporting structure so as not to restrict thermal expansion in the vertical direction. In order to restrain pendular behavior in horizontal directions, stoppers are attached at speci-fic points. Hereafter, these stoppers are referred to as "Seismic ties".

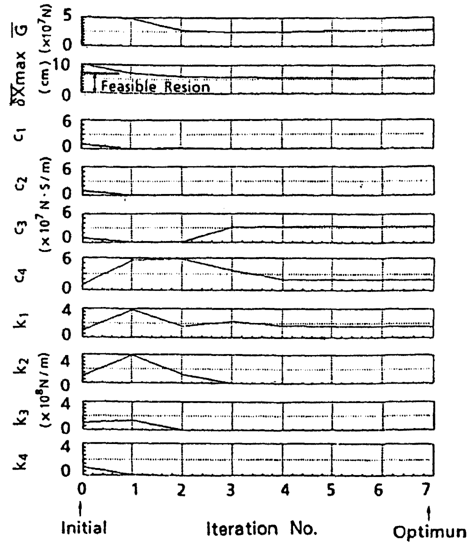
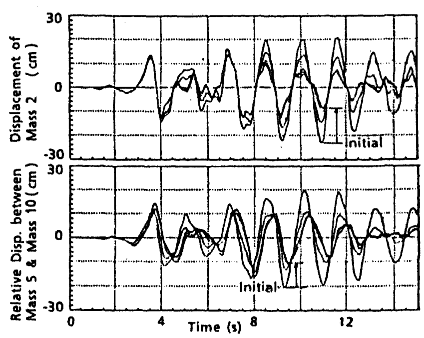


Fig. 8 Process of Optimum Calculation for Visco - Elastic Ties



9 Time - Response Displacement in Each Iteration for Visco - Elastic Ties

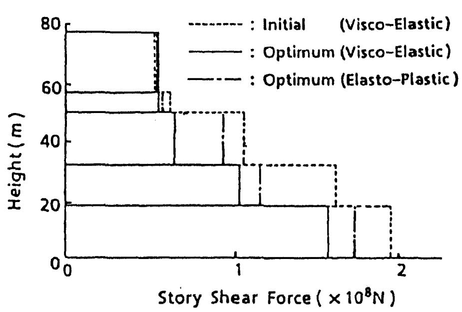


Fig. 10 Distribution of Story Shear Force (Max. Value)

Conditions for optimization

Fig. 6 shows the fundamental model of the boiler structure. The boiler and the supporting structure are modeled by five lumped masses and shear beam elements. To simplify the problem, only y-directional response is considered and structural damping is neglected. Four seismic ties are equipped and two types of ties are studied; the visco-elastic tie and the elasto-plastic tie. In both ties, characteristics of the tie are specified with two parameters, so eight design variables are processed in the optimization. Taft (E-W) record is used as the input, and discretized by an interval of 0.02 seconds. Fig. 7 shows the time histories of this record.

Table 1 shows the conditions of optimization. The objective function is defined by an average of story shear force yielded on the supporting structure;

$$\overline{G} = \frac{1}{5}\left(\sum_{i=1}^{5}\overline{G_i}\right) \tag{17}$$

where $\overline{G_i}$ is the rms value of i-th story shear force. The constraint for the relative displacement is defined as follows;

$$\overline{\delta x}_{max} = \max\left(\overline{\delta x}_1, \ldots, \overline{\delta x}_5\right) < 7 \text{ cm} \tag{18}$$

where $\overline{\delta x_i}$ is the rms value of relative displacement at i-th seismic tie. In the case of elasto-plastic ties, taking account of the strength and specifications of the seismic ties, additional constraints are considered for the ductility factor, d, and yield displacement, x_y; $d < 20$ and $x_y < 1$ cm. In eq.(17) and (18), rms values are adopted, because this type of value is more stable than the peak value.

Table 2 Results of Optimization for Elasto - Plastic Ties

Tie No.	k_i ($\times 10^6$N/m)		d_i		x_{yi} ($\times 10^{-2}$m)	
	Initial	Optimum	Initial	Optimum	Initial	Optimum
1	100.00	40.32	4.00	13.49	1.56	1.00
2	100.00	0.02	4.00	13.90	1.83	1.00
3	100.00	88.81	4.00	20.00	2.78	0.72
4	100.00	71.80	4.00	20.00	3.48	0.70

------: Constraint is not satisfied. ——: Constraint is active.

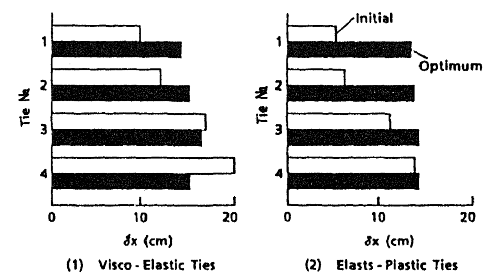


Fig. 11 Distribution of Relative Displacement (Max. Value)

Optimization of visco-elastic ties

After 7 iterations the calculation converged. Fig. 8 shows the trends of the objective function, the item of constraint and eight design variables in the process of iterations. The time histories of seismic response in each iteration are shown in Fig. 9. The objective function becomes constant after second iteration, and the design variables, after fourth iteration.

The results of optimization indicate that the highest seismic tie should consist of a spring element and that the two lowest ties should consist of dashpot devices. The objective function, $\overline{G}$, is reduced to about half the initial value. Distribution of maximum story shear force is shown in Fig. 11. As a result of optimization, apploximately twenty percent reduction is achieved for the base shear force. This reduction seems to be smaller than that expected from the reduction of the objective function. The reason exists in the difference of behaviors between the rms value and the peak value, which are used in the objective function and story shear force evaluation, respectively. Fig. 9 indicates the reason; the process of optimization reduces the amplitude of the latter half of time histories, whereas the first half are not reduced so much. Therefore, as the iteration proceeds, the peak point which existed in the latter half, moves to the first half. The time-histories of story shear force show the same behavior. This is the cause of the smaller reduction of the peak value than the rms value.

Optimization of elasto-plastic ties

Fig. 10 shows the comparison of distribution of story shear force between the elasto-plastic ties and visco-elastic ties. Elasto-plastic ties yield relatively large forces after optimization. This result can be explained by Table 2 which shows the elasto-plastic parameters before and after optimization. This table shows that additional constraints for the ductility factor, d, and yield displacement, x_y, become active, which are underlined in this table. These constraints have restricted the process of optimization. In Fig. 11 the distributions of the maximum relative displacement are shown for both types of seismic ties. In both cases, the optimization seems to lead the uniform distributions.

As a result, the proposed optimum design method has proven practical and efficient for aseismic design of boiler structures.

CONCLUSION

This paper presents a practical optimum design method of connecting elements in complex structures excited by earthquakes. Fundamental remarks are summarized as follows:

(1) Optimum design formulation is achieved for the aseismic design of adjacent structures with visco-elastic connecting elements.

(2) Optimum design method is proposed based on seismic response simulation with block diagram modeling of the structures, and nonlinear programming.

(3) Optimization method of elasto-plasticity of connecting elements is proposed based on the equivalent linearization technique.

(4) Through the numerical simulation for the boiler structures, this method has proven practical and efficient for aseismic design of complex structures such as boiler plant structures.

REFERENCES

1. Caldwell D.L. 1990, "Catawba Nuclear Station Snubber Reduction Application of ASME Code Case N-411-1, "Proceedings of Pressure Vessel and Piping Conference, the American Society of Mechanical Engineers, PVP-Vol-197, Jun. 1990, PP. 33-38.
2. Ohkawa E., Seto K. 1990, and Mitsuta S., "Vibration Control of Flexible Structure Arranged in Parallel (Modeling the Flexible Structure by Physical Model), "Proceedings of 1990 dynamics and Design Conference, Japan Society of Mechanial Engineers, Vol. B, No. 900-44, Jul. 1990, PP. 435-440.
3. Yamakawa H. 1989, "A Study on a Unified Method for the Dynamic Analysis of the Electro-Mechanical Systems and the Optimum Control Methods Based on It. (1st Report. the Basic Idea of the Unified Method and the Optimum Design and the Optimum Control Methods), "Transactions of the Japan Sociery of Mechanical Engineers (Series C), Vol. 55, No. 519, Nov. 1989, PP. 2777-2783.
4. Hirami N., Yamakawa H. 1986, "Optimum Structural Design for Nonlinear Dynamic Response by the Incremental Transfer Matrix Method, "Transactions of the Japan Society of Mechanical Engineers (Series C), Vol. 52, No. 483, Nov. 1986, PP. 2875-2880.
5. Kajiwara I., Nagamatsu A. 1990, "A Structural Optimization Method Considering Time History Response, "Transactions of the Japan Society of Mechanical Engineers (Series C), Vol. 56, No. 522, Feb. 1990, PP. 391-397.
6. Nagamatsu A., Nakao A., Iwamoto T., and Nagaike M. 1983, "Vibration Analysis by Substructure Synthesis (1st Report, the Basic Study), "Transactions of the Japan Society of Mechanical Engineers (Series C), Vol. 49, No. 437, Jan. 1983, PP. 3-11.