Aseismic Optimization of Nonlinear Joint Elements in Boiler Plant Structures Based on Substructure Synthesis Method*

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This paper deals with an optimum design method for joint elements in boiler plant structures which are excited by earthquakes. Characteristics of joint elements which connect the boiler and its supporting structure are assumed to be viscoelastic, elastoplastic, or a combination of both. Considering the expansion of this study to an active or semiactive aseismic structural control of joint elements, the structures are modeled with the aid of a block diagram. In order to improve the efficiency of calculation, a substructure synthesis method is introduced. Time-domain optimization is carried out using a nonlinear programming technique. To prevent seismic damage of pipes and ducts, limitations for relative displacements between the boiler and its supporting structure is introduced as inequality constraints. Elastoplasticity and viscoelasticity of joint elements are simulated by a combination of a spring, a Coulomb friction and a dashpot. These joint element characteristics are optimized to minimize seismic time response of the structures. This method is applied to actual boiler plant structures and has been proven effective and practical for aseismic designs of boiler plant structures.

Key Words: Optimum Design, Vibration, Aseismic Design, Seismic Response, Joint Element, Elastoplasticity, Boiler Plant

1. Introduction

The aseismic design of joint elements between adjacent structures is considered to be one of the important subjects in design procedures of industrial plant structures. The design of piping support in nuclear power stations is recognized as a typical case⁽¹⁾. A similar subject exists in the design of joint elements of boiler structures in thermal power plants, which is mainly what is dealt with here.

Regarding the function of joint elements, this subject is classified into three types: passive, active and semiactive structural control. In the case of the passive type, it is essential to develop a method of

tuning the characteristics and locations of joint elements. In the case of the active type, actuators must be incorporated in the joint elements and their real-time control must be executed⁽²⁾, while for the semiactive type, instead of actuators, the characteristics of joint elements (spring, or damping constants) are controlled. Concepts of "optimum design" and "vibration control" techniques are essential in the design process of these types of joint elements. Recently, studies of simultaneous optimum design methods for structures and control systems have been conducted^{(3),(4)}.

The objective of this study is to develop a practical aseismic design system of joint elements for adjacent structures, where the three types of elements mentioned above can be treated in a unified way. This paper deals with the first stage of the study in which the optimum design of the passive elements is proposed. Time-domain optimization is necessary in the aseismic designs⁽⁵⁾⁻⁽⁷⁾, and this is achieved by a combination of seismic response simulation in the time domain and optimization by a nonlinear programming technique. Considering future expansion of this study to active or semiactive vibration control

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problems, a block diagram modeling is introduced to enable the incorporation of sensing and control systems.

In the previous study⁽⁸⁾, the characteristics of joint elements were simulated viscoelastically. In this paper, the elastoplastic model is incorporated. Nonlinear simulation consumes much computational time, so a reduced-order model is formulated based on the substructure synthesis method⁽⁹⁾.

This method is applied to an actual boiler plant structure composed of the boiler, its supporting structure and joint elements installed between them. The seismic response shear force on the supporting structure is adopted as an objective function for optimization. As a result of this study, the proposed optimization method has been proven effective and practical for aseismic designs of boiler plant structures.

2. Optimum Design of Joint Elements

2.1 Formulation for optimization

Figure 1 shows a general expression of the structure investigated in this study. This structure is composed of three parts: two substructures and a series of joint elements having viscoelastic or elastoplastic characteristics. The optimum design problem is defined as

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

Here, x is referred to as the vector of design variables, which consists of viscoelastic or elastoplastic constants specifying characteristics of joint elements. $f(x)$ is a scalar value referred to as an objective function. Here 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 joint elements, or the relative displacement between the two substructures, is adopted as $h(x)$. In the case of the boiler structures, many pipes

Fig. 1 Complex structure with joint elements

and ducts expand between the boiler and its supporting structure, so there are allowable values for relative displacement to prevent seismic damage of pipes and ducts. Neither $f(x)$ nor $h(x)$ is defined as the explicit function of x , so optimization is executed by the combination of a nonlinear programming technique and seismic response simulation in the time domain.

2.2 Optimum design system

The composition of the optimum design system is illustrated in Fig. 2. This system is composed of three subsystems: finite-element method (FEM) structural analysis, seismic response simulation with block diagram modeling, and optimization using nonlinear programming. At the stage of FEM analysis, each substructure is transformed to a numerical model, a modal analysis is executed to introduce the modal model, and a reduced-order model is achieved. This model is transformed to an equivalent block diagram. The block of design variables (characteristics of joint elements) are also incorporated. This block diagram is transformed to the state equation and seismic response simulation is executed. In the stage of nonlinear programming, seismic response simulation is repeated renewing the design variables according to optimization guide, which leads to the optimum solution where the defined objective function is minimum. In the above-mentioned system, part of the structural analysis is realized by SAP and the remaining parts consist of the optional software of MATRIXx.

2.3 Modeling with block diagram

Figure 3 shows the concept of block diagram modeling based on the substructure synthesis⁽⁹⁾. This diagram has three subblock diagrams: two blocks of substructures and a block of a series of joint elements.

Mathematical formulation is described as follows. For the substructure i ($i=1, 2$) excited by base acceleration $\ddot{z}_0$, the equation of motion becomes

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

Fig. 2 Joint elements optimum design system

Fig. 3 Block diagram based on substructure synthesis

where M_i , C_i and K_i are n_i -by- n_i mass, damping, and stiffness matrices, respectively; $\mathbf{x}_i$ is the n_i -by-1 displacement vector; and $\mathbf{F}_i$ is the n_i -by-1 force vector generated by the reaction of joint elements. Here, the substructure synthesis method is introduced to reduce the order of the model. Neglecting higher modes and using n_i -by- l_i modal matrix U_i , displacement vector $\mathbf{x}_i$ is expressed by

$$\mathbf{x}_i = U_i \mathbf{y}_i, \quad (2)$$

where $\mathbf{y}_i$ is the l_i -by-1 modal coordinate vector. In general cases of seismic excitation, only a few lower modes are dominant and higher modes can be neglected, which result in $n_i \gg l_i$. Given this, a reduced-order model is acquired. Substitution of Eq. (2) into Eq. (1) and the assumption of orthogonality of the damping matrix lead to

$$\ddot{\mathbf{y}}_i + D_i \dot{\mathbf{y}}_i + W_i \mathbf{y}_i = -\mathbf{b}_i \ddot{Z}_0 \pm U_i^T \mathbf{F}_i, \quad (3)$$

where

$$\begin{aligned} D_i &= \text{diag}(2\xi_a \omega_a), \quad (\alpha=1 \sim l_i) \\ W_i &= \text{diag}(\omega_a^2) \\ \mathbf{b}_i &= (U_i^T M_i U_i)^{-1} U_i^T M_i I_i. \end{aligned} \quad (4)$$

Rewriting Eq. (3) as a state space expression,

$$\dot{\mathbf{Y}}_i = A_i \mathbf{Y}_i + J_i \ddot{Z}_0 \pm P_i \mathbf{F}_i \quad (5)$$

is obtained, where

$$\begin{aligned} \mathbf{Y}_i &= (\dot{\mathbf{y}}_i, \mathbf{y}_i)^T \\ A_i &= \begin{bmatrix} -D_i & -W_i \\ E_i & O \end{bmatrix} \\ J_i &= (b_i, O)^T \\ P_i &= (U_i^T, 0)^T. \end{aligned} \quad (6)$$

In the following, the dynamic behavior of the joint elements is investigated. Let $\mathbf{a}_i$ refer to the n -by-1 jointed point displacement vector in i -th substructure. Here n is the total count of joint elements. Two coordinate vectors, $\mathbf{a}_i$ and $\mathbf{x}_i$, are related as

$$\mathbf{a}_i = \mathbf{T}_i \mathbf{x}_i, \quad (7)$$

where $\mathbf{T}_i$ is the n -by- n_i coordinate transformation matrix. Here, the force vector of joint elements $\mathbf{F}_i$ and the state vector in the modal coordinates $\mathbf{Y}_i$ are related as

$$\mathbf{F}_i = \mathbf{T}_i^T \cdot q (\mathbf{T}_{w2} \mathbf{Y}_2 - \mathbf{T}_{w1} \mathbf{Y}_1), \quad (8)$$

where n by $2n$ matrix q is expressed with the characteristics of joint elements. The detailed expression of matrix q is discussed again: $\mathbf{T}_{wi}$ ($i=1, 2$) in Eq. (9) is the $2n$ by- $2l_i$ matrix.

$$\mathbf{T}_{wi} = \begin{bmatrix} \mathbf{T}_i U_i & O \\ O & \mathbf{T}_i U_i \end{bmatrix} \quad (9)$$

The block diagram based on this formulation is shown in Fig. 4. The symbols in each block correspond to the above matrices. Blocks r_1 , r_2 and r_{12} just before the outputs are expressed as

$$\begin{aligned} r_i &= [O, U_i], \quad (i=1, 2) \\ r_{12} &= [O, \text{diag}(1)]. \end{aligned} \quad (10)$$

Here, two kinds of joint elements are considered: viscoelastic elements and elastoplastic elements. In

Fig. 4 Block diagram of jointed structure

Fig. 5 Modeling of elastoplastic ties

the case of the viscoelastic elements, the block designated 'q' is expressed by

$$q = [\text{diag}(c_j), \text{diag}(k_j)], \quad j=1, 2, \dots, n, \quad (11)$$

where c_j and k_j are damping and spring constants of the j -th joint element, respectively.

In order to express the characteristics of elastoplastic elements, the mechanical model shown in Fig. 5 is introduced. This model includes a Coulomb friction force F_c , which is expressed using the nomenclature in Fig. 5 as

$$\begin{aligned} F_c &= F_y \frac{\dot{x}_c - \dot{x}_A}{|\dot{x}_c - \dot{x}_A|}; \quad \dot{x}_c \neq \dot{x}_A \\ &= k_b(x_B - x_c); \quad \dot{x}_c = \dot{x}_A, \end{aligned} \quad (12)$$

where F_y corresponds to the yield force. This relation is expressed as the block diagram and incorporated into block 'q'. The spring k' , which implies the second modulus in the elastoplastic model in Fig. 5, is also incorporated in block 'q'. 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.

3. Application to Boiler Structures: Simulation Model

3.1 Modeling of boiler structures

Figure 6 shows a view of a typical large-scale boiler plant in a thermal power station. In the case of a 1000-MW-class plant, the structure is over 80 meters high. The boiler itself has an asymmetrical box-type structure and weighs approximately 10 000 tons. It is suspended from the roof girders of its supporting structure so as not to restrict thermal

Fig. 6 Boiler structure

Fig. 7 Simulation model of boiler structure

expansion in the vertical direction. To restrain pendular motion in horizontal directions, joint elements are attached at specific points. Hereafter, these joint elements are referred to as “seismic ties”.

The simulation model of the boiler structure, which consists of lumped mass and spring elements, is illustrated in Fig. 7. In order to reduce the order of the model, a 3-dimensional steel frame of the supporting structure is compressed in the direction of seismic input, and expressed by an equivalent 2-dimensional lumped mass model. The total degrees of freedom (DOFs) of this model are reduced to 102, which is still too large to adopt in the optimization which requires many repetitions of seismic response simulation in the time domain. Therefore, further reduction of DOFs is achieved by the substructure synthesis method. Figure 8 shows the results of a modal analysis of each substructure. A parametric study is carried out on the maximum order l_i ($i=1, 2$) in the mode superposition for each substructure.

3.2 Accuracy of simulation model

Modal analysis of the entire structure and seismic response simulation are performed for various pairs of l_i , which is the maximum order in modal superposition for the supporting structure, and l_2 , that for the boiler. The results are compared with those of the

Table 1 Comparison of natural frequencies (Hz)

	$l_1 = 5$ $l_2 = 3$	$l_1 = 10$ $l_2 = 5$	$l_1 = 20$ $l_2 = 5$	MARC (Participation Factor)
f_1	0.737	0.724	0.695	0.687 (4.937)
f_2	—	—	1.228	1.223 (0.072)
f_3	1.507	1.370	1.300	1.283 (0.881)
f_4	1.812	1.645	1.498	1.478 (0.543)
f_5	2.059	1.765	1.709	1.678 (0.869)

l_1 : Max. Mode No. of Supporting Structure

l_2 : Max. Mode No. of Boiler

Fig. 8 Eigen modes of substructures

nonlinear FEM Code, MARC.

Table 1 shows the results of modal analysis. The pair of $l_1=20$ and $l_2=5$ yields excellent agreement with MARC results. For the pair of $l_1=5$ and $l_2=3$, higher-mode natural frequencies of the proposed

method yield discrepancies of approximately 20%, but in the fundamental mode which has the largest participation factor, the discrepancy is only 7%.

Comparative studies are performed for the seismic response simulation and it is concluded that the pair of $l_1=5$ and $l_2=3$ yields sufficient accuracy for practical designs. The simulation data shown in Figs. 9 and 10 confirm the above-mentioned results. In this simulation, the Taft (E-W) earthquake record, shown in Fig. 11, is used as input. As the seismic tie characteristics, elastoplasticity acquired by optimum calculation, which is shown in Table 3, is adopted. For the reaction force of the seismic ties, the proposed method yields a slightly deformed hysteresis loop. However, in terms of response displacement, the results of the proposed method agree very well with MARC results. Speedy calculations can be achieved by the proposed model, which is essential for optimum calculation. Actually, using this model, the computational time of this simulation is only 58 s with VAX station 3100. Therefore this model could be adopted in the optimum calculation.

Fig. 9 Comparison of response displacement

Fig. 10 Comparison of tie 1 reaction force (Case 1, optimum)

4. Application to Boiler Structures: Optimization

4.1 Conditions for optimization

Using the above-mentioned model excited by the Taft (E-W) record, optimum calculation for the seismic ties is carried out. Table 2 and Fig. 12 show the conditions for optimization. The objective function is defined by the seismic response shear force yielded on the column elements of the supporting structure:

$$\bar{G} = \sum_{i=1}^N G_i / N, \quad (13)$$

where G_i is the maximum value of the i -th element shear force. The constraint condition for the relative displacement is defined as

$$\delta x_{\max} = \max(\delta x_1, \delta x_2, \dots, \delta x_n) < 15 \text{ cm}, \quad (14)$$

where δx_i is the maximum value of relative displacement.

Table 2 Conditions for optimization

Items	Viscoelastic Ties	Elastoplastic Ties
Design Variables & Side Constraints	$0 < k < 5 \times 10^9 \text{ N/m}$ $0 < c < 5 \times 10^8 \text{ N}\cdot\text{s/m}$	$0 < k < 5 \times 10^9 \text{ N/m}$ $0 < x_y < 1.0 \text{ cm}$
Behavior Constraints	$\delta x_{\max} < 15.0 \text{ cm}$	$\delta x_{\max} < 15.0 \text{ cm}$ $0 < \mu_{\max} < 20$
Objective Function	$\bar{G} = \sum_{i=1}^N G_i / N$ G_i : Shear Force of Column Element i	

δx : Relative Displacement $\mu = \delta x / x_y$: Ductility Factor

Table 3 Comparison of tie specifications
(k : 10^6 N/m , x_y : $\times 10^{-2} \text{ m}$, c : $\times 10^6 \text{ N}\cdot\text{s/m}$)

Items	Conventional	Case 1		Case 2	
		Initial	Optimum	Initial	Optimum
Tie 1	$k = 260.0$	$k = 300.0$	$k = 513.9$	$k = 10.0$	$k = 0.0$
	$x_y = 0.7$	$x_y = 0.5$	$x_y = 0.4$	$c = 10.0$	$c = 24.0$
Tie 2	$k = 350.0$	$k = 300.0$	$k = 518.0$	$k = 300.0$	$k = 458.6$
	$x_y = 0.7$	$x_y = 0.5$	$x_y = 1.0$	$x_y = 0.5$	$x_y = 1.0$
Tie 3	$k = 360.0$	$k = 300.0$	$k = 5.2$	$k = 300.0$	$k = 55.0$
	$x_y = 0.7$	$x_y = 0.5$	$x_y = 0.6$	$x_y = 0.5$	$x_y = 0.3$
Tie 4	$k = 510.0$	$k = 150.0$	$k = 71.3$	$k = 150.0$	$k = 308.2$
	$x_y = 0.7$	$x_y = 0.5$	$x_y = 1.0$	$x_y = 0.5$	$x_y = 1.0$

—: Constraint is active.

Fig. 11 Input time data (Taft, E-W)

Fig. 12 Arrangement of seismic ties

ment at the i -th seismic tie. Two kinds of seismic ties are prepared: viscoelastic ties, and elastoplastic ties. A viscoelastic tie is specified by two design variables: spring constant k , and damping constant c . For an elastoplastic tie, the positive bilinear model shown in Fig. 5 is adopted, and the relation between the spring constant k and the second modulus k' is assumed to be $k'=0.02k$. Therefore this seismic tie is specified by the two design variables, elastic spring constant k and yield displacement x_y . Taking into account the strengths and specifications of this kind of seismic tie, additional constraint conditions are considered for the ductility factor μ and yield displacement x_y :

$$\mu_{\max} = \max(\mu_1, \mu_2, \dots, \mu_n) < 20 \quad (15)$$

$$x_y < 1 \text{ cm},$$

where μ_i is defined as the ratio of relative displacement δx_i and yield displacement x_{yi} at the i -th seismic tie.

Usually, viscoelastic ties are superior in their ability to absorb kinetic energy and are more expensive than elastoplastic ties. Considering these facts, two cases for optimization, shown in Fig. 12, are carried out: Case 1 where only elastoplastic ties are adopted, and Case 2 where viscoelastic ties are incorporated at the bottom of the boiler. In both cases, ten seismic ties are used. Here, in order to reduce the computational time in the optimization which depends on the total number of design variables, these seismic ties are divided into four groups. Seismic ties in one group are assumed to have the same characteristics, so eight design variables are optimized.

4.2 Results of optimization

As an example of optimum calculation, the process of optimization in Case 2 is given in Fig. 13. In this figure the trends of the objective function, the constraint functions and eight design variables are illustrated. The objective function $\bar{G}$ is reduced approximately 35% in comparison with its initial value. Side constraints for yield displacements (x_{y2} , x_{y3} and x_{y4}) have become active. These constraint conditions have restricted the process of optimization. In addition,

Fig. 13 Process of optimization (Case 2)

Fig. 14 Comparison of shear force distribution

this figure implies that the seismic ties at the bottom of the boiler should consist of only dashpot devices with no spring elements.

The seismic tie characteristics before and after optimization in Cases 1 and 2 are listed in Table 3. For Case 1, this table indicates that only two spring constants, k_1 and k_2 , remain after optimization. Here, again, side constraints for yield displacement (x_{y2} , x_{y4}) have become active. It is also confirmed that in the process of optimization, the pendular motion of the boiler generated large displacements at the bottom of

the boiler, and this phenomenon activates the behavior constraint $\mu_{\max}$. On the other hand, the lowest ties in Case 2 are assumed to have viscoelastic characteristics and are free from such constraints. Thus Case 2 achieves better optimization than Case 1. This is clear in Fig. 14 which shows the distribution of maximum shear force on two representative frames of the supporting structure. The location of these frames are shown in Fig. 12. Here three kinds of data are shown: conventional, Case 1 and Case 2. Case 2 yields excellent reduction of seismic load distribution on the supporting structure.

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

5. Conclusion

We presented a practical optimum design method of joint elements in plant structures excited by earthquakes. Fundamental conclusions are summarized as below.

(1) Optimum design formulation is achieved for the aseismic design of adjacent structures with viscoelastic and elastoplastic joint elements.

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

(3) The model reduction method based on substructure synthesis is adopted. In the seismic response simulation for elastoplastic ties, this method achieved practical accuracy and speedy calculation.

(4) Through the numerical study for the optimum calculation using actual boiler plant structures, this method has been proven practical and efficient for aseismic designs of complex structures such as boiler plant structures.

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