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RESEARCH ON SEISMIC RETROFIT USING ADDITIONAL OUTSIDE FRAME WITH BUILT-IN DYNAMIC MASS AND DAMPERS

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Abstract

This study proposes a new seismic retrofit system which uses soft spring devices connecting the main structure and a subsystem using response control devices. The subsystem is composed of additional outside frames which are attached on the outside of the main structure to control seismic response. The seismic retrofit methods by response control devices can be classified into two major methods. One is the method of using the response control frames on the outside of existing building. The other is the method of attaching them in frames of existing building. This study draws attention to the former method. In this study, there are two common approaches to connect the main structure and subsystem:(1)using high rigidity members so that they respond as an integrated structure; and (2) using the coupling damping method which is connected with the response control devices between the main structure and subsystem without them. In the former case, it is often difficult to attach the rigid members to the main structure (e.g., concreate) because of significant material degradation. In the latter case, a large mass is required for the subsystem because the performance of main structure is determined by the mass of the subsystem. This study addresses the use of the dynamic mass (D.M.) for the outside frame to improve the seismic retrofit system to avoid the above problems. In this new system soft springs are used for the connection devices rather than rigid members. It is also possible to increase the mass of the subsystem by using the damping frame as the D.M. Such improvements have been achieved by the use of the D.M. to control the mass term in the equation of motion. This paper derives a theoretical formula for this system. Based on "invariant point theory," optimal tuning and optimum damping formulas are derived. In addition, by expressing these formulas as function of natural periods, a multi-degree of freedom system can be applied with eigen-value analysis. The effectiveness of the proposed approach is illustrated with a practical design method and an example of its application.

Keywords: seismic retrofit using additional outside frame, response control, dynamic mass

1. Introduction

Japan is in need of early and efficient seismic retrofit of existing buildings in preparation for long-predicted mega-earthquakes. On the whole, earthquake preparedness efforts in Japan are not going as well as hoped for. The reason for this, it is said, is that seismic retrofit makes it necessary for residents to temporarily move out during construction and there are also problems associated with the construction period.

A seismic retrofit method that has been used in recent years for existing low-rise and medium-rise reinforced concrete buildings as a way to address those problems is the seismic retrofit using additional outside frame. The seismic retrofit using additional outside frame can be achieved either by using steel brace frames or by using steel frames with built-in response control devices.

In the seismic retrofit using additional outside frame, unlike in the popular seismic retrofit, the grid line of main frame is not aligned with the grid line of the reinforcing frame as shown in Reference [1]. It is therefore necessary to take into consideration stress and deformation at the joints of the two frames, which do not need to be considered in conventional seismic retrofit projects. Main factors that need to be taken into consideration in this connection include eccentric moment due to the non-alignment of the grid line and the effect of frame joints when subjected to ground motion in the perpendicular direction. When planning for seismic retrofit, it is also necessary to take into consideration other factors affecting design stress such as the difference between the statically calculated stress and the dynamic response stress, increases in the shear force to be resisted because of the additional outside frame, concrete strength and reinforcement details of the existing frame, and construction accuracy. The joints between the existing frame and the additional outside frame must be designed so as to ensure a sufficient level of joint member strength needed to transfer the shear forces and tensile forces acting at and near the joints. Those joint members are shear connectors such as post-installed anchors and studs. It is generally believed, therefore, that a large number of shear connectors are needed and the number of construction work steps increases.

By applying the seismic retrofit method using additional outside frame mentioned above, this study proposes a new seismic retrofit method that connects the existing structural frame with outside frames with built-in dampers and dynamic mass (DM) systems capable of providing a rotating inertia mass to the existing frame.

In the proposed method, the existing frame and the outside frame can be connected together at the highest floor level alone. Figure 1-1 illustrates the proposed method. Figure 1-2 compares the conventional connection method and the connection method used in the proposed method. The built-in DM damper system of the outside frame makes it possible to adjust the mass of the outside frame for effective seismic response control. In short, the proposed system connects the outside frame equipped with a dynamic mass system and a viscous damper system to the existing frame to control the seismic response of the existing frame by use of the phase difference between the two frames. Hereafter in this paper, this system is referred to as the "DM Outside Frame Coupling Vibration Control System." Since this system reduces the numbers of joints and outside frames, it may also reduce the number of construction steps needed to achieve retrofit goals.

The authors think that in order to put this system into practical use, it is necessary to [1] develop a design method for optimal attunement of the existing frame and the outside frame and [2] reduce the influence of higher modes of outside frame vibration and increase the mass. To achieve the first objective, design formulas for optimizing attunement and damping by a control method that uses the reinforcing frame as an additional mass are derived by using a simple model, and a formula for joint stiffness calculation is derived. Then, the relations of the formulas thus derived are used to show how effective the additional mass effect of the reinforcing frame is in controlling the seismic response of the main structural frame. The second objective can be achieved by using the complete mode control method proposed by Furuhashi and Ishimaru [2] and the method of adjusting the natural period while retaining the eigenvector.

The rest of this paper discusses the effectiveness of the proposed DM outside frame coupling vibration control system.

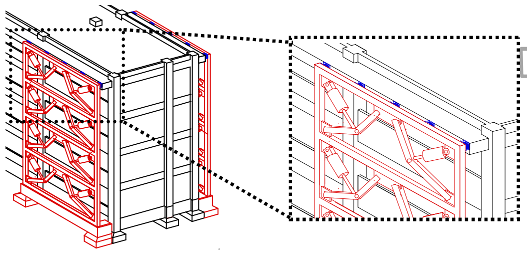

Fig. 1-1—DM outside frame coupling vibration control system

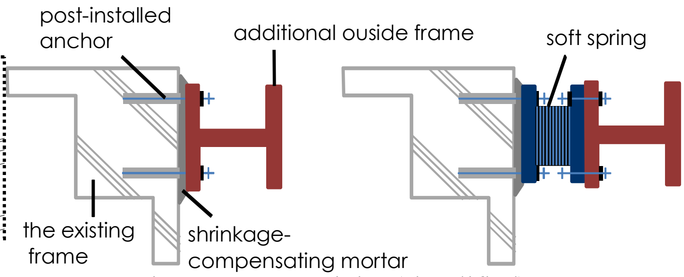

Fig. 1-2—Frame joint (simplified)
(left: conventional retrofit, right: proposed retrofit)

2. Overview of DM Outside Frame Coupling Vibration Control System

The DM outside frame coupling vibration control system proposed in this paper is an outside frame connected to the existing frame by soft springs formed by a viscous damper system with a dynamic mass as shown in Figure 2-1. As the first step, the vibration equation of the proposed model is derived. Then, an optimal tuning equation and an optimal damping equation are derived accordingly.

2.1 Optimal tuning equation

The vibration equation shown in Figure 3-1 is given as Eq. (1), where m_m and m_s are the masses of the existing model and the outside frame, respectively; km and k_s, their stiffness; m_d and c_d, the dynamic mass and damping provided to the outside frame; k_d, the stiffness of the connection between the existing frame and the outside frame; and , input acceleration.

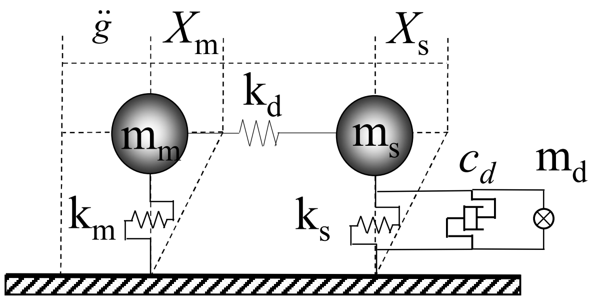

Fig. 2-1—DM outside frame coupling vibration control model

$$\begin{bmatrix} m_m & \\ & m_s + m_{d,s} \end{bmatrix} \begin{Bmatrix} \ddot{x}_m \\ \ddot{x}_s \end{Bmatrix} + \begin{bmatrix} & \\ & c_{d,s} \end{bmatrix} \begin{Bmatrix} \dot{x}_m \\ \dot{x}_s \end{Bmatrix} + \begin{bmatrix} k_m + k_d & -k_d \\ -k_d & k_s + k_d \end{bmatrix} \begin{Bmatrix} x_m \\ x_s \end{Bmatrix} = -\begin{bmatrix} m_m & \\ & m_s \end{bmatrix} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \ddot{g} \tag{1}$$

Dividing by mm for the existing frame and by ms for the outside frame, we obtain

$$\begin{bmatrix} 1 & \\ & 1+\eta_m \end{bmatrix} \begin{Bmatrix} \ddot{x}_m \\ \ddot{x}_s \end{Bmatrix} + \begin{bmatrix} & \\ & 2h_s \omega_s \sqrt{\dfrac{\gamma_k}{\gamma_m}} \end{bmatrix} \begin{Bmatrix} \dot{x}_m \\ \dot{x}_s \end{Bmatrix} + \begin{bmatrix} \omega_m^2 (1+\kappa_k) & -\kappa_k \omega_m^2 \\ -\dfrac{\kappa_k \omega_m^2}{\gamma_m} & \dfrac{(\gamma_k + \kappa_k)\omega_m^2}{\gamma_m} \end{bmatrix} \begin{Bmatrix} x_m \\ x_s \end{Bmatrix} = -\begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \ddot{g} \tag{2}$$

The symbols in Eq. (2) are defined as follows:

$$\omega_m = \sqrt{\frac{k_m}{m_m}}, \ \omega_s = \sqrt{\frac{k_s}{m_s}}, \ \gamma_m = \frac{m_s}{m_m}, \ \gamma_k = \frac{k_s}{k_m}, h_s = \frac{c_{d,s}}{2\omega_s \cdot m_s}, \ \kappa_k = \frac{k_d}{k_m}, \ \eta_m = \frac{m_d}{m_s} \tag{3}$$

If the steady response solutions to Eq. (2) are assumed to be $x_m = X_m e^{i\omega t}$, $= -\omega^2 G e^{i(\omega t+\varphi)}$, then the amplitude amplification factor X_m/G can be expressed as

$$\lambda = \frac{\omega}{\omega_m}$$

$$\left|\frac{X_m}{G}\right| = \sqrt{\frac{\lambda^2\{(\gamma_k+\kappa_k+\gamma_m\kappa_k)-\gamma_m(1+\eta_m)\lambda^2\}^2+\left(2h_s\sqrt{\gamma_m\gamma_k}\,\lambda^3\right)^2}{\left[\{(\gamma_k+\kappa_k)-\gamma_m(1+\eta_m)\lambda^2\}\{(1+\kappa_k)-\lambda^2\}-\kappa_k^2\right]^2+\{(1+\kappa_k)-\lambda^2\}^2\left(2h_s\sqrt{\gamma_m\gamma_k}\,\lambda\right)^2}} \tag{4}$$

As the next step, the optimum conditions that minimize the peak of the response amplification factor curve are derived by using fixed point theory:

Amplitude amplification factor when $h_s = 0$:

$$\left|\frac{X_m}{G}\right|_{h_s=0} = \lambda^2\frac{\{\gamma_k+\kappa_k+\gamma_m\kappa_k\}-\gamma_m(1+\eta_m)\lambda^2}{\{(\gamma_k+\kappa_k)-\gamma_m(1+\eta_m)\lambda^2\}\{(1+\kappa_k)-\lambda^2\}-\kappa_k^2} \tag{5}$$

Amplitude amplification factor when hs = ∞:

$$\left|\frac{X_m}{G}\right|_{h_s=\infty} = \frac{\lambda^2}{\lambda_\infty{}^2-\lambda^2} \tag{6}$$

Amplitude amplification factor at a fixed point determined irrespective of hs:

$$\left(\frac{X_m}{G}\right)^2 = \frac{C+Dh_s{}^2}{A+Bh_s{}^2} = \frac{D}{B}\left[\frac{(C/D)+h_s{}^2}{(A/B)+h_s{}^2}\right] \tag{7}$$

$$A = \left[\{(\gamma_k+\kappa_k)-\gamma_m(1+\eta_m)\lambda^2\}\{(1+\kappa_k)-\lambda^2\}-\kappa_k{}^2\right]^2$$

$$B = \{(1+\kappa_k)-\lambda^2\}^2\left(2\sqrt{\gamma_m\gamma_k}\,\lambda\right)^2,\ C = \lambda^2\{(\gamma_k+\kappa_k+\gamma_m\kappa_k)-\gamma_m(1+\eta_m)\lambda^2\}^2,\ D = \left(2\sqrt{\gamma_m\gamma_k}\,\lambda^3\right)^2$$

Thus, the amplitude amplification factor equation does not include an hs term under the condition of $A/B = C/D$, and calculation can be made irrespective of h_s. This fixed point that can be determined irrespective of h_s is the point of intersection between Eq. (5) and Eq. (6), and Figure 2-2 shows this relationship. In Figure 2-2, there are two points of intersection if it is assumed that the existing frame is the only thing to be controlled. By equalizing the heights of the fixed points P and Q, the conditions that maximize the two fixed points are derived.

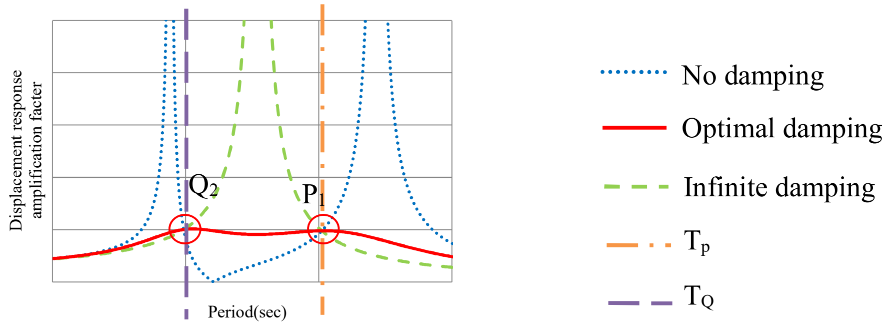

Fig. 2-2—Displacement response amplification factor curve for existing frame

To find the points of intersection between Eq. (5) and Eq. (6), the following equation is considered:

$$\lambda^2 \frac{\{\gamma_k + \kappa_k + \gamma_m \kappa_k\} - \gamma_m (1+\eta_m)\lambda^2}{\{(\gamma_k + \kappa_k) - \gamma_m (1+\eta_m)\lambda^2\}\{(1+\kappa_k) - \lambda^2\} - \kappa_k^2} = -\frac{\lambda^2}{(1+\kappa_k) - \lambda^2} \tag{8}$$

Rewriting this equation with respect to λ, we obtain

$$\lambda^4 - \left\{\frac{2\gamma_k + 2\kappa_k + \gamma_m \kappa_k}{2\gamma_m (1+\eta_m)} + 1 + \kappa_k\right\}\lambda^2 + \frac{2\gamma_k + 2\kappa_k + \gamma_m \kappa_k}{2\gamma_m (1+\eta_m)} + \frac{\kappa_k (2\gamma_k + \kappa_k + \gamma_m \kappa_k)}{2\gamma_m (1+\eta_m)} = 0 \tag{9}$$

For the frequencies λ_p and λ_Q at the fixed points P_1 and Q_2, this polynomial of λ can be rewritten as

$$\begin{aligned} &(\lambda - \lambda_P)^2 (\lambda - \lambda_Q)^2 = 0 \\ &\therefore \lambda^4 - \left(\lambda_P{}^2 + \lambda_Q{}^2\right)\lambda^2 + \lambda_P{}^2 \lambda_Q{}^2 = 0 \end{aligned} \tag{10}$$

Comparing the coefficients of Eq. (9) and Eq. (10), we obtain

$$\begin{aligned} &\lambda_P{}^2 + \lambda_Q{}^2 = \frac{2\gamma_k + 2\kappa_k + \gamma_m \kappa_k}{2\gamma_m (1+\eta_m)} + 1 + \kappa_k = A \quad , \\ &\lambda_P{}^2 \lambda_Q{}^2 = \frac{2\gamma_k + 2\kappa_k + \gamma_m \kappa_k}{2\gamma_m (1+\eta_m)} + \frac{\kappa_k (2\gamma_k + \kappa_k + \gamma_m \kappa_k)}{2\gamma_m (1+\eta_m)} = B \end{aligned} \tag{11}$$

Since A in Eq. (7) is a characteristic equation of the system for h_s, if its roots are represented by $\lambda_{0.1}$ and $\lambda_{0.2}$, then, because of the nature of roots, the following relation holds true:

$$\begin{aligned} &\lambda^4 - \left\{\frac{\gamma_k + \kappa_k}{\gamma_m (1+\eta_m)} + (1+\kappa_k)\right\}\lambda^2 + \left\{\frac{\gamma_k + \kappa_k + \gamma_k \kappa_k}{\gamma_m (1+\eta_m)}\right\} = 0 \\ &\therefore \quad \lambda_{0,1}{}^2 + \lambda_{0,2}{}^2 = \frac{\gamma_k + \kappa_k}{\gamma_m (1+\eta_m)} + \lambda_\infty{}^2 \;,\;\; \lambda_{0,1}{}^2 \lambda_{0,2}{}^2 = \frac{\gamma_k + \kappa_k + \gamma_k \kappa_k}{\gamma_m (1+\eta_m)} \end{aligned} \tag{12}$$

Hence, Eq. (9) can be rewritten as

$$\begin{aligned} &\lambda^4 - A\lambda^2 + B = 0 \\ &A = \lambda_\infty^4 + \lambda_\infty^2 - \frac{2\gamma_k \kappa_k + \gamma_m \kappa_k^2}{2\gamma_m (1+\eta_m)} \quad , \quad B = \lambda_\infty^2 + \frac{\kappa_k^2}{2\gamma_m (1+\eta_m)} \end{aligned} \tag{13}$$

and the roots can be rewritten as

$$\lambda_P^2 = \frac{1}{2}A - \frac{1}{2}\sqrt{A^2 - 4B} \quad , \quad \lambda_Q^2 = \frac{1}{2}A + \frac{1}{2}\sqrt{A^2 - 4B} \tag{14}$$

This is also the basis for Eq. (11) as well.

Now, since the response amplification factor heights in Eq. (7) at the fixed points *P* and *Q* are the same, in view of the fact that points *P* and *Q* are in opposite phases, the following relation holds true:

$$\left.\frac{X_m}{G}\right|_{h_s=\infty,P} = -\left.\frac{X_m}{G}\right|_{h_s=\infty,Q} \tag{15}$$

Substituting Eq. (6) in Eq. (15), we obtain

$$\frac{\lambda_P^{\ 2}}{\lambda_\infty^{\ 2}-\lambda_P^{\ 2}}=-\frac{\lambda_Q^{\ 2}}{\lambda_\infty^{\ 2}-\lambda_Q^{\ 2}} \Rightarrow \frac{2\lambda_P^{\ 2}\lambda_Q^{\ 2}}{\lambda_P^{\ 2}+\lambda_Q^{\ 2}}=\lambda_\infty^{\ 2}=\frac{2B}{A} \tag{16}$$

Substituting Eq. (11) in Eq. (16) gives

$$\lambda_\infty^{\ 4}=\frac{\gamma_k+\kappa_k+\gamma_k\kappa_k}{\gamma_m(1+\eta_m)}+\frac{\kappa_k}{2(1+\eta_m)}(1+\kappa_k) \tag{17}$$

Substituting $\lambda_{0.1}^{\ 2}$ and $\lambda_{0.2}^{\ 2}$ and $(1+\kappa_k)=\lambda_\infty^{\ 2}$ in Eq. (12) in Eq. (17) and rewriting gives

$$\lambda_\infty^{\ 4}=\lambda_{0,1}^{\ 2}\lambda_{0,2}^{\ 2}\left\{\frac{2(1+\eta_m)(1+\kappa_k)}{2(1+\eta_m)(1+\kappa_k)-\kappa_k}\right\} \tag{18}$$

Transforming Eq. (18) into a natural period relation gives Eq. (19):

$$T_\infty=\sqrt{T_{0,1}T_{0,2}\sqrt{1-\frac{\kappa_k}{2(1+\eta_m)(1+\kappa_k)}}} \tag{19}$$

Equation (19) gives an optimal tuning condition if κ_k is adjusted and eigenvalue analysis is conducted so as to achieve a natural period under infinitely large damping, T_∞.

This means that even in a multi-mass system, optimal tuning can be achieved if this relation holds true.

2.2 Optimal damping equation

In this section, an optimal damping equation for calculating the damping factor that maximizes the response amplification factor at a fixed point as in the optimal damping shown in Figure 2-2 is derived.

As the first step, from Eq. (15) and Eq. (16), we obtain

$$\left.\frac{X_m}{G}\right|_{P1,Q2}=\frac{\lambda_{P1}^{\ 2}}{\lambda_\infty^{\ 2}-\lambda_{P1}^{\ 2}}=\frac{\lambda_{P1}^{\ 2}}{\dfrac{2\lambda_{P1}^{\ 2}\lambda_{Q2}^{\ 2}}{\lambda_{P1}^{\ 2}+\lambda_{Q2}^{\ 2}}-\lambda_{P1}^{\ 2}}=\frac{\lambda_{P1}^{\ 2}+\lambda_{Q2}^{\ 2}}{\lambda_{Q2}^{\ 2}-\lambda_{P1}^{\ 2}} \tag{20}$$

Substituting Eq. (13) and Eq. (14) in the above equation gives Eq. (21):

$$\left.\frac{X_m}{G}\right|_{P1,Q2}=\frac{\lambda_{P1}^{\ 2}+\lambda_{Q2}^{\ 2}}{\lambda_{Q2}^{\ 2}-\lambda_{P1}^{\ 2}}=\frac{A}{\sqrt{A^2-4B}} \tag{21}$$

Equation (21) expresses the response amplification factors at fixed points P_1 and Q_2. Since resonance curves centered around λ_∞^2 are expected, Eq. (22) has been derived on the assumption that $1/2h$ is the same as Eq. (21). In the outside frame retrofit model, however, the influence of the existing frame and the outside frame is great. Consequently, participation functions of systems whose response is not to be controlled also become large so that their influence is reflected greatly in eigenvalue results. The values, therefore, of the first-mode and second-mode damping factors (h_1 and h_2) in the retrofit case do not agree.

For this reason, in the DM outside frame coupling vibration control model, Eq. (22) is used as the optimal damping equation.

$$h_{opt} = \sqrt{\frac{h_1^2 + h_2^2}{2}} \approx \frac{1}{2}\sqrt{1 - 4 \cdot \frac{B}{A^2}} \tag{22}$$

$$A = (1+\kappa_k)^4 + (1+\kappa_k)^2 - \frac{2\gamma_k \kappa_k + \gamma_m \kappa_k^2}{2\gamma_m (1+\eta_m)} \quad , \quad B = (1+\kappa_k)^2 + \frac{\kappa_k^2}{2\gamma_m (1+\eta_m)}$$

2.3 Relationship of the viscous damping factor with the mass ratio

Since the proposed model uses the outside frame connected to the existing frame for the purpose of seismic response control, the damping factor that can be obtained tends to become larger as the mass ratio between the existing frame and the outside frame (m_s/m_m) increases. As can be seen from Figure 2-3, therefore, damping efficiency improves as the mass ratio or the period ratio (T_s/T_m) increases. The procedure for preparing a diagram showing the relationship of the viscous damping factor with the mass ratio (Figure 2-3) of the proposed model is described below.

The relations shown in Figure 2-3 were calculated from Eq. (19) (optimal tuning equation) and Eq. (22) (optimal damping equation).

A more detailed procedure is as follows. In the model shown in Figure 2-1, the mass ratio is kept constant and the period ratio is varied by adjusting the stiffness of the outside frame. The stiffness of the connections at each period ratio can be calculated by satisfying the optimal tuning equation. Then, an optimal viscous damping factor is calculated by using the optimal damping equation. Figure 2-3 shows plots of the results thus obtained. Figure 2-3 enables structural designers to roughly calculate the mass ratio and the period ratio if a target damping factor is determined.

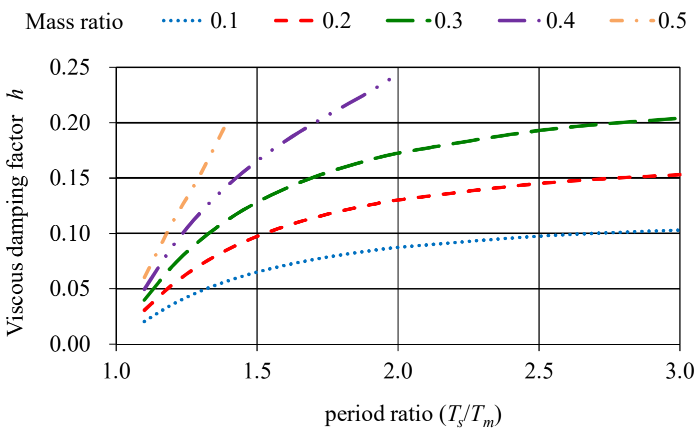

Fig. 2-3—Damping factor–period ratio relationship by mass ratio

3. How to Extend DM Outside Frame Coupling Vibration Control System into Multi-Mass System

The DM outside frame coupling vibration control model is that by adding a dynamic mass to the outside frame, it is now possible to make mass adjustments, which is difficult to achieve with a conventional outside frame, so that the response control retrofit system is capable of mass and period adjustments. Furthermore, in other models, it is necessary to either place many anchor bolts over the entire area of contact of the outside frame or place soft spring materials such as laminated rubber connectors to the beams of the existing building. In the proposed model, laminated rubber connectors need to be installed to the beans at the highest floor level only. This is illustrated in Figure 1-1.

If the proposed model is to be extended into a multi-mass system model, the first-mode generalized mass and first-mode generalized stiffness of the existing frame shown in Figure 3-1 are calculated through eigenvalue analysis and normalized to a multi-mass system (Step 1).

The next step is to assume the generalized mass and generalized stiffness of the outside frame on the basis of the performance goals in terms of the viscous damping factor and the period ratio (Step 2).

Then, the mass and stiffness of the outside frame in the multi-mass system are back-calculated so that the generalized mass and generalized stiffness of the outside frame calculated in Step 2 are met. In accordance with the complete mode control method proposed by Furuhashi and Ishimaru, [2] the material point masses of the outside frame are determined, and the mass of the outside frame is determined by making dynamic mass adjustments (Step 3).

The reason for the modal control of the outside frame is that it is necessary to reduce higher modes to zero and control structural response so that only the first mode occurs because higher modes of the outside frame would affect the existing frame.

The final step is to perform eigenvalue analysis to calculate the initial stiffness of the joints that satisfies Eq. (19) (optimal tuning equation) and calculate the amount of viscous damping of the outside frame by using Eq. (22) (optimal damping equation) to complete the design of the multi-mass system in the proposed model (Step 4).

The next section shows an example of a system designed by the proposed method.

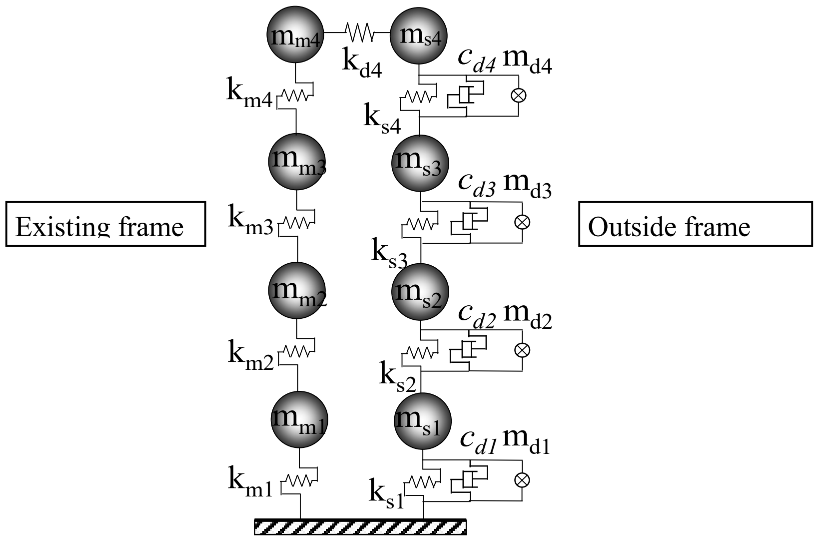

Fig. 3-1—DM Outside Frame Coupling Vibration Control model

4. Design Example of DM Outside Frame Coupling Vibration Control System

4.1 Design example

Step 1: Calculate the generalized mass and generalized stiffness of the existing frame.

The first step in this design method is to calculate the generalized mass and generalized stiffness of the existing frame for the purpose of outside frame modeling. The generalized mass and the generalized stiffness can be calculated from Eq. (23). The first-mode generalized mass and stiffness are shown in Table 4-1.

$$\hat{m}, \hat{k} = r_j^T M r_j \quad , \quad r_j^T K r_j \qquad (23)$$

$\hat{m}$: generalized mass $\hat{k}$: generalized stiffness M: mass matrix K: stiffness matrix rj: jth natural mode

Table 4-1—Generalized mass and stiffness of existing frame

Mode	Natural point Mass (ton)	Initial stiffness (kN/m)
1st	7,338.3	569,559.3

Step 2: Calculate the generalized mass and generalized stiffness of the outside frame.

In this step, the generalized mass and generalized stiffness of the outside frame are calculated. First, the structural designer freely determines the mass of the outside frame in the DM outside frame retrofit model by using the target damping factor and Figure 3-3. In this particular case, in view of the relationship with the other models to be considered for comparison, the damping factor is assumed to be 10% or less. If, therefore, the mass ratio is assumed to be 0.10 according to Figure 2-3, the period ratio is 2.0. The mass ratio in this case is calculated so that the ratio between the story mass, which is the sum of the material mass and the dynamic mass, and the material point mass of the existing frame becomes 0.10.

Step 3: Adjust mass distribution by the complete mode control method.

The next step is to determine mass distributions (material point mass and dynamic mass) by using the complete mode control method. For the proposed model, the mass ratio of 0.10 is distributed into an outside frame mass (material point mass) of 0.05 and a dynamic mass of 0.05. Substituting the material point mass and initial stiffness of the outside frame in Eq. (24) gives the dynamic mass, and the results shown in Table 4-2 are obtained.

$$\begin{aligned}
&{}_1\omega^2 = \frac{1}{\sum_{i=1}^{n}\left(\frac{1}{k_i}\sum_{s=i}^{n} m_s\right)} \\
&\eta_0 = 0 \\
&\eta_i = \eta_{i-1} + \frac{{}_1\omega^2}{k_i}\sum_{s=i}^{n} m_s \qquad (1 \le i \le n) \\
&\{{}_{n+1}u\} = \{1-\eta\} \\
&D_i = \frac{{}_{n+1}u_i}{{}_{n+1}u_{i-1}} \\
&m'_n = 0 \\
&m'_i = \frac{m_i + m'_{i+1}(1 - D_{i+1})}{\frac{1}{D_i} - 1} \qquad (1 \le i \le n-1)
\end{aligned} \qquad (24)$$

${}_1\varpi^2$: eigenvalue for a story

m: mass of each story (ton)

k: stiffness of each story (kN/m)

u: natural mode of each story

η: reduction factor

Table 4-2—DM settings for modal control

Floor	Natural point Mass (ton)	Initial stiffness (kN/m)	$\sum_{s=i}^{n} m_s$	${}_1\omega^2$	η_i	${}_{n-1}u$	D_i	Mass of DM system (ton)
4	191.645	39340.1	191.6	205.3	1.0000	0.0000	0.0000	0
3	182.970	41964.3	374.6	72.5	0.6470	0.3530	0.6737	99.85
2	205.910	46323.5	580.5	38.0	0.4759	0.5241	0.6387	297.84
1	263.310	146428.6	843.8	31.2	0.1796	0.8204	0.8204	1850.78
0	—	—	—	—	0.0000	1.0000	—	—

As a next step, the mass and natural period of the outside frame are adjusted. Since the dynamic mass does not meet the condition of 5% of the mass of the existing frame, this step involves increasing the dynamic mass as a proportional multiple of the initial stiffness of the outside frame to adjust the period ratio so that the period ratio requirement is met. A manipulation like this can be done because of a characteristic of the complete mode control method: by increasing the mass of a dynamic mass system attached to a structural frame as a proportional multiple of the stiffness of the structural frame, the mass can be increased while keeping higher modes at zero.

Step 4: Determine joint stiffness and viscous damper settings.

The fourth step is to determine the stiffness of the existing frame–outside frame connections and design the viscous damper system in the outside frame. The stiffness of the connections is determined through eigenvalue analysis by making adjustments so that the optimal tuning equation shown in Eq. (19) is met. Outside frame viscous damper details are then determined by changing damper performance in proportion to the stiffness of the outside frame. Tables 4-3 and 4-4 show the specifications of the proposed model and the eigenvalue analysis results in the retrofit case. Figure 4-1 shows the fourth-floor response amplification factors of the existing frame and the outside frame.

Table 4-3—Specifications of DM outside frame coupling vibration control model

Floor	Outside frame				Joint	
	Material point mass (ton)	Initial stiffness (kN/m)	Damping factor (kN・s/m)	Mass of DM system (ton)	Damping factor (kN・s/m)	Initial stiffness (kN/m)
4th	191.6	39,340.1	3,147.2	765.2	31,000.0	-
3rd	183.0	41,964.3	3,357.1	916.1	-	-
2nd	205.9	46,323.5	3,705.9	1,198.8	-	-
1st	263.3	146,428.6	11,714.3	4,698.8	-	-

Table 4-4—Results of eigenvalue analysis of DM outside frame coupling vibration control model

Mode	Natural period (sec)	Damping facter
1st	0.750	0.088
2nd	0.654	0.062
3rd	0.265	0.010
4th	0.177	0.013
5th	0.151	0.014

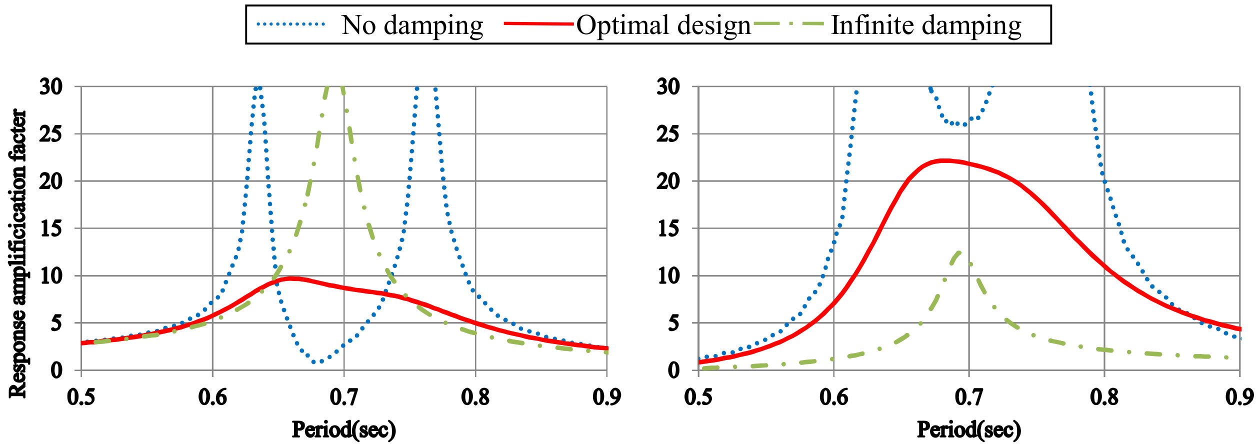

Fig. 4-1—Response amplification factor of DM outside frame coupling vibration control model

(left: existing frame, right: outside frame)

4.2 Time history response analysis results

This section shows the results of the time history response analysis of the proposed model. The BCJ-L1 ground motion has been normalized to 25 cm/s for the purpose of the time history response analysis. The BCJ-l1 is design input BCJ-L1 recommended by BCJ (Building Center of Japan).

As can be seen from the existing building results shown in Figure 4-2, shear force is significantly smaller in the proposed model than in the non-retrofit-control model, indicating that the building resists shear force jointly with the outside frame. Figure 4-3 shows that the amount of response is smaller on the existing building side in all models.

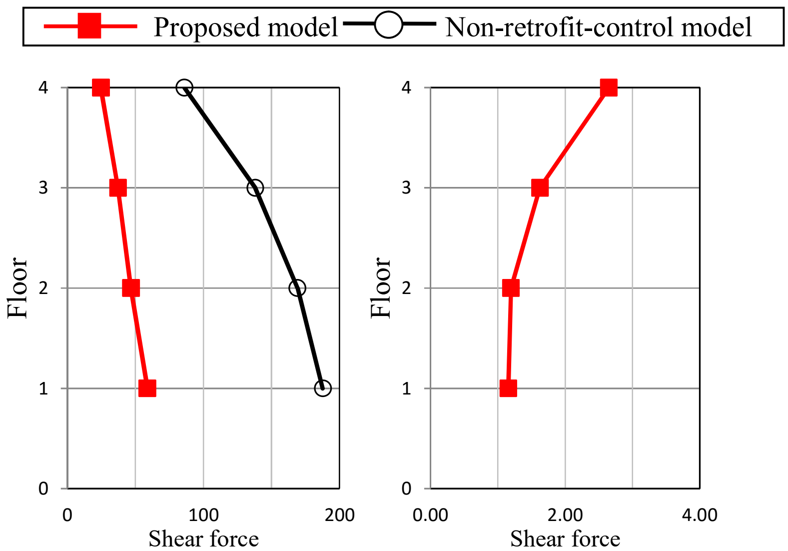

Fig. 4-2—Time history response analysis results (maximum shear force Q (kN))

(left: existing frame, right: outside frame)

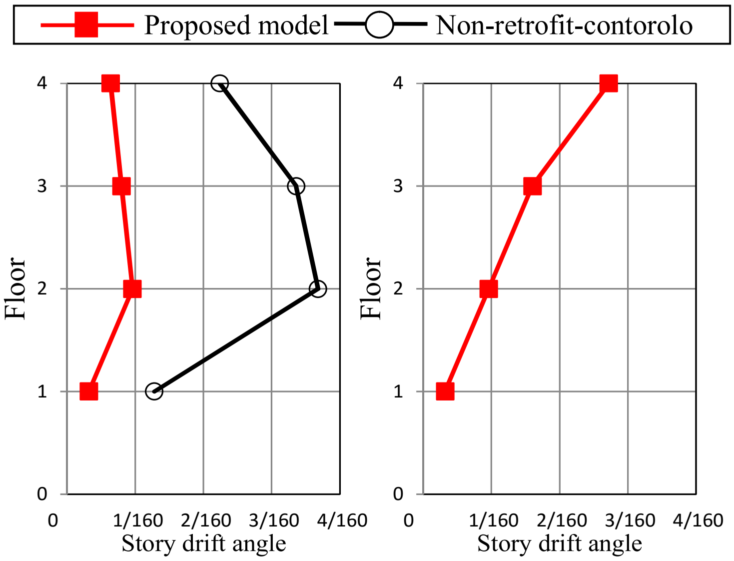

Fig. 4-3—Time history response analysis results

(left: existing frame, right: outside frame)

5. Conclusion

This study has proposed a newly developed the DM Outside Frame Coupling Vibration Control System designed to replace the conventional exterior steel reinforcement frame retrofit system (seismic strengthening model). At present, strength-based seismic retrofit systems designed so that the existing building and exterior reinforcement frames together resist seismic forces by means of similar behaviors are widely used. This paper has proposed a system, referred to as the DM Outside Frame Coupling Vibration Control System, that achieves structural response control through the interaction between an outside frame with a built-in dynamic mass (DM) system and the existing structural frame. This paper has also proposed a simple design optimization method, showing that effective response control can be achieved by use of a large ratio between the masses of the existing structural frame and the outside frame. It is believed that retrofit work efficiency can be improved by using soft spring connectors that do not strongly resist shear force as in the conventional seismic retrofit structures and designing the outside frame so that it can be connected to the existing frame at the uppermost floor level alone.

The authors believe that the proposed retrofit system opens up new possibilities of seismic retrofit using additional outside frame.

6. References

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