Hybrid optimization design approach of asymmetric base-isolation coupling system for twin buildings

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Abstract
This study proposes a new configuration of asymmetric base-isolation coupling system for the vibration control of twin buildings, and also presents an efficient design method of using a hybrid optimization technique integrated with preference-based dimensionality reduction technique. The purpose of the proposed optimization approach is to guarantee the compromise optimal solution of well-balancing the mutually conflicting design objectives. In order to demonstrate the proposed approach, the adjacent 20-story twin buildings subjected to earthquake excitations were adopted as target buildings and it was verified through numerical examples that the proposed optimization technique can successfully find the optimal solution to achieve various design objectives in a balanced manner. The seismic performance was also compared with the existing different-story connection system with uniform distribution of dampers. The comparative results of the seismic performances between two systems clearly demonstrate that the proposed system can achieve great performance improvement over the existing system while maintaining balanced design preferences. Thus, it can be concluded that the proposed system can be a very effective system for the vibration control problem of the twin buildings.

Keywords
Hybrid optimization, asymmetric coupling control system, symmetry perturbation control, twin parallel buildings, base isolation

Introduction
Vibration control of twin buildings is a challenging problem due to the lack of phase difference between two buildings. As observed in the previous studies,¹⁻⁷ the dampers to interconnect two adjacent buildings at the same floor have been recognized as a very efficient way to control two adjacent buildings with different frequency characteristics. However, such inter-building connection dampers do not produce any significant damping effect when the two buildings vibrate with similar frequency characteristics.⁸⁻¹⁰ This is due to the fact that the damper force depends on the relative displacement or relative velocity between the two ends of the damper and the two buildings with similar frequency characteristics do not show any significant difference in the relative responses between the two ends of the damper. More specifically, the relative displacement and the relative velocity of the connecting damper between the two identical structures will become close to zero, which leads to the resultant damping force being small and meaningless in control effect.
In order to overcome such difficulties in controlling adjacent twin buildings with the inter-building damper connection approach, some researchers have focused on how to amplify the relative response of the two ends of the damper. Accordingly, they proposed a slightly modified configuration in which the two buildings are interconnected with dampers in a similar way as before but the dampers are installed to connect the different stories of the two buildings. For example, Makita et al. proposed a cantilevered structure with a difference in connection height so that the two ends of the dampers are connected into different stories of the dynamically similar structures. Instead of connecting the same stories between two buildings, this different-story connection method enables the damper to exert the damping force on both buildings even for the twin buildings. However, as noted by the authors, the mechanism of the different-story damper connection method is conceptually the same as the conventional inter-story damper connection approach in a single building where the damper is connected between two stories of a single building in a diagonal bracing form. In other words, when the two buildings have identical dynamic properties and identical connector link, the equation of motion for the different-story-connected twin buildings can be interpreted as that for the different-story-connected single building but the dynamic properties such as mass, damping coefficient, and stiffness are doubled. With the same concept as that used by Makita et al., Patel and Jangid also proposed three configurations of inter-connecting damper distributions for the dynamically similar adjacent structures in order to amplify the relative response of the two ends of the damper in a different manner. Although the detailed configurations are different, these studies are conceptually similar to each other. These studies adopted a configuration of inter-building different-story damper connection, which can be regarded as a kind of inter-story damping connection approach in a single building.

As a new method for vibration control of adjacent twin structures, this study proposes an asymmetric base-isolation coupling system. The proposed control scheme started from the following facts: The existing inter-building connection method is very effective for two different buildings. For twin structures, however, it becomes invalid due to the behavioral symmetry or lack of phase difference. Then, we figured out the following question: Can we still utilize the benefits of the conventional inter-building connection method for the twin structures if the dynamic characteristics of the twin structures are intentionally made different from each other? In order to answer this question, the following configuration has been devised: One of the twin buildings is intentionally base-isolated to perturb the symmetry of the twin’s frequency characteristics, and then the two buildings, which were originally the same but changed to be different from each other by the base isolation, are coupled with the connecting damper as in the conventional inter-building connection method. Under these intentional asymmetric conditions, the proposed system is expected to be able to take full advantage of the control efficiency of the conventional inter-building connection approach.

The optimal design problem of the proposed asymmetric coupling system involves the simultaneous minimization of several conflicting measures in terms of performance and cost. The performance-related measures may include peak responses of the two buildings such as story drift, floor displacement, absolute acceleration, shear force, bending moments, and so on. The cost-related measures may include the total amount of control resources, such as damping capacity, stiffness amount, maximum damper force, and so on. In addition to these quantities, the maximum displacement of the base-isolation bearing also needs to be included in the design objective because the isolation system can cause the displacement of the building to be excessive. In these regards, the optimal design of the proposed asymmetric base-isolation coupling system for the vibration control of twin buildings to be dealt with in this study entails many objectives to be minimized as well as many design variables to be explored. In order to deal with two issues such as simultaneous optimization of many objectives and exploration of many design variables, this study employs two methods such as a hybrid optimization technique and a preference-based dimensionality reduction technique. The hybrid optimization technique is newly developed for searching the large design-variable space and is known to be efficient. The preference-based dimensionality reduction technique has been applied in literature to handle the conflict of many design objectives, thereby successfully leading to a well-balanced compromising solution between mutually conflicting multiple objectives. Unlike previous studies that used GA as an optimization method, this study uses a hybrid optimization framework as an optimization method. The hybrid optimization technique simultaneously uses three optimization methods such as particle swarm optimization (PSO), genetic algorithm (GA), and harmony searching algorithm (HSA), and selectively allows more participation of one method than the others. This participation adjustment of three optimization methods enables efficient search of large-scale design-variable space and rapid convergence to an optimal solution.

In order to demonstrate the proposed approach, example design has been performed with a system of 20-story twin buildings equipped with the proposed asymmetric base-isolation coupling system. The numerical results are
then investigated in comparison with those of the conventional different-story damper connection system, followed by conclusions.

**Problem Statement**

**Inter-building damper connection system**

Figure 1 illustrates the conceptual drawing of the typical inter-building connection approach where the \( k \)-th and \((k-1)\)-th floors of the two buildings are inter-connected by the dampers. If the coupling dampers correspond to a linear viscous damper, their damping forces are defined as

\[
\begin{align*}
F_{d(k-1)}^c(t) &= c_{k-1} \times \Delta \dot{x}_{k-1}^c = c_{k-1} \times (\dot{x}_{k-1}^2 - \dot{x}_{k-1}^1) \\
F_{dk}^c(t) &= c_k^c \times \Delta \dot{x}_k^c = c_k^c \times (\dot{x}_k^2 - \dot{x}_k^1)
\end{align*}
\]

where \( F_{d(k-1)}^c(t) \) and \( F_{dk}^c(t) \) are the damping forces of the coupling dampers installed at the \((k-1)\)-th and \( k \)-th floors of the two buildings, respectively; \( c_{k-1} \) and \( c_k^c \) are the damping coefficients of the corresponding coupling dampers; \( \dot{x}_i^j \) is the \( j \)-th floor velocity of the \( i \)-th building; and \( \Delta \dot{x}_k^c \) is the relative velocity of the \( k \)-th floor between the two buildings in which the coupling damper is attached. Note that the damping force is increased in proportion not only by the damping coefficient \( c_k^c \) but also by the relative velocity \( \Delta \dot{x}_k^c \) between the two ends of the damper. Hence, it indicates that the efficiency of the damper can be improved if the relative response across the damper can be amplified, even for the same capacity of the damper.

In the vibrations of the two adjacent buildings, the relative response between two adjacent buildings (inter-building response) occurs more largely than the relative response between two successive floors of a single building (inter-story response) in most cases. Thus, the inter-building damper connection approach can utilize a more amplified response, i.e. the inter-building response, rather than the inter-story response. This explains the reason that the inter-building damper connection configuration can be more efficient than the inter-story damper connection configuration. However, as described in the introduction, the inter-building damper connection approach does not exhibit any control effect on twin buildings because of the behavioral symmetry of the twins.

**Asymmetric base-isolated coupling control system**

Figure 2 illustrates the conceptual drawing of the newly proposed asymmetric base-isolation coupling system for the vibration control of twin buildings. The proposed system consists of three subsystems such as one asymmetric base-isolation bearing, one inter-building coupling damper, and a set of inter-story diagonal bracing dampers distributed within the twin buildings. The base-isolation bearing induces asymmetry in the twin buildings and an inter-building coupling damper facilitates the control efficiency through the interaction of damping forces on both buildings. The use of the base-isolation bearing and the coupling damper would not provide sufficient damping capacity to dissipate the vibration energy of the twin structures. This insufficient damping capacity will be covered by using the inter-story diagonal bracing dampers distributed within the two buildings, as shown in Figure 2. Note that the inter-building damper connection is assumed to be fixed to the top floor only where the relative response across the damper can be amplified most significantly. This proposed system can be considered as a kind of hybrid system consisting of the base-isolation bearing, coupling damper, and diagonal bracing dampers. This hybrid system is referred to as the asymmetric base-isolation coupling system in this study. For simplicity, this system will now be designated as the ABiC system.

When this structural system is subjected to ground motion, its equation of motion can be expressed as

\[
\mathbf{M} \ddot{x}(t) + \mathbf{C} \dot{x}(t) + \mathbf{K} x(t) = -\mathbf{M} \ l \ \ddot{x}_g(t)
\]

where \( x(t), \dot{x}(t) \) and \( \ddot{x}(t) \) are the displacement, velocity, and acceleration vectors of the twin buildings at time \( t \); \( \mathbf{M}, \mathbf{C} \) and \( \mathbf{K} \) are the mass, damping, and stiffness matrices of the system; \( \mathbf{l} \) is a column vector with 0 s and 1 s that positions a ground acceleration \( \ddot{x}_g \) into the corresponding DOFs of the floor masses.
As shown in Figure 2, the displacement vector $x(t)$ of the $n$-story twin buildings can be defined as $\left[ x_1(t), x_2(t), \ldots, x_{n-1}(t), x_n(t), x_{n+1}(t), \ldots, x_{2n-1}(t), x_{2n}(t), x_b(t) \right]^T$. Then, the mass, stiffness and damping matrices are defined as

$$
M = 
\begin{bmatrix}
M_1 & 0_{n \times 1} & 0_{n \times 1} \\
0_{n \times n} & M_2 & 0_{n \times 1} \\
0_{1 \times n} & 0_{1 \times n} & m_b
\end{bmatrix}
= 
\begin{bmatrix}
m_1 & \cdots & 0 & 0 \\
\vdots & \ddots & \vdots & \vdots \\
0 & \cdots & m_{2n} & 0 \\
0 & \cdots & 0 & m_b
\end{bmatrix}
$$

(2)

Figure 1. Inter-building damper connection approach.

Figure 2. Asymmetrically isolated twin buildings coupled with a viscous damper.
where $\mathbf{M}$ is the $(2n+1) \times (2n+1)$ mass matrix of the structural system; $\mathbf{M}_i$ is the mass matrix of the $i$-th building ($i=1,2$), e.g. 1 for left building and 2 for right building; $m_b$ is the mass of the base floor of the building 2; $\mathbf{K}$ is the $(2n+1) \times (2n+1)$ stiffness matrices of the structural system; $\mathbf{K}_i$ is the stiffness matrix of the $i$-th shear-type building with components of $[k_1, k_2, \cdots, k_n]^T$ for building 1 and $[k_{n+1}, k_{n+2}, \cdots, k_{2n}]^T$ for building 2; $k_{n+1}$ is the stiffness of the first floor of the building 2; $k_b$ is the stiffness of the base-isolation bearing; and $\mathbf{C}$ is the $(2n+1) \times (2n+1)$ damping matrix of the structural system consisting of $\mathbf{C}_a$, $\mathbf{C}_b$, $\mathbf{C}_c$ and $\mathbf{C}_d$. These matrices are defined as:

$$\mathbf{K} = \begin{bmatrix} \mathbf{K}_1 & 0_{n \times n} & 0_{n \times 1} \\ 0_{n \times n} & \mathbf{K}_2 & \begin{bmatrix} -k_{n+1} \\ 0_{(n-1) \times 1} \end{bmatrix} \\ 0_{1 \times n} \begin{bmatrix} -k_{n+1} \\ 0_{1 \times (n-1)} \end{bmatrix} & 0_{1 \times n} & k_{n+1} + k_b \end{bmatrix}$$

$$\mathbf{C} = \mathbf{C}_a + \mathbf{C}_b + \mathbf{C}_c + \mathbf{C}_d$$

where $\mathbf{C}_a$ is the structural damping matrix in which $\mathbf{C}_1$ and $\mathbf{C}_2$ are the damping matrices of buildings 1 and 2. In this study, each damping matrix $\mathbf{C}_i$ is defined by the Rayleigh damping model. Thus, the coefficients $\alpha_i$ and $\beta_i$ ($i=1,2$) can be determined from the two modal damping ratios which are usually assumed for the first and second modes by the designer; $\mathbf{C}_b$ is the damping matrix of the base-isolation bearing with the damping coefficient $c_b$; $\mathbf{C}_c$ is for the inter-building coupling damper with the capacity $c_c$; and $\mathbf{C}_d$ is the damping matrix of the inter-story diagonal bracing dampers. Here, $\mathbf{C}_{d1}$ and $\mathbf{C}_{d2}$, respectively denote the damping matrices of the bracing dampers for each building, e.g. $[c_{d1}, c_{d2}, \cdots, c_{dn}]^T$ for building 1 and $[c_{d1(n+1)}, c_{d1(n+2)}, \cdots, c_{dn}]^T$ for building 2. Note here that, when the two buildings are twin, the following equality relations hold true: $m_k = m_{n+k}, k_k = k_{n+k}$ ($k = 1, 2, \cdots, n$), $\alpha_1 = \alpha_2, \beta_1 = \beta_2, \mathbf{M}_1 = \mathbf{M}_2, \mathbf{K}_1 = \mathbf{K}_2$, and $\mathbf{C}_1 = \mathbf{C}_2$. It is also noteworthy that the properties of the AbIC system such as $k_b$, $c_b$, $c_c$ and $[c_{d1}, c_{d2}, \cdots, c_{d(2n-1)}]$, $[c_{d2n}]^T$ will become the design variables to be explored and determined in the optimization process.
Design optimization of ABiC system

Formulation of optimization problem

In general, control performance can be improved as more control capacity is used, but it necessarily leads to an increase in cost. Therefore, when evaluating control performance, not only the structural response but also the total control capacity required should be compared at the same time. From this point of view, the design optimization problem of the proposed ABiC system involves simultaneous minimization of both performance-related and cost-related measures. Although various responses can be used as measures to be minimized, this study takes the following responses into account.

The first and second measures \( \lambda_1 \) and \( \lambda_2 \) are, respectively, defined as the sum of the r.m.s. (root-mean-square) values of the story drifts of the two buildings such that

\[
\lambda_1 = \sum_{k=1}^{n} |d_k|_{\text{rms}}
\]

(9)

\[
\lambda_2 = \sum_{k=1}^{n} |d_{n+k}|_{\text{rms}}
\]

(10)

where \(| \cdot |_{\text{rms}}\) represents the r.m.s. operator of a quantity; \(d_k\) and \(d_{n+k}\) correspond to the story drifts between \(k\)-th and \((k-1)\)-th floors of the buildings 1 and 2, respectively. Note here that the first-story drifts are defined as \(d_1 = x_1\) for building 1 and \(d_{n+1} = x_{n+1} - x_b\) for building 2, where \(x_1\), \(x_{n+1}\) and \(x_b\) are the first-floor and base-floor displacements of the two buildings as shown in Figure 2.

The third and fourth measures \( \lambda_3 \) and \( \lambda_4 \) are respectively defined as the maximum r.m.s. value of the story drifts of the two buildings such that

\[
\lambda_3 = \max_{k=1,\ldots,n} \{d_k|_{\text{rms}}\}
\]

(11)

\[
\lambda_4 = \max_{k=1,\ldots,n} \{d_{n+k}|_{\text{rms}}\}
\]

(12)

where the subscript \(k\) represents the floor of the building.

The fifth and sixth measures \( \lambda_5 \) and \( \lambda_6 \) are defined as the sum of the r.m.s. values of the damper forces for each building such that

\[
\lambda_5 = \sum_{k=1}^{n} F_{dk}|_{\text{rms}} = \sum_{k=1}^{n} c_{dk}|_{\text{rms}}\Delta x_k
\]

(13)

\[
\lambda_6 = \sum_{k=1}^{n} F_{d(n+k)}|_{\text{rms}} = \sum_{k=1}^{n} c_{d(n+k)}|_{\text{rms}}\Delta x_{n+k}
\]

(14)

where \(F_{dk}\) corresponds to the damping force of the diagonal bracing damper installed between \(k\)-th and \((k-1)\)-th floors of the building 1; \(\Delta x_k\) is the relative displacement between \(k\)-th and \((k-1)\)-th floors of the building 1; \(F_{d(n+k)}\) and \(\Delta x_{n+k}\) correspond to those of building 2.

The seventh measure \( \lambda_7 \) is defined as the r.m.s. displacement of the base floor of the isolated building 2 such that

\[
\lambda_7 = x_b|_{\text{rms}}
\]

(15)

The first and second measures are to minimize the overall performance on story drift responses, and the third and fourth measures are to prevent the story drift of any particular floor from being excessively amplified by
sacrificing the responses of the other floors. These four measures are intended to ensure the control performance on reducing the excessive vibrations of the structures. The fifth and sixth measures are to minimize the total capacity of the dampers which is related to the cost. Therefore, these two measures are associated with cost savings. The last seventh measure is to limit the maximum displacement of the base-isolation bearing, which otherwise would be excessive.

A common difficulty in optimizing these multiple design objectives is the conflict of the multiple design objectives. None of the feasible solutions will allow simultaneous minimization of all objectives. Reducing one measure may adversely cause an increase in the other measures. Therefore, the optimization approach needs to consider the trade-off relations between the multiple design objectives. A multi-objective optimization approach can be one of the effective methods to handle such an objective-conflicting issue in a compromising manner. However, as pointed out by Costa and Oliveira, the multi-objective optimization approach would be practically implausible to apply when the number of the objectives is 3 or more. For more than three objectives, the 2D visualization of the multiple objectives simply looks like a cloud of points, and thus it is not straightforward for the decision-maker to understand their trade-off relations through the visualization. Furthermore, high dimensionality of the objective space requires generating much more searching points for the representation of the Pareto optimal surface, which can cause significant difficulties in computational aspects. It is also well described in Park and Ok that the evolutionary multi-objective optimization algorithms scale poorly when the problems have many objectives, and the decision-making task becomes harder as more objectives are involved.

In order to effectively address the simultaneous optimization of high dimensional objectives, this study employs a preference-based dimensionality reduction technique. This technique introduces a preference function to represent the degree of desirability for each objective criterion. Each objective with a different design metric is normalized to the design preferences and these normalized preference values are then aggregated to a single metric to represent the multiple objectives. In this study, the peak responses of twin buildings, the total damping capacity, and the peak displacement of the base-isolation bearing have different physical quantities, but they are all normalized to the same scale, i.e. preference value, and aggregated into a single quantity. As a result, the multi-objective optimization problem is formulated into the single objective optimization problem to find the best compromising solution in view of the designer’s preferences on performance and cost. This can avoid computational difficulty and the design preference-based normalization eliminates the need for searching the relative weights between the objectives. It also has the benefit of integration of the optimization and decision-making processes based on design preferences.

In this study, the preference-to-objective relationship is constructed by classifying the design preferences into four categories of “very desirable,” “desirable,” “acceptable,” and “unacceptable” and mapping the corresponding objective function values to the boundary value of each section. This is illustrated in Figure 3. The four sections are denoted as (1) very desirable range \( \lambda_i \leq c_{\text{hi}} \), (2) desirable range \( c_{\text{hi}} < \lambda_i \leq c_{\text{li}} \), (3) acceptable range \( c_{\text{li}} < \lambda_i \leq c_{\text{ui}} \), (4) unacceptable range \( c_{\text{ui}} < \lambda_i \), respectively. The corresponding preference functions for the minimization problem can be defined as

\[
P_l(\lambda_i) = \left\{ \begin{array}{ll}
\frac{\lambda_i - c_{\text{hi}}}{\sqrt{x^2}} & \text{for } \lambda_i \leq c_{\text{hi}} \\
\frac{1}{\sqrt{\frac{c_{\text{ui}} - c_{\text{li}}}{c_{\text{li}} - c_{\text{hi}}}} (\lambda_i - c_{\text{li}}) + \sqrt{x^2 - 1}} & \text{for } c_{\text{hi}} < \lambda_i \leq c_{\text{li}} \\
\frac{1}{\sqrt{\frac{c_{\text{ui}} - c_{\text{li}}}{c_{\text{li}} - c_{\text{hi}}}} (\lambda_i - c_{\text{hi}}) + 1} & \text{for } c_{\text{li}} < \lambda_i \leq c_{\text{ui}} 
\end{array} \right.
\]

(16)

where \( x \) and \( n_p \) are the parameters to determine the shapes of the preference functions. In this study, the gaps between two different levels of design preferences are defined to be inversely proportional to the parameter \( x \), and the preference function is assumed to follow the \( n_p \)-th power function. These considerations create significant gaps between two preferences, which would prevent the solution with lower preference from being selected over the solution with higher preference in the design process.

Accordingly, the optimization problem can be formulated as follows

\[
\min J_{\text{obj}}(\lambda_1, \lambda_2, \cdots, \lambda_7) = \sum_{l=1}^{7} P_l(\lambda_l(y))
\]

(17)
where $\lambda_i(v)$ ($l = 1, 2, \cdots, 7$) corresponds to the physical measures of the design objectives defined in equations (9) to (15). These measures are a function of the design variable vector $v = \{c_0, c_2, \cdots, c_d(2m-1), c_{d2m}, c_3, k_b, e_b\}$. Therefore, the design optimization problem of the ABiC system reduces to the determination of the design variables to minimize the preference-aggregated objective function in equation (17).

**Hybrid optimization technique**

In order to deal with the design optimization of the proposed ABiC system, this study incorporates the preference-aggregated objective function into the hybrid optimization technique. Here, the hybrid optimization technique is a kind of combinatorial optimization approach, and it thus employs combinations of multiple optimization algorithms to search the optimal solution. This is due to the fact that the best results found for many practical or academic optimization problems are obtained by hybrid algorithms. Among various hybrid algorithms of interest in this study is the multiple offspring sampling (MOS) algorithm. The MOS algorithm has been developed for general-purpose applications to the large-scale global optimization problems so that it can serve as a framework for combining any specific optimization algorithms that the user selects.

Now let us describe the concept of the MOS algorithm. The MOS algorithm is slightly modified from traditional evolutionary algorithms by adding the capability of using several different recombination techniques simultaneously. Therefore, the overall outline of the MOS algorithm is similar to those of traditional evolutionary algorithms, but it differs slightly in that it uses several recombination techniques at the same time. Figure 4 illustrates the algorithmic flowchart of the proposed MOS approach.

First, it starts with the creation of an initial population $P_0$ that consists of $m$ individuals. The individuals correspond to the design variable vector $(v^k, k = 1, 2, \cdots, m)$ in equation (17) and they are represented as the genotype set. Second, each individual $(k = 1, 2, \cdots, m)$ is reversely decoded into the phenotypes in order to evaluate the objective function $\mathcal{J}_k^{obj}$ in equation (17). After the evaluation of the objective function for the $m$ individuals, the algorithm termination is checked in terms of the maximum iteration number. If the iteration reaches the maximum iteration number, the evolutionary process is terminated; otherwise, it proceeds to the next recombination stage.
In the recombination stage, the \( m \) individuals in the population are distributed and assigned to the \( s \) different techniques \( T_i \) \((i = 1, 2, \ldots, s)\). The techniques \( T_i \) are the key terms of the MOS approach. LaTorre et al.\(^{14} \) denoted the technique as a mechanism, decoupled from the main algorithm, to generate new candidate solutions or new offsprings. In this study, three reproductive mechanisms, decoupled from PSO, GA, and HSA, are chosen as the techniques. These techniques are performed simultaneously within the MOS framework to search the new candidate solutions or the better offsprings.

At the initial stage, the individuals are uniformly distributed to each technique. Note that the group of the individuals distributed to the \( i \)-th technique is denoted as \( O_i \). Each group goes with the corresponding technique during the current iteration. However, as the iteration proceeds, the \( s \) techniques compete with each other and the number of the individuals assigned to each technique will be varied according to the competition results. The competition of the techniques is made by the quality function \( Q_j^{(i)} \) and the resultant output is produced as the adjusted participation number \( D^{(i)(j+1)} \). Note here that the subscript \( i = \{1, 2, \ldots, s\} \) is the index of the techniques and the superscript \( j \) corresponds to the iteration number of the optimization process. Thus, the adjusted participation number \( \Delta^{(i)(j+1)} \) determines the increased (or decreased) number of the individuals assigned to (or removed from) the technique \( T_i \) during the next \((j + 1)\) iteration.

The quality function is defined as the average value of the preference-aggregated objective functions for the top 25\% of the individuals such that

\[
Q_j^{(i)} = \frac{\text{mean}_{v^o \in O_i^{(j)}} \left\{ f_{\text{obj}}^{(i)}(v^o) \right\}}{\text{top } 25\%} \quad (18)
\]

where \( O_i^{(j)} \) is a group of the individuals distributed to the \( i \)-th technique at the \( j \)-th iteration step; \( v^o \) is an individual that belongs to the group \( O_i^{(j)} \); \( f_{\text{obj}}^{(i)} \) is the objective function value evaluated by equation (17) at the \( j \)-th iteration step for the individuals \( v^o \); and \( \text{mean}\{ \cdot \} \) denotes the operator of averaging the quantities that are selected as the top 25\% of the individuals in terms of the objective function value.

These quality function values are then used in the following participation function to adjust the participation number of the individuals of each technique such that

\[
\Pi_j^{(i)(j+1)} = \begin{cases} 
\Pi_j^{(i)(j)} + \sum_{k \in \Omega_{\text{test}}} \Delta_k^{(j)} & i \in \Omega_{\text{test}} \\
\Pi_j^{(i)(j)} - \Delta_j^{(j)} & i \notin \Omega_{\text{test}}
\end{cases} \quad (19)
\]
where \( \Delta_i^{(j)} \) is the adjusted participation number of the individuals for the \( i \)-th technique at the \( j \)-th step; \( \Pi_i^{(j)} \) is the total number of the individuals allocated for the \( i \)-th technique at the \( j \)-th step; and \( \Omega_{\text{best}} \) is the index of the technique that produced the best quality value among the \( s \) techniques, i.e. \( \Omega_{\text{best}} \in \{1, 2, \ldots, s\} \). Therefore, as shown in equation (19), the total number of the individuals assigned to the best technique \((i \in \Omega_{\text{best}})\) will be increased at the next iteration \((j + 1)\) by the sum of the adjusted participation numbers \( \Delta_i^{(j)} \). On the other hand, the other techniques that did not produce the best quality function value will be assigned the decreased number of the individuals by removing the adjusted participation number of the individuals \( \Delta_i^{(j)} \) from the current number of the individuals \( \Pi_i^{(j)} \). In equation (19), the adjusted participation number \( \Delta_i^{(j)} \) is again computed by

\[
\Delta_i^{(j)} = \xi \cdot \frac{Q_{\Omega_{\text{best}}}^{(j)} - Q_i^{(j)}}{Q_{\Omega_{\text{best}}}^{(j-1)}} \cdot \Pi_i^{(j-1)} \quad \forall i \in \{1, \ldots, s\} \land i \notin \Omega_{\text{best}}
\]

where \( \Pi_i^{(j-1)} \) is the total number of the individuals assigned to the \( i \) technique at the previous stage \((j-1)\); \( Q_{\Omega_{\text{best}}}^{(j)} \) is the best quality value at the \( j \)-th stage; and \( \xi \) is a reduction ratio, i.e. a ratio of the individuals that are transferred from one technique to the other technique. Usually, a minimum or maximum reduction ratio can be established to guarantee that all the techniques can participate during all the iterative searching process. For example, if a certain technique takes all the participants in the early steps of the search, then the algorithm may converge prematurely to a poor region of the solution space. Thus, the use of the minimum reduction ratio will provide the chance that the other techniques can collaborate and compete at the latter stages of the process and thus proceed towards better solutions. In order to avoid premature convergence, we introduce a minimum adjusted participation number \( \Delta_{\text{min}} \) instead of using the minimum reduction ratio.

Thereafter, each technique reproduces its own offspring with the newly adjusted number of the offspring. With these adjusted participations of individuals, all those recombination techniques compete with each other iteratively in order to search for better solutions. Note that the total number of the new offspring gathered from the \( s \) techniques will remain equal to \( m \). However, if any efficient technique works better than others, then the participation ratio will be increased and more individuals will be assigned to that technique. Therefore, this dynamic adjustment of the participation of the multiple recombination techniques is expected to provide significant improvement in seeking the global optimal solutions more efficiently. In addition, the proposed algorithm provides a general framework of combining any specific optimization algorithms so that it will be able to realize the desired features of the algorithms effectively, e.g. rapid convergence to an optimal path with reduced computational effort. Although the proposed hybrid optimization technique was developed for the vibration control problem of twin structures, it can be extended to a general design problem of the structural control system with many design objectives to be minimized and many design variables to be explored.

### Illustrative example

For an illustration purpose, adjacent 20-story twin buildings are considered. The structural properties of the 20-story building are given in Table 1. The base floor mass will apply to the isolated building only, i.e. building 2 in Figure 2. The damping ratios are assumed to be 2% for both the first and second modes. By using them for the Rayleigh damping model \((C_i = x_i M_i + \beta_i C_i)\), the coefficients \( x_1 \) and \( \beta_1 \) can be determined to be 0.2016 and 0.0015 which apply to both buildings, e.g. \( x_1 = x_2 \) and \( \beta_1 = \beta_2 \). For the given structural properties, the eigenvalue analysis has been performed to estimate the modal frequencies and damping ratios, and the top 10 modal properties are provided in Table 2.

Now, the proposed ABiC system has been applied to these 20-story twin buildings, and the hybrid optimization algorithm integrated with preference-based dimensionality reduction technique has been applied to optimally design the proposed ABiC system. In the optimal design of the proposed ABiC system, the design load for the ground motions is represented by Kanai-Tajimi filter model, and its power spectral density function is given by the following

\[
S_{g \times g}(\omega) = \frac{\omega^4 + 4\omega^2 \omega^2 \omega^2}{(\omega^2 - \omega^2)^2 + 4\omega^2 \omega^2 \omega^2} S_0
\]
where $\omega_g$, $\zeta_g$, and $S_0$ are the parameters representing the dominant frequency, bandwidth, and intensity of the ground acceleration $\ddot{x}_g$, respectively; and $\omega$ corresponds to the excitation frequency of the ground motion. This power spectral density function is represented equivalently in the time domain, as follows

$$
\ddot{x}_g(t) + 2\zeta_g\omega_g\dot{x}_g(t) + \omega_g^2 x_g(t) = w(t)
$$

where $\ddot{x}_g$ is a relative ground acceleration with respect to the fixed base; $w(t)$ is zero-mean Gaussian white noise with an intensity of $S_0$; and $\ddot{x}_g$ is the absolute ground acceleration in equation (1). The two parameters of the dominant frequency and bandwidth are set to be $\omega_g=2\pi$ and $\zeta_g=0.5$, which represents the firm ground conditions. The seismic intensity $S_0$ is chosen to be 9.0 through preliminary analysis in which the ground acceleration with the parameters of $\omega_g=2\pi$, $\zeta_g=0.5$ and $S_0=9.0$ was calculated to have an r.m.s. value of 7.520. For example, when the El Centro, Mexico, and Northridge earthquakes are normalized to have peak ground acceleration (PGA) of 0.4 g, their r.m.s. values for strong motion duration were calculated to be 6.718, 7.994, and 9.732, respectively.

The parameters of hybrid optimization algorithms and the preference functions are summarized in Tables 3 and 4. As already described in equation (17), the proposed ABiC system is represented by a vector of the design variables such as $\mathbf{v} = \{k_b, c_p, c_e, c_{d1}, c_{d2}, \ldots, c_{d2n-1}, c_{d2n}\}$. Therefore, the hybrid optimization algorithm explores the optimal design variables in the design space. Table 5 shows the searching ranges of the design variables. Given this information, the optimal design results of the ABiC system obtained by the preference-integrated hybrid optimization algorithm are provided next.

### Optimization results

The proposed hybrid optimization approach has been performed for the given parameters and the convergence results are shown in Figure 5. The horizontal axis corresponds to the iteration number of the optimization process, and the vertical axis represents the objective function value in equation (17). The three plots denote the convergence histories of the best solutions searched by the three algorithms such as PSO, GA, and HSA. It can be seen that GA and HSA show similar results in the convergence history of optimal solutions, whereas PSO produces the better solution over GA and HSA in the early stage of the convergence history. After roughly 30 iterative optimizations, the three algorithms produce very similar convergence histories. Thereafter, the three
algorithms will compete with each other to find better solutions, and the MOS algorithm selects the best solution among the optimal solutions found by each algorithm, which can be observed by the last plot of Figure 5. For clarity, the enlarged view of the competitive convergence history was provided in Figure 6, where the black solid line corresponds to the best solution chosen by the MOS algorithm. In this regard, the algorithm that finds the best solution in each optimization step may be changed, but the proposed MOS algorithm always obtains the best solution through competition between the three algorithms. In the early stage of the optimization process, PSO showed a good searching performance as shown in Figure 5, but HSA achieved the best searching performance at the end of the searching process as shown in Figure 6.

Figure 7 is additionally given to illustrate the change in population redistribution according to the competition results of the three algorithms. Initial populations start with the same number of individuals, i.e. 80, for the three algorithms but their populations significantly change after the third iteration which corresponds to the initial

| Parameters | Values |
|------------|--------|
| Number of techniques | 3 (GA, PSO, HSA) |
| Average ratio for quality function | Top 25% of individuals |
| Initial numbers of individuals allocated for each technique | $\Pi_1^0 = \Pi_2^0 = \Pi_3^0 = 80$ |
| Reduction ratio | $\xi = 4$ |
| Minimum adjusted participation number | $\Delta_{min} = 8$ |
| Iteration number to start adjusting the participation number | 3 |
| Maximum iteration number | 300 |

### Table 4. Parameters of preference functions.

| Parameters | Values |
|------------|--------|
| $z$ | 5.0 |
| $n^p$ | 2.0 |
| $\xi_{11}$ | $\xi_{12}$ | $\xi_{13}$ |
| Sum of r.m.s. story drift for building 1 ($x_1$; cm) | 30 | 40 | 60 |
| Sum of r.m.s. story drift for building 2 ($x_2$; cm) | 30 | 40 | 60 |
| Maximum of r.m.s. story drift for building 1 ($x_3$; cm) | 2.4 | 3.2 | 4.8 |
| Maximum of r.m.s. story drift for building 2 ($x_4$; cm) | 2.4 | 3.2 | 4.8 |
| Sum of r.m.s. story damper force for building 1 ($x_5$; N) | $1.0 \times 10^5$ | $1.4 \times 10^5$ | $2.0 \times 10^5$ |
| Sum of r.m.s. story damper force for building 2 ($x_6$; N) | $1.0 \times 10^5$ | $1.4 \times 10^5$ | $2.0 \times 10^5$ |
| R.m.s. displacement of base floor for building 2 ($x_7$; cm) | 12 | 15 | 20 |

### Table 5. Searching ranges of design variables.

| Design variables | Ranges |
|------------------|--------|
| Damping coefficients of viscous dampers ($c_{d1}$–$c_{d3}$; $\times 10^5$ kg/s/m) | 0–1000 |
| Damping coefficient of connection damper ($c_d$; $\times 10^5$ kg/s/m) | 0–1000 |
| Stiffness of base-isolation bearing ($k_b$; $\times 10^5$ kN/m) | 0.1–1000 |
| Damping ratio of base-isolation bearing ($c_b$; %) | 2–50 |

On the other hand, it can be seen that the number of population adjustment of each algorithm decreases or increases only up to 8 since the minimum adjusted participation number is set to 8, which avoids the premature convergence of one particularly algorithm that luckily picks up a good initial solution. Another observation is that the PSO population does not drop below 48...
number to start adjusting the participation number. On the other hand, it can be seen that the number of population adjustment of each algorithm decreases or increases only up to 8 since the minimum adjusted participation number is set to 8, which avoids the premature convergence of one particularly algorithm that luckily picks up a good initial solution. Another observation is that the PSO population does not drop below 48

Figure 5. Convergence histories of optimal solutions by hybrid optimization algorithm.

Figure 6. Enlarged view of competitive convergence history.
corresponding to the minimum population assigned to each algorithm, which guarantees that all the techniques can participate during all the iterative searching process.

The proposed hybrid optimization approach integrates the preference-based dimension reduction technique into the existing MOS algorithm in order to balance the multiple design preferences. In order to demonstrate how well the proposed hybrid optimization approach works for balancing the design preferences, two initial individuals are selected among the initial population that has been randomly generated by the proposed hybrid optimization approach. Then, their initial design preferences are compared with those of the finally obtained optimal solution. Figure 8 illustrates the preference evaluation results of the two initial solutions and the final optimal solution. The horizontal axis corresponds to design preferences and the vertical axis represents the seven measures denoted as \( k_1-k_7 \). The horizontal axis is divided into four sections such as “very desirable region,” “desirable region,” “acceptable region” and “unacceptable region.” The initial solution is drawn by blue circle (O) and the final optimal solution is drawn by red circle (O). Figure 8(a) is the comparative result of initial solution 1 and final optimal solution, and Figure 8(b) compares the final optimal solution with initial solution 2. These two initial solutions show very different design preferences.

As shown in Figure 8(a), initial solution 1 shows “acceptable preference” for \( k_2-k_6 \) measures, while “unacceptable preference” for \( k_1 \) and \( k_7 \) measures. However, although the \( k_3 \) and \( k_5 \) measures belong to “acceptable region,” they are very close to the boundary of “unacceptable region.” Now let us compare the initial solution 1 with the optimal solution denoted as red circle (O). The final optimal solution shows “acceptable preference” for all measures such as \( k_1-k_7 \). The \( k_1 \) and \( k_7 \) measures belonging to “unacceptable region” for the initial solution 1 are shifted into “acceptable region,” and the \( k_3 \) and \( k_5 \) measures being close to the boundary of “unacceptable region” are also shifted toward lower level of “acceptable region.” Especially, the \( k_5 \) measure is moved to the boundary of “desirable region.” These results indicate that the optimal solution reduces the story drift of the buildings (\( k_1-k_3 \)) while simultaneously saving the damping force (\( k_3 \) and \( k_6 \)). The displacement of the base floor of building 2 (\( k_7 \)) is reduced as well.

On the other hand, as shown in Figure 8(b), initial solution 2 exhibits very excellent performances on \( k_1-k_6 \) measures, but its \( k_7 \) measure belongs to “unacceptable region.” This \( k_7 \) measure is the floor displacement of building 2 and at the same time the horizontal displacement of the seismic isolation system. Seismic isolation system is well known for its excellent performance against floor displacement in buildings by using horizontally flexible stiffness. However, the use of flexible stiffness causes excessive displacement of the bearing, which should be handled by the seismic isolation system. If the bearing displacement exceeds its design limit, the safety of the structure cannot be guaranteed. Therefore, the unacceptable preference for the displacement of the isolation bearing cannot be accepted in the design. These unbalanced design preferences of the initial solution 2 converge to the overall balancing design preferences of the final optimal solution through the optimization process, by sacrificing the other design measures such as \( k_1-k_6 \) to some extent.
The optimization results such as the distribution of the damping coefficients and stiffness values of the ABiC system are depicted in Figure 9. The vertical axis corresponds to the floors of the two buildings, and the horizontal axis is split into two parts: the left part represents the damping capacity of the ABiC system for the building 1 and the right part represents the damping capacity of the ABiC system for the building 2. Therefore, the blue ($C_{Bld1}^d$) and orange ($C_{Bld2}^d$) bars show the distribution of the damping coefficients of the inter-story diagonal bracing dampers installed inside the two buildings. Accordingly, the optimal distribution of the diagonal bracing damper is determined such that, for building 1, a capacity of approximately 958–1000 ($\times 10^5$ kg/s/m) needs to be placed from the first floor to the sixth floor, and a capacity of approximately 879–1000 ($\times 10^5$ kg/s/m) is required to be arranged from the first floor to the eighth floor for building 2. However, it should be noted that the fourth-floor damper of building 1 and the seventh-floor damper of building 2 are determined to have a capacity of 698 ($\times 10^5$ kg/s/m) and 679 ($\times 10^5$ kg/s/m), respectively. Next, the optimally designed inter-building coupling damper is represented by the red bar ($C_c$) on the twentieth floor. Since the coupling damper is installed between the two buildings, the length of the red bar is expressed in both directions by half of the optimally designed damping capacity, i.e. about 2 $\times$ 36 ($\times 10^5$ kg/s/m). Lastly, the damping coefficient and stiffness of the optimally designed base isolation system is depicted at the 0th floor of building 2 in the right part. The purple bar ($C_b$) corresponds to the damping capacity of 192 ($\times 10^5$ kg/s/m) and the yellow bar ($K_b$) corresponds to the stiffness of 1000 MN/m, respectively. As already mentioned for this ABiC system, the base-isolation system installed at the building 2 only induces asymmetry in the twin buildings, and the inter-building coupling damper facilitates the control efficiency through the interaction of damping forces on both buildings. Then, the inter-story diagonal bracing dampers distributed within the two buildings provide the sufficient damping capacity to dissipate the vibration energy of the twin structures.

Figure 8. Optimization results of balancing preferences: (a) Case 1: initial solution 1, and (b) Case 2: initial solution 2.
Comparative performance assessment

For comparison purpose, the previous inter-building different-story damper connection system proposed by Patel and Jangid\(^\text{12}\) has been considered, where the dampers are installed to connect the two buildings and both ends of each damper are connected to different floors of each building. Although Patel and Jangid\(^\text{12}\) proposed three configurations, we only consider one configuration with uniform damper distribution for simplicity, as shown in Figure 10. This comparative system is designated as the inter-building uniform damper connection system, in short, iUDC system.

This iUDC system has been designed to have the same damping coefficient in all dampers as proposed by Patel and Jangid\(^\text{12}\). Although Patel and Jangid\(^\text{12}\) proposed the different damping coefficients for another configuration, we simply assume the uniform distribution of all dampers. Under this assumption, the design of the iUDC system reduces to the determination of the damping coefficient, i.e. \(c_{\text{di}}^{1} = c_{\text{di}}^{2} = c_{\text{d}}, i = 1, 2, \cdots, n\). For comparison with the proposed ABiC system, the iUDC system should be designed to have a similar control capacity to the ABiC system. However, since the ABiC system provides stiffness to the seismic isolator, it is difficult to design the same control capacity as the iUDC system. For this reason, the iUDC system is designed to have a total damping coefficient of \(14,000 \times 10^5\) kg s/m, which is slightly larger than \(13,304 \times 10^5\) kg s/m for the ABiC system.

In order to investigate the seismic performances of the twin buildings interconnected with ABiC or iUDC systems, the r.m.s. values of the story drifts have been evaluated and they are depicted along with the floors in Figure 11. The responses of the original buildings without any damping devices, denoted as UNC, are also presented for comparison. As you can see, the iUDC system improves the seismic performances on the story drifts of the two buildings over the UNC system, but the proposed ABiC system further improves the seismic performances over the iUDC system.

Although the iUDC system was not designed in terms of design preference but was simply designed according to the existing method by Patel and Jangid\(^\text{12}\), its design preferences are computed for the purpose of performance comparison, and the comparison results with the proposed ABiC system and the UNC system are displayed in Figure 12. Since the UNC system does not have dampers, its measures are only computed for \(\lambda_1 - \lambda_4\). Also, note that only the performance measures \(\lambda_1 - \lambda_6\) can be evaluated for the iUDC system since the iUDC system does not have the seismic isolation system. Although the iUDC system shows significantly improved performance compared to the UNC system in Figure 11, it can be seen in Figure 12 that the iUDC system can exhibit unbalanced performance in terms of design preferences. Therefore, in order to satisfy the design preferences, the damper capacities (\(\lambda_5\) and \(\lambda_6\)) should be increased which will reduce the story drifts of the two buildings (\(\lambda_1 - \lambda_4\)). This result

![Figure 9. Distributions of dampers (10^5 \times \text{kg/s/m}) and stiffness (kN/m).](image)
Figure 10. Damper connection configuration of iUDC system.

Figure 11. Comparison of story drifts of twin buildings between UNC, iUDC, and ABiC.
clearly confirms that the proposed preference-based design approach can guarantee the balanced performance among several conflicting objective functions in the design aspects.

In order to demonstrate the practical applications, historical earthquake records such as El Centro, Mexico City and Northridge earthquakes are used as the input ground motion, and the seismic response analyses have been further performed in the time domain by solving equation (1). The time history curves of the top floor displacements and the base shear forces are presented in Figure 13. Similar to the previous r.m.s. response results, it can be confirmed from Figure 13 that the iUDC system shows improved seismic performance than the UNC system, and the proposed ABiC system further improves seismic performance than the iUDC system. These
results clearly verify that the proposed ABiC system is able to exhibit efficient seismic performance by perturbing the frequency characteristics of the twin structures through the arrangement of the asymmetric base isolation system.

**Performance contribution of subsystems**

The proposed ABiC system consists of three subsystems such as the inter-story diagonal damper system, the inter-building coupling system, and the asymmetric base isolation system. Here, we investigate the contribution of the three subsystems to the overall seismic performance. For this purpose, the control capacity of each subsystem has been varied by multiplying the coefficient $a_c$, and the resultant seismic performance has been examined while the capacities of the remaining subsystems are fixed to their optimal values. The performance evaluation results are displayed in Figure 14. The horizontal axis represents the coefficient $a_c$, and thus $a_c = 2$ is a case where the corresponding control capacity is doubled. The vertical axes in Figure 14(a) to (c) represent the control performances on story drifts of two buildings and displacement of base isolator, i.e. $k_1$, $k_2$, and $k_7$, respectively.

As shown in Figure 14(a), the increase in the damping capacities of the inter-story bracing dampers inside the building 1 ($c_{d1}, c_{d2}, \ldots, c_{d20}$) contributes to the reduction of the r.m.s. story drift of the building 1 ($\lambda_1$). Thus, the bracing damper system installed at the building 1 directly contributes to the seismic performance of the building 1. Although not as large as the bracing dampers of the building 1, such a tendency is similarly observed for the bracing dampers inside the building 2 ($c_{d21}, c_{d22}, \ldots, c_{d40}$), and the damper of the base isolation ($c_b$). On the other hand, the increase in the stiffness of the base isolator ($k_b$) rather increases the story drift of the building 1 ($\lambda_1$). Thus, the isolator stiffness installed at the building 2 adversely contributes to the seismic performance of the story drift response of the building 1. Alternatively, increasing the capacity of the coupling damper shows the trade-off effect of decreasing the story drift of the building 1 ($\lambda_1$) up to a certain point and then increasing $\lambda_1$ over the point. The existence of such an optimal damping capacity for the inter-connecting damper was also observed in previous studies. When looking at the sensitivity of $\lambda_1$ due to the variation of the coefficient $x_c$ in Figure 14(a), the most dominant subsystems turn out to be the inter-story bracing dampers inside the building 1 ($c_{d1}, c_{d2}, \ldots, c_{d20}$) and the stiffness of the base isolator ($k_b$). Based on this result, the most efficient way of reducing the story drift of the building 1 is either to increase the damping capacity of the inter-story bracing dampers inside the building 1 ($c_{d1}, c_{d2}, \ldots, c_{d20}$) or to decrease the stiffness of the base isolator ($k_b$).
Figure 14(b) shows the story drift of the building 2 ($\lambda_2$). In this case, most subsystems affect positively the seismic performance of the building 2 except for the stiffness of the isolator ($k_b$). Increasing the damping capacities of the bracing dampers, coupling damper and the isolator damper all act to reduce the story drift of the building 2. Unlike the case of the building 1, the trade-off effect of the coupling damper ($c_c$) is not observed for the building 2. The reason is inferred that the optimal point for the building 2 may exist outside the searching range of the capacity coefficient, e.g. $x_c > 2$. Similar results were also confirmed in previous studies\(^3\)–\(^6\) that the optimal damping capacity of each building is different from each other for the inter-building damper connection of two buildings with different frequency characteristics. In Figure 14(b), the most efficient way of reducing the story drift of the building 2 is to decrease the stiffness of the base isolator ($k_b$). However, this will adversely increase the displacement of the base floor of the building 2 excessively, as observed in Figure 14(c), which will not be acceptable in the design aspect. The second efficient way is then to increase the damping capacity of the bracing dampers inside the building 2 ($c_{d1}, c_{d2}, \ldots, c_{d80}$).

As shown in Figure 14(c), the displacement of the base floor is not much affected by the damping capacities of the bracing dampers and the isolator damper. Increasing the stiffness of the base isolator ($k_b$) can significantly reduce the displacement of the base floor ($\lambda_7$). However, as already described above, it can cause excessive increases in responses of the two buildings ($\lambda_1$ and $\lambda_2$). Therefore, it can be confirmed that the story drifts of the two buildings and the displacement of the seismic isolator conflict with each other based on the optimal point ($x_c = 1$), and the optimal point is the most balanced solution between these mutually conflicting performances.

Concluding remarks

This study proposes an asymmetric base-isolation coupling system to deal with the vibration control problem of the twin buildings. Since the proposed system entails high-dimensional mutually-conflicting objectives, a hybrid optimization technique incorporated with a preference-based dimensionality reduction technique was used to optimally design the twin buildings equipped with the asymmetric base-isolation coupling system. The purpose of the proposed optimization approach is to guarantee the compromise optimal solution of well-balancing the mutually conflicting design objectives.

In order to demonstrate the proposed approach, the adjacent 20-story twin buildings subjected to earthquake excitations were adopted as target buildings, and the existing different-story connection system with uniform distribution of dampers was considered as the comparison system. The comparative results of the seismic performances between two systems clearly show that the proposed ABiC system can achieve the well-balancing compromising performances between multiple design objectives and also exhibit improved performances over the existing iUDC system. Thus, it can be concluded that the proposed ABiC system can be a very effective system for controlling the vibrations of the twin buildings.

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Data Accessibility Statement

The source code and data used to support the findings of this study have been deposited in the github repository (https://github.com/WonsukPark-MNU/HybOpt_BSTwin).

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