Translated Paper

Modeling of resilience based on categorized recovery scenario and improving resilience with viscous damper

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Funding information
Grant-in-Aid for Scientific Research (KAKENHI)

The Japanese version of this paper was published in Volume 86, Number 782, pages 577–588, https://doi.org/10.3130/aijs.86.577 of the Journal of Structural and Construction Engineering (Transactions of AIJ). The authors have obtained permission for secondary publication of the English version in another journal from the Editor of Journal of Structural and Construction Engineering (Transactions of AIJ). This paper is based on the translation of the Japanese version with some slight modifications.

Received April 7, 2022; Accepted June 16, 2022
doi: 10.1002/2475-8876.12273

Abstract
In this study, a model for the evaluation of a building's resilience and recovery time is proposed, and a new method is developed for the optimal viscous damper placement for a targeted resilience. The features of this model are as follows: 1) building components are categorized into systems in view of their functionality, 2) recovery time is regarded as a function of the damage to building components and human resources for repairing the components, 3) the model is applicable to structural design. This design method uses a type of real-coded genetic algorithm (GA). The effective use of a constraint on the sum of the added damper damping coefficients enables an efficient search for the solution.

Keywords
facility, multi-objective optimization, real-coded genetic algorithm, recovery time, resilience, viscous damper

1. Introduction
It is well-known that the recovery of a damaged building is delayed by damage to non-structural components and facilities after earthquakes as well as structural damage.1 In the case of corporate office buildings, for example, a rapid recovery and business continuity management are thought to be important in view of minimizing the economic loss. Thus, there is a need to develop a resilience-based design method. In this context, one of the main roles of passive dampers is to reduce structural damage, that is, to reduce interstory deformations.

The reduction of structural responses by passive dampers and increase of the strength of non-structural components and facilities enhance a building’s resilience. The structural responses (floor acceleration and interstory deformation) and damages to non-structural components and facilities are strongly correlated because the structural responses are regarded as the inputs to the non-structural components and facilities. In addition, reducing the floor accelerations also contributes to reducing building member costs and human damages. For these reasons, it appears effective to reduce the structural responses to a building to prevent damage to non-structural components and facilities and improve the recoverability of building functions.

Recently, research studies on resilience and recovery time have been extensively conducted in the fields of architectural and civil engineering. Bruneau and Reinhorn2 defined the resilience of systems as constituting of the following four properties: robustness, redundancy, resourcefulness, and rapidity. Many researchers have investigated the recovery time (or downtime) of lifelines and critical infrastructures.1,3,4 Porter and Ramer1 considered the damage states of the non-structural components for the estimation of downtimes. Cimellaro et al.5 addressed the post-earthquake functionality of hospital systems. De Iuliis et al.6 presented a fuzzy logic-based method for estimating the downtime of buildings. Comerio7 pointed out the difference between the rational and irrational components of downtime. The modeling of the latter was considered as difficult, because of the uncertainty.

As stated above, lifelines and critical infrastructures have mainly been discussed from the viewpoint of the evaluation and estimation of the resilience and recovery time. However,
the resilience and recovery times of buildings have been hardly investigated in the process of structural design.

In contrast, there have been many research studies on the optimal placement of passive dampers. Takewaki developed an optimality criterion-based approach for minimizing the sum of the amplitudes of the transfer functions evaluated at the undamped fundamental natural frequency of a structural system. Aydin et al. applied this approach to the minimization of the amplitude of a base shear transfer function evaluated at the fundamental natural frequency. Akehashi and Takewaki extended the concept presented by Takewaki into the higher modes. Zhang and Soong proposed a sequential algorithm for damper placement and Garcia simplified and extended this algorithm. Kanno considered a mixed-integer programming problem for the discrete optimal allocation of viscous dampers. Silvestri and Trombetti compared several optimization techniques. Other researchers have considered the damper optimization problems for elastic–plastic structural frames.

Notably, the genetic algorithm (GA), one of the most famous methods in metaheuristics, has been adopted as a powerful means for structural optimization and vibration control. As random numbers are used in the GA and searching is performed at multiple points in GA, it works effectively even when the objective function has discontinuity points and/or multiple peaks. It is also known that a GA can easily perform multi-objective optimization. Although a gene is usually expressed by 0 or 1 (binary expression) in an ordinary GA, in a real-coded genetic algorithm (real-coded GA), design variable vectors are directly treated to create new individuals. Binary expression is not required in the real-coded GA. However, an appropriate crossover is required in the real-coded GA to obtain good solutions for each problem. BLX-α is one of the most famous crossover methods.

The purpose of this paper is to propose both an evaluation model for a building’s resilience and recovery time and a new optimal viscous damper placement method for a targeted resilience. The evaluation model has the following features: 1) building components (structural frame, non-structural components and facilities) are categorized into systems from the perspective of their functionality; 2) recovery time is considered as a function of the degree of the damages to the building components and human resources for repairing the components; and 3) the model is applicable to structural design. The damage to infrastructures and delay of the response are not considered for the evaluation of the resilience and recovery time, because the proposed method does not aim for an accurate estimation of them. The design method proposed in this paper uses a type of real-coded GA. The effective use of a constraint on the sum of the added damper damping coefficients enables an efficient search for the solution. The proposed method can reflect the uncertainty of the process in recovering from damaged states in a non-stochastic manner. In other words, this uncertainty can be reflected in the damper design through the multi-objective optimization for minimizing the recovery time based on the two remarkable recovery scenarios: a scenario denoted by “FA (Full Ability to Recover)” where the manpower is fully available, and a scenario denoted by “LA (Limited Ability to Recover)” where the manpower is limited. It is shown that the minimization of the recovery time with the limited ability LA (manpower) corresponds to the minimization of the total damage to the components and minimization of the recovery time, whereas the full (unlimited) ability FA corresponds to the minimization of the maximum damage among all components. Numerical examples are presented to investigate the influences of the damper designs on the recovery time, and to demonstrate the effectiveness of the proposed method.

2. Evaluation Model of Building’s Resilience and Recovery Time

Bruneau and Reinhorn thought that minimizing the time integration of the performance reduction of a building corresponds to an enhancement of the resilience. An evaluation model for a building’s resilience is proposed herein based on the same concept. The proposed model can easily be applied to a structural design. In this section, the evaluation method for the recovery time is introduced, and the performance reduction is explained.

2.1 Basic concept of evaluation model

The total recovery time $T_{total}$ of a building is expressed as follows:

$$T_{total} = T_{total}^S + T_{total}^F,$$

where $T_{total}^S$, $T_{total}^F$ denote the total recovery time of the structural frame and that of the facilities and the non-structural components, respectively. When a structural frame is damaged, the occupation is usually regulated because the structural safety is not guaranteed. In such cases, the facilities and non-structural components are repaired after the structural frame is repaired. Assume that the facilities and non-structural components start to be repaired after the structural frame is totally repaired. Then $T_{total}$ is expressed as the sum of $T_{total}^S$ and $T_{total}^F$. Notably, the external factors and uncertainty (for example, the damage to supply chains and transportation systems and delay of response) influence the performance reductions and recovery times of buildings. In this study, such external factors and uncertainty are not considered in the evaluation of the resilience and recovery time, although the uncertainty can be considered to some extent. The evaluation model considers the damage to the structural frame, facilities, and non-structural components, which are strongly related to the structural responses.

2.2 Evaluation of recovery time of facilities and non-structural components

In the evaluation of the recovery time, each facility (or non-structural component) in a building is regarded as a component contributing to the functionality of the building. When a function of a component links up with that of another component, they are classified into the same functional system. In other words, a functional system consists of plural components contributing to the same function. For example, switchgears, conduit cables, and distribution panels work together for a power supply. When any one of them is damaged, the function of the power supply fails, as their functions are linked up in series. The details will be explained in Section 2.4. The recovery time $T_{ij}$ of a component $j$ which belongs to a functional system $i$ can be expressed as follows:

$$T_{ij}(I) = \int f_{ij}(I, D) \cdot \tau_{ij}(D) dD,$$

where $I$, $D$, $f_{ij}$, $\tau_{ij}$ denote the level of the input to the component, damage state of the component, joint distribution between $I$ and $D$ for the component, and recovery time.
corresponding to $D$ (see Figure 1). The maximum responses of the structural frame, such as the maximum floor accelerations and maximum interstory drifts, are adopted as $I$. The correlations between one component and another component are not considered.

When all of the components in the same functional system have been repaired, the function is recovered. Let us define the repair time $T_i$ of the system $i$ and number $M_i$ of the components in the system $i$. Then, a relation between $T_i$ and $T_{ij}$ can be obtained as follows:

$$\max\{T_{ij}\} \leq T_i \leq \sum_{j=1}^{M_i} T_{ij}. \quad (3)$$

The case where $T_i$ is equal to $\max\{T_{ij}\}$ corresponds to the case where all of the components in the system $i$ simultaneously begin to be repaired. In other words, the ability (manpower) to repair the components is fully available in such a case. In contrast, a case where $T_i$ is equal to $\sum_{j=1}^{M_i} T_{ij}$ corresponds to a case where the components are sequentially repaired. In other words, the ability (manpower) to repair the components is limited in such a case.

For an accurate evaluation of the resilience and recovery time of buildings, the recovery scenario should be assumed (designated) beforehand, or a stochastic model should be constructed for the ability to recover. The latter will be unrealistic because all of the probable recovery scenarios are required to be considered. Hereafter, the resilience and recovery time are formulated based on two remarkable recovery scenarios; a scenario where the manpower is fully available, and a scenario where the manpower is limited. Beck et al.\textsuperscript{28} proposed a similar concept (the upper and lower limits of recovery scenarios).

### 2.2.1 Scenario LA [limited ability to recover]

Scenario LA corresponds to the case where the manpower is limited and components are sequentially repaired. Let us define the number of functional systems $n$ and performance reduction $r_i$ by the failure of the functional system $i$. Then, the resilience index $R_{\text{reduction}}$, recovery time $T_i$ of the system $i$, and total recovery time $T_{\text{total}}$ are expressed as follows:

$$R_{\text{reduction}} = \sum_{i=1}^{n} T_i \left( \sum_{k=1}^{n} r_k \right), \quad (4)$$

$$T_i = \sum_{j=1}^{M_i} T_{ij}, \quad \text{and} \quad (5)$$

$$T_{\text{total}} = \sum_{i=1}^{n} T_i = \sum_{i=1}^{n} \sum_{j=1}^{M_i} T_{ij}. \quad (6)$$

$R_{\text{reduction}}$ corresponds to the area surrounded by the red line in Figure 2A. The recovery process (or recovery curve) is expressed as a pile of rectangulars. In other words, the performance reduction $r$ is recovered by repairing all of the components in system $i$. $T_{\text{total}}$ is independent of the repair sequence of the systems, although $R_{\text{reduction}}$ depends on it. In Scenario LA, the recovery time can be calculated in the same manner as in a general risk analysis method.

### 2.2.2 Scenario FA [full ability to recover]

Scenario FA corresponds to the case where the manpower is fully available and all of the components in the building simultaneously begin to be repaired (see Figure 2B). $R_{\text{reduction}}$, $T_i$, and $T_{\text{total}}$ are expressed as follows:

$$R_{\text{reduction}} = \sum_{i=1}^{n} T_i \cdot r_i, \quad (7)$$

$$T_i = \max\{T_{ij}\}, \quad \text{and} \quad (8)$$

$$T_{\text{total}} = \max\{T_i\} = \max_{i,j}\{T_{ij}\}. \quad (9)$$

When the recovery scenario is uncertain (the availability of manpower is uncertain), an inequality expression for the total recovery time can be obtained as follows:

$$\max_{i,j}\{T_{ij}\} = T_{\text{FA}} \leq T_{\text{total}} \leq T_{\text{LA}} = \sum_{i=1}^{n} \sum_{j=1}^{M_i} T_{ij}. \quad (10)$$

Figure 2C illustrates the relation between Scenario LA and Scenario FA. With an increase of the number of components (facilities, non-structural components), the number of probable recovery scenarios also increases. The two types of recovery time based on Scenario LA and Scenario FA correspond to the upper and lower limits of the recovery time of the probable recovery scenarios, respectively, and the actual scenario exists between them. When a design has a small difference in the recovery time between Scenario LA and Scenario FA, such a design will be a good design because it has a small uncertainty with regard to the recovery time. A design which minimizes the recovery time based only on one scenario (either Scenario LA or Scenario FA) is not always effective for reducing the recovery time based on any other probable scenarios. In other words, such a design may insufficiently reduce the uncertainty with regard to the recovery time. In Section 4, this uncertainty is considered in a damper design through a multi-objective optimization for minimizing the recovery time based on Scenario LA and Scenario FA.

The convolution of the performance reduction $r$ and the above-mentioned recovery time provides the resilience index $R_{\text{reduction}} \cdot r$ can be set from various viewpoints, e.g., the repair cost of components or business interruption loss per day. The

![Figure 1. Outline of evaluation of recovery time](image-url)
former can be easily calculated by the same procedure as in a general risk analysis. In contrast, the business interruption loss has large uncertainty in stochastic modeling. When unpredictable events (for example, supplier interruption) occur, the business interruption loss will be quantified after such events.

As stated above, \( r \) can be set from various viewpoints, and \( r \) should be determined in terms of the building’s use. When \( r \) is difficult to determine, it will be reasonable to design dampers for the reduction of the recovery time. Hereafter, the recovery time will be considered, but \( r \) will not.

2.3 Evaluation of recovery time of structural frames

The total recovery time \( T_{\text{total}}^{S} \) of a structural frame can be calculated stochastically in the same manner as \( T_{\text{total}}^{F} \). In contrast, the criteria with regard to the maximum interstory drifts are usually set for the structural design. Step functions whose thresholds correspond to those criterion values can be applied to the fragility curves of the structural frame. In this study, the step functions are applied to the fragility curves of the structural frame.

2.4 Examples of system’s functional recovery

Examples of a system’s functional recovery are shown in this section. As an example, consider a 12-story building model. The electrical equipment shown in Figure 3A are treated. The function of the power supply at each floor is regarded as one functional system. Thus, 12 functional systems exist in total. As the switchgear at the 1st floor links up with all of the systems, the failure of the switchgear leads to the failure of all of the systems.

Figures 3B–D illustrate examples. In the case of Figure 3B, the distribution panels at the 11th and 12th floors and conduit cable at the 11th floor fail. In the case of Figure 3C, the distribution panel at the 12th floor and switchgear at the 1st floor fail. In the case of Figure 3D, the distribution panels at the 12th floor, conduit cable at the 5th floor, and structural frame fail. In the case of Figure 3B, the power supply is damaged at the 11th and 12th floors. The total recovery time in Scenario FA is determined by the conduit cable, as it requires the longest repair time. In the case of Figure 3C, the power supply is damaged at all floors, as the switchgear fails. The functionality at the 1st–11th floors recovers after the repair of the switchgear in Scenario LA. In contrast, the function at all of the floors simultaneously recovers in Scenario FA, because the repair times of the distribution panel and switchgear are identical. In the case of Figure 3D, the repair of the electrical equipment starts after the repair of the structural frame. In this latter case, the performance reduction \( r \) by the failure of the structural frame is set to zero.

3. Influences of Damper Designs on Recovery Time

In this section, the influences of damper designs as optimized for different objective functions on the recovery time are investigated through numerical examples.

3.1 Models

Consider two shear building models of 12-story steel frames with different story stiffness distributions. The undamped fundamental natural period of these two models is 1.2[s], and the structural damping ratio is 0.01 (stiffness proportional type). All of the floor masses have the same value. The common story height is 4 [m], and the common yield interstory drift \( d_{y} \) is 4/150 [m]. The story shear-interstory drift relation obeys an elastic perfectly-plastic rule. Model 1 has a uniform distribution of story stiffnesses at every four stories (1–4, 5–8, 9–12: stiffness ratio is 2:1.5:1 from the bottom). Model 2 has a trapezoidal distribution of story stiffnesses \((k_{1}/k_{12} = 4)\). Figure 4 shows the 1–4th undamped participation vectors and undamped natural periods.
It is assumed that the fragility curves of the structural frames depend only on the maximum interstory drift \( d_{\text{max}} = \max(d_{\text{max},i}) \), and the step functions are applied to the fragility curves (see Figure 5A and Table 1). As discussed in Section 4, the proposed optimization algorithm for minimizing the recovery time works effectively, although the objective

**FIGURE 3.** Examples of recovery process of building's function. (A) Electrical equipment system, (B) Case where conduit cable in 11th story and distribution panels in 11th and 12th stories are damaged, (C) Case where switchgear in 1st story and distribution panel in 12th story are damaged, (D) Case where distribution panel in 12th story, conduit cable in 5th story, and structural frame are damaged.
function has multiple discontinuity points owing to the fragility curves of the structural frames.

The properties of the facility systems and non-structural components are explained herein (Figures 5B, 5C and Table 2). They are common to both Model 1 and Model 2. For simplicity, only the electrical equipment used in Section 2.4 is used (again). The parameters of the fragility curves are shown in Table 2. The log-normal distributions are used. The switchgear and distribution panels are susceptible to the maximum floor accelerations, and the conduit cables are susceptible to the maximum interstory drifts. Although the maximum stress as calculated according to both the interstory drifts and floor accelerations at the upper and lower stories may provide a more accurate evaluation of the damage to the conduit cables, only the maximum interstory drifts are used for simplicity.

The values of the recovery time and parameters of the fragility curves are set with reference to documents from FEMA (2018).

### 3.2 Numerical examples

The El Centro NS component during the Imperial Valley earthquake (1940) is employed, and the peak ground velocity (PGV) is set to 0.75 m/s.

#### 3.2.1 Comparisons between damper design optimized for maximum interstory drift and that optimized for top acceleration

At the top left in Figures 6A–D, the recovery times are shown for the models optimally designed for the maximum interstory drifts and top floor accelerations. The parameters of the maximum interstory drifts and those of the maximum floor accelerations are also plotted for the cases where the sum of added damping coefficients corresponds to 10, 20, ..., 50 × 10^7 [Ns/m]. At the top right in the Figures 6A–D, the damper placements are also illustrated for the cases where the

### Table 1. Parameters of fragility functions for structural frame

| Damage state | Recovery time [month] |
|---------------|------------------------|
| Slight        | 0.1                    |
| Moderate      | 3                      |
| Extensive     | 12                     |

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The sum of the added damping coefficients corresponds to $30 \times 10^7$ [Ns/m]. The real-coded GA (BLX-α$^{27}$) is used for the optimization. The details of the real-coded GA are explained in Section 4. It can be understood from Figures 6B and D that when the dampers are optimally designed for the maximum top floor accelerations (with a small added damping), large plastic deformations occur. However, it can be understood from Figures 6A and C that when the dampers are optimally designed for the maximum interstory drifts, the maximum floor accelerations are not effectively reduced, even in the case where the dampers are sufficiently provided.

Notably, the recovery time decreases almost monotonically with an increase of the sum of the added damping coefficients. When the sum of the added damping coefficients is small, the optimal design for the maximum interstory drifts reduces the recovery time more effectively than the optimal design for

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**TABLE 2. Parameters of fragility functions for facilities**

| Component          | Story  | Damage state | Median $a_{max}$ [m/s²] | Logarithmic standard deviation | Recovery time [month] |
|--------------------|--------|--------------|-------------------------|-------------------------------|-----------------------|
| Switchgear         | 1st story | Slight     | 6.5 m/s²                | 0.4                           | 0.25                  |
|                    |          | Extensive   | 13 m/s²                 | 0.4                           | 1                     |
| Distribution panel | Each story | Slight     | 6.5 m/s²                | 0.4                           | 0.25                  |
|                    |          | Extensive   | 13 m/s²                 | 0.4                           | 1                     |
| Conduit cable      | Each story | Replacement required | 4/50 m                   | 0.4                           | 0.5                   |

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**FIGURE 6.** Damper placements for optimized maximum interstory drift and optimized top acceleration, (A) Optimized maximum interstory drift (Model 1), (B) Optimized top acceleration (Model 1), (C) Optimized maximum interstory drift (Model 2), (D) Optimized top acceleration (Model 2)
the top floor accelerations. In contrast, when dampers are sufficiently provided, the latter reduces the recovery time more effectively than the former. The recovery time of the latter designs are about 1.1–1.2 times less than that of the former design. This is because many of the facility components are susceptible to the maximum floor accelerations. Although conduit cables are susceptible to the maximum interstory drifts, the failure probability is almost equal to zero when the structural frames remain elastic. The facilities and non-structural components susceptible to maximum interstory drifts are usually more ductile than structural frames. Therefore, the reduction of the maximum floor accelerations leads to a reduction of the recovery time when the dampers are sufficiently provided. In the case of Model 1 (optimally designed for the maximum top floor accelerations), the curve of the recovery time suddenly and temporarily drops down at the point where the sum of added damping coefficients almost corresponds to $12 \times 10^7$ [Ns/m]. This is because the maximum interstory drift is smaller than $2d_r$.

### 3.2.2 Comparisons of optimal damper designs with respect to transfer function amplitudes at natural frequencies

The first-mode optimal damper placement $c_{opt,1}$, second-mode optimal damper placement $c_{opt,2}$, and third-mode optimal damper placement $c_{opt,3}$ are investigated from the perspective of the recovery time. $c_{opt,1}, c_{opt,2}, c_{opt,3}$ are optimally designed for minimizing the sum of the amplitudes of the interstory drift transfer function at the 1st–3rd undamped natural circular frequencies (see references 11, 13). Figures 7 and 8 illustrate the sum of the amplitudes of the interstory velocity transfer functions and distributions of the added damping coefficients for the cases where the sum of the added damping coefficients corresponds to $10, 30, 50 \times 10^7$ [Ns/m]. It can be observed that $c_{opt,1}$ effectively reduces the transfer function amplitudes near the fundamental natural circular frequency. However, $c_{opt,1}$ does not effectively reduce those in the high frequency range. $c_{opt,2}$ does not effectively reduce those near the fundamental natural circular frequency. Nevertheless, $c_{opt,3}$ effectively reduces those in the wide frequency range.

The $n$-th mode optimal damper placement provides a larger damping coefficient to the stories which show relatively large interstory drifts in the $n$-th mode participation vector, and this tendency is remarkable when the sum of added damping coefficients is small. Compared to $c_{opt,1}$ and $c_{opt,2}$, $c_{opt,3}$ provides a small amount of damping to relatively many stories. Consequently, $c_{opt,3}$ effectively reduces the transfer function amplitudes not only near the 3rd natural circular frequency, but also in other frequency ranges.

Figure 9 shows the recovery time. When the sum of the added damping coefficients is $10 \times 10^7$ [Ns/m], the maximum interstory drifts surpass $d_r$ for all of the models. In those cases, it is difficult to clearly describe the relation between the damper placement and recovery time, as these are optimally designed for the transfer functions of elastic models. In the cases where the sum of the added damping coefficients is $20, \ldots, 50 \times 10^7$ [Ns/m], the curves of the recovery time show relatively stable changes. This is because the maximum interstory drifts are smaller than $d_r$ for $c_{opt,1}, c_{opt,3}$, and those for $c_{opt,2}$ are smaller than $2d_r$. In those cases, $c_{opt,3}$ reduces the recovery time the most effectively. However, $c_{opt,1}$ does not effectively reduce the transfer function amplitudes in the high-frequency range or the floor acceleration responses. $c_{opt,2}$ does not effectively reduce the interstory drift responses. Therefore, the recovery times for $c_{opt,1}, c_{opt,2}$ surpass that for $c_{opt,3}$.

### 4. Damper Optimization for Minimizing Recovery Time

#### 4.1 Optimization algorithm for minimizing recovery time

In this section, an optimization algorithm is presented for minimizing the recovery time. The proposed algorithm uses a type of real-coded GA. Although a gene is usually expressed by 0 or 1 (binary expression) in an ordinary GA, in a real-coded GA, design variable vectors are directly processed to create new individuals. Figure 10 shows the difference between the ordinary GA (Figure 10A) and real-coded GA (Figure 10B). The self-programming of the ordinary GA is difficult because it requires advanced techniques for encoding the variables, and GA-implemented commercial software are expensive. In addition, the success of the optimization largely depends on whether the design variables are appropriately transformed into the binary expression or not. The self-programming of the real-coded GA is relatively easy, because it does not require the binary expression of the variables.

However, the success of the optimization largely depends on whether a suitable crossover method is adopted or not. In other words, a crossover method should be selected with a good understanding of the properties of the problem. Notably, the real-coded GA can also easily treat continuous variables for optimization.

Various types of crossover methods have been proposed for the real-coded GA, and BLX-$\alpha$ is a simple one. Figure 10B illustrates an overview of BLX-$\alpha$ as an example of the real-coded GA. The optimization by BLX-$\alpha$ is described in a later section to demonstrate the effectiveness of the proposed method. The proposed method effectively uses a constraint on the sum of the added damper damping coefficients to reduce the number of dimensions of the search range from $N$ to $(N-1)$, greatly decreasing the total computational load.

The proposed optimization algorithm uses the real-coded GA for the following reasons.

- The objective function (recovery time) has strong nonlinearity and discontinuity points and/or multiple peaks. Moreover, elastic–plastic structural frames are considered. The use of sensitivity-based optimization methods may lead to local minimum solutions (non-global optimum solutions). Therefore, an optimization method which effectively uses random numbers is more suitable for such problems.
- The multi-objective optimization can be easily conducted, and the computational load for the multi-objective optimization is not large relative to that in the case of a single-objective optimization.
- It does not require the binary expression of the design variables.

The merits of the constraint (that the sum of the added damping coefficients is kept constant) are described below.

- The number of the dimensions of the search range decreases from $N$ to $(N-1)$, decreasing the total computational load. Moreover, the combinational use of the proposed crossover method and local search operator efficiently searches for solutions for cases where the sum of the added damping coefficients changes.
- The values of the maximum structural responses change more stably compared to those in the case where the sum of the added damping coefficients changes in the process of the optimization (the multimodality of the objective function is greatly weakened). However, when the crossover
methods proposed by the previous studies are adopted, the sum of the added damping coefficients is not kept constant. In those cases, careful use is required, for the following reasons.

- When individuals are generated, the sum of the added damping coefficients is not well-controlled.
- Many individuals should be generated in the first step to improve the accuracy of the solutions.

**FIGURE 7.** Comparison of optimal damper placements with respect to transfer function amplitude at natural frequency, (A) Model 1, (B) Model 2
The accuracy of all of the individuals gradually improves. When solutions are sought with the limited range for the sum of the added damping coefficients, such types of crossover methods will be inefficient.

When an individual with a small amount of added damping and another individual with a large amount of added damping are selected for the crossover, the generated individual may not be a good solution.

In the next section, the optimization algorithm for minimizing the recovery time based on one specified scenario is described. This corresponds to a single-objective optimization.

4.1.1 Optimization algorithm for minimizing recovery time based on one specified scenario

Step 1 Randomly generate on one specified scenario

Step 2 Choose individuals among the obtained ones by roulette wheel selection. Then, newly obtain N models by the crossover operator (the details of the crossover operator are explained below).

Step 3 Choose M2 individuals among all of the individuals by elitist selection, and randomly create M2 models. Then choose (M1−M2−M3) models among the remaining individuals by roulette wheel selection. Return to Step 2. The procedures in Steps 1–3 are repeated for the designated number of times before proceeding to Step 4.

Step 4 Apply the local search operator to the last chosen M2 individuals (the details of the local search operator are explained below). When the objective function is improved, select and update the individuals. These procedures are repeated for the designated number of times.

Crossover operator

\( \mathbf{c}_i = (c_{1,i}, \ldots, c_{N,i})^T \) denotes the added damping coefficient vector of the i-th individual (\( i = 1, \ldots, N \)). Obtain N individuals from \( \mathbf{c}_i' = \mathbf{c}_i + \sum_{j=1}^{N-1} \epsilon_j (\mathbf{c}_j - \mathbf{c}_i) \), where \( \epsilon_j \) is a uniform random number, and \( \epsilon_j \) takes both positive and negative values. When any value of the components in \( \mathbf{c}_i' \) becomes negative, change the value of the corresponding component to zero, and then multiply a constant on \( \mathbf{c}_i' \) so that the constraint on the sum of added damping coefficients continues to be satisfied.

Local search operator

Obtain a new individual with the added damping coefficient vector \( \mathbf{c'} = \mathbf{c} + (\mathbf{c'}^T \cdot \mathbf{1}) \sum_{j=1}^{N-1} \epsilon_j \Delta_j \) from the model with \( \mathbf{c} = (c_1, \ldots, c_N)^T \), where \( \epsilon_j \) is a uniform random number, and \( \epsilon_j \) takes both positive and negative values. \( \Delta_j (j = 1, \ldots, N-1) \) is an N-dimensional vector whose j-th and (j+1)-th components are (+1, -1), and the remaining components are 0. When any value of the components in \( \mathbf{c'} \) becomes negative, change the value of the corresponding component to zero, and then multiply a constant on \( \mathbf{c'} \) so that the constraint on the sum of the added damping coefficients continues to be satisfied.

Figure 11A illustrates an overview of the proposed crossover method. In the application of the proposed crossover method, the sum of the added damping coefficients is kept constant. This is because all of the selected individuals have an identical value for the sum of added damping coefficients, and \( (\mathbf{c}_i - \mathbf{c}_j)^T \cdot \mathbf{1} = 0 \) is satisfied for all i, j. In other words, all of the individuals exist in the hyperplane \( c_1 + \ldots + c_N = W \), and \( (\mathbf{c}_i - \mathbf{c}_j) \) corresponds to the vector from the i-th individual to the j-th individual. Therefore, the proposed crossover method
gives the $i$-th individual the change of the distance with the $j$-th individual.

The proposed local search operator aims for a faster and more accurate search of the solutions. The crossover operator dynamically searches for the optimal solution. Then, the local search operator is used for improvement, i.e., to search around the obtained solution by elitist selection.

The above-stated algorithm is a single-objective optimization algorithm, and one recovery scenario is specified beforehand. As stated in Section 2.2, a design which minimizes the

![Comparison of recovery time, interstory deformation, and floor acceleration. (A) Model 1, (B) Model 2](image)

**FIGURE 9.** Comparison of recovery time, interstory deformation, and floor acceleration. (A) Model 1, (B) Model 2
recovery time based only on one scenario (either Scenario LA or Scenario FA) is not always effective for reducing recovery times based on any other probable scenarios. Nevertheless, the consideration of all the probable scenarios for the optimization is unrealistic. In this study, this uncertainty in the recovery scenarios is considered in the damper design through the multi-objective optimization for minimizing the recovery time based on Scenario LA and Scenario FA.

The above-mentioned algorithm is easily extended to a multi-objective optimization algorithm. In the case of multi-objective optimization, the reciprocal number of the Pareto rank is applied to the fitness function in the elitist selection and roulette wheel selection.

### 4.1.2 Optimization algorithm for minimizing recovery time based on non-specified scenarios

#### Step 1
Randomly generate $M_1 (N)$ individuals with a constant sum $c_1 + \ldots + c_N = W$ of the added damping coefficients.

#### Step 2
Choose $N$ individuals among the obtained individuals by roulette wheel selection. Then, newly obtain $N$ models by the crossover operator.

#### Step 3
Save the data of the individuals whose Pareto ranks are one. Choose $M_3 (N)$ individuals among all of the individuals by roulette wheel selection, and randomly create $M_3$ models. Return to Step 2. After repeating the procedures in Steps 1–3 for the designated number of times, choose the Pareto solutions among the saved individuals and ultimately obtained individuals. Then, proceed to Step 4.

#### Step 4
Choose $M_4$ individuals by roulette wheel selection, and apply the local search operator to those individuals. Re-evaluate the Pareto ranks and delete the data of the individuals whose Pareto ranks exceed one. Repeat these procedures for the designated number of times.

The above-mentioned two algorithms effectively use the constraint on the sum of the added damping coefficients.
optimization algorithm for the cases where the sum of the added damping coefficients changes is explained below. An overview of the algorithm is illustrated in Figure 11B.

4.1.3 Optimization algorithm for various total amounts of damper

Step 1 Obtain the optimal solutions (or Pareto solutions) under \( c_1 + \ldots + c_N = W \) by the above-mentioned algorithms.

Step 2 Multiply \((c_1, \ldots, c_N)\) of the obtained Pareto solutions by \( W/W_0 \) and create new individuals with \( c_1 + \ldots + c_N = W_0 \).

Step 3 Conduct the search by the local search operator to obtain the optimal solutions (or Pareto solutions) under \( c_1 + \ldots + c_N = W_0 \). Then, return to Step 2.

Notably, a large difference between \( W \) and \( W_0 \) may decrease the accuracy of the solutions, and even a large number of the repetitions of the local search operator may not improve the accuracy. In contrast, when the difference is small, the optimal solutions (or the Pareto solutions) can be searched for with a small number of repetitions of the local search operator. In these two cases, the total computational load does not change much. Therefore, the latter is appropriate for the accurate search of the solutions.

4.2 Numerical examples

Figures 12 and 13 show the results of the multi-objective optimization for minimizing the recovery time based on Scenario LA and Scenario FA, respectively. An El Centro NS component whose PGV = 0.75 m/s is adopted. At first, the optimization is conducted under the constraint that the sum of the added damping coefficients is kept at 50 \( \times 10^7 \) [Ns/m]. Then, the sum of the added damping coefficients is decreased by 1 \( \times 10^7 \) [Ns/m] from 50 \( \times 10^7 \) [Ns/m] to 10 \( \times 10^7 \) [Ns/m]. \( M_1 = 2N + M_3 = 27 \) and \( M_3 = 3 \) are employed. The crossover operator is applied for 150 times, and the uniform random number \([-0.15, 0.15]\) is adopted. The local search operator with \( M_4 = N \) is used for 50 iterations, and the uniform random number \([-0.03, 0.03]\) is adopted. Figures 12A-B and 13A-B illustrate the optimal results for Scenario LA and Scenario FA. Those results are extracted from all of the Pareto solutions. It takes approximately 2700 s to complete the whole optimization procedure.

Figures 12C and 13C show a comparison between the results from the proposed method and those from BLX-\( \alpha \). In the application of BLX-\( \alpha \), 2000 individuals are generated in the first step. \( 4N = 48 \) individuals are generated in each step, and \( \alpha = 0.3 \) is adopted. These procedures are repeated for 500 iterations. Notably, \( \alpha \) is the crossover parameter, as shown in Figure 10B. In the application of BLX-\( \alpha \), two individuals are selected as the parents; then, both sides of the intervals defined by the coordinates of the two individuals are expanded by 100\( \alpha \)%%. By using the expanded intervals and uniform random numbers, a new individual is generated. All of the Pareto solutions are saved for the next generation at each step. The difference between the sums of the added damping coefficients of the two individuals selected for the crossover is arranged so as not to be extensively large. It takes approximately 5500 s to complete the whole optimization procedure. Figures 12D and 13D illustrate the expected values of the repair time by the failure of each facility component for the cases where the sums of the added damping coefficients correspond to 10, 30 \( \times 10^7 \) [Ns/m]. The repair time for the failure of the switchgear is not indicated, as the switchgear and distribution panels have identical fragility curves and recovery times. The results from Figures 12 and 13 are summarized as follows.
The proposed method provides accurate solutions. When the recovery time based on Scenario LA is optimized, the reduction of the total damage of all of the components is prioritized. In contrast, when the recovery time based on Scenario FA is optimized, the reduction of the maximum damage among all of the components is prioritized. This tendency is remarkable for the case where the sum of the added damping coefficients corresponds to $10 \times 10^7 \text{Ns/m}$. Although the latter designs reduce the maximum top floor accelerations well, the damage to the distribution panels and conduit cables in the middle stories become large.

When the dampers are sufficiently provided, the maximum interstory drifts are sufficiently reduced, and the structural frames do not suffer. The failure probabilities of the conduit cables become almost zero in such cases. When the dampers are provided more sufficiently, the floor acceleration responses should be preferentially reduced.

When the sum of the added damping coefficients is smaller than $20 \times 10^7 \text{Ns/m}$, the dampers are designed so that the maximum interstory drifts are smaller than $2d_y$. This comes from the setting of the fragility curve of the structural frames (see Figure 5A). In contrast, when the sum of the added damping coefficients is $10 \times 10^7 \text{Ns/m}$, the dampers are designed so that the maximum interstory drifts are slightly smaller than $2d_y$, and the floor acceleration responses are reduced.

When the sum of the added damping coefficients are $40, 50 \times 10^7 \text{Ns/m}$, the optimal designs for Scenario LA preferentially reduce the floor acceleration responses in the upper stories. In the cases of the optimal designs for Scenario FA, the added damping to the lower stories becomes small, and the maximum floor accelerations in the bottom and top stories become almost identical. The floor acceleration response in the 1st story almost corresponds to the ground acceleration, and the added damping in the lower stories slightly increases the maximum floor acceleration in the 1st story. In other words, the added damping to the lower stories becomes small because the prevention of the slight increase of the maximum floor acceleration in the 1st story is prioritized more than the reduction of the maximum top floor acceleration.

5. CONCLUSIONS

In this paper, an evaluation model for a building’s resilience and recovery time was presented, and a new optimal viscous damper placement method was proposed for targeted resilience. The main conclusions can be summarized as follows.

1. The proposed evaluation model regards the structural frame, facilities, and non-structural components in the building as the components contributing to the functionality of the building. The model has the following features: 1) the building components (structural frame, non-structural components, and facilities) are categorized into systems from the perspective of functionality; 2) the recovery time is considered as a function of the damage to building components and human resources for repairing the components; and 3) the model is applicable to structural design.

2. The proposed evaluation model quantifies the resilience and recovery time by using the maximum structural
The vulnerability of a building is a function of the seismic demand and the building's structural and non-structural elements. The objective of seismic design is to reduce the vulnerability of buildings to seismic loads. The multi-objective optimization for minimizing the recovery time based on Scenario LA and Scenario FA is conducted so that the uncertainty in the recovery scenario can be reflected in the damper design. It is clarified that the optimization for Scenario CA corresponds to the minimization of the total damage to all of the components, and that the optimization for Scenario FA corresponds to the minimization of the maximum damage among all of the components.
How to cite this article: Akehashi H, Takewaki I. Modeling of resilience based on categorized recovery scenario and improving resilience with viscous damper. Jpn Archit Rev 2022;5:279–294. https://doi.org/10.1002/2475-8876.12273

Appendix A: Method for randomly generating damper designs with constant sum of added damping coefficients

Step 1 Independently generate random numbers $x_1, \ldots, x_{N-1}$ as follows:

$$f(x_i) = \begin{cases} 
(N-i) \cdot (1-x_i)^{N-1-i} & (0 \leq x_i \leq 1) \\
0 & (x_i < 0, 1 < x_i) 
\end{cases} \quad (i = 1, \ldots, N-1)$$

(A1)

When $i = N-1$, $f$ corresponds to the uniform distribution.

Step 2 The added damping coefficients $c_1, \ldots, c_N$ are determined as follows:

$$\begin{cases} 
\frac{c_i}{W} = x_i \\
\frac{c_i}{W} = (1-x_1) \ldots (1-x_{i-1})x_i & (i = 2, \ldots, N-1) \\
\frac{c_N}{W} = (1-x_1) \ldots (1-x_{N-1}) 
\end{cases}$$

(A2)

where $W$ denotes the sum of added damping coefficients.

The above-stated procedures are repeated for as many times as required.

It is noted that the uniform random numbers cannot be applied to $x_1, \ldots, x_{N-1}$ because the constraint on the sum of the added damping coefficients is set. When $c_1, \ldots, c_N$ follow Equation (A1), the joint distribution $f(c_1, \ldots, c_N)$ can be expressed as follows:

$$f(c_1, \ldots, c_N) = f(c_1)f(c_2|c_1)f(c_3|c_1,c_2) \cdots f(c_{N-1}|c_1,\ldots,c_{N-2})f(c_N|c_1,\ldots,c_{N-1})$$

$$= \frac{N-1}{W} \left( 1 - \frac{c_1}{W} \right)^{N-2} \frac{N-2}{W-c_1} \left( 1 - \frac{c_2}{W-c_1} \right)^{N-3} \cdots \frac{N-i}{W-\sum_{j=1}^{i-1}c_j} \left( 1 - \frac{c_i}{W-\sum_{j=1}^{i-1}c_j} \right)^{N-1-i} \cdots \frac{1}{W-(c_1+\ldots+c_{N-2})} \cdot 1$$

$$= \frac{1}{W^{N-1}}.$$  

(A3)

It is understood from Equation (A3) that the value of $f(c_1, \ldots, c_N)$ is constant and independent of $c_1, \ldots, c_N$. In other words, the likelihood is constant at any point on the hyperplane $c_1 + \ldots + c_N = W (c_i \geq 0$ for all $i$).

It is noted that $x_1, \ldots, x_{N-1}$ can be easily obtained from inverse transform sampling. The cumulative distribution $F(x_i)$ of $x_i$ is expressed as follows:

$$F(x_i) = \begin{cases} 
0 & (x_i < 0) \\
1 - (1-x_i)^{N-i} & (0 \leq x_i \leq 1) \\
1 & (1 < x_i) 
\end{cases} \quad (i = 1, \ldots, N-1).$$

(A4)

$F$ is obtained by the uniform random number whose interval corresponds to [0 1]; then, $x_i$ is accordingly calculated as follows:

$$1 - x_i = (1-F)^{1/(N-i)}.$$  

(A5)