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Derivation and Evaluation of Superior Design Solutions for Steel Buildings

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Abstract A multiple start local search (MSLS) method was proposed to simultaneously perform local optimization of both the main frame and multiple types of damping devices, such as buckling restrained braces (BRBs) and oil dampers (ODs). The discrete design variables include the cross-sectional dimensions of beams and columns, as well as the layout and performance parameters of BRBs and ODs. Superior design solutions (SDSs) were derived by minimizing the total steel volume of the building, including the equivalent steel volume of BRBs and ODs. The SDSs satisfy both allowable stress design constraints under sustained and moderate seismic loads, and dynamic response constraints under major earthquakes. The proposed method was applied to a 16-story steel office building, and the structural characteristics of the SDSs were evaluated.

Keywords: optimization, steel structure, multiple start local search, multiple-type damping device, response history analysis, superior design solution

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1. Introduction

Optimization in seismic design of buildings can be used not only for assisting advanced design but also for evaluating structural characteristics. However, only a limited number of past studies (Idels, O. and Lavan, O. (2020), Pavlovčič, L., et al. (2004), Pedamallu, C. S. and Ozdamar, L. (2008), Xu, L., et al. (2018)) have addressed computationally demanding problems in which the objective and constraint functions require nonlinear analysis for evaluation. It remains challenging to apply optimization methods involving nonlinear static pushover analysis or response history analysis (RHA) under complex design constraints in compliance with practical design standards. In past studies on optimization using the properties of damping devices as design variables (Adachi, F., et al. (2013), Balling, R. J., et al. (2009)), many approaches have assumed that the structural members of main frames are not variable. Furthermore, few studies have explored multiple-type damping devices as the design variables. Comprehensive evaluations under stringent design constraints, such as those encountered in actual engineering practice, have yet to be achieved.

The authors previously proposed a method for deriving rational design solutions (termed "superior design solutions," hereinafter SDSs) that locally minimize the steel weight using a Multiple Start Local Search (MSLS) method (Takagi, J., et al. (2020, 2021, 2023, 2024)). The design variables included the cross-sectional dimensions of structural members, as well as the strength and placement of buckling-restrained braces (BRBs) and oil dampers (ODs). The derived solutions satisfied standard structural design constraints, considering not only width-to-thickness ratios and column-to-beam strength ratios (CBR), but also dimensional limitations due to connection detailing. For large earthquakes, additional constraints were imposed based on the safety limits of ultimate lateral strength design and the results of response history analyses, evaluating the seismic energy dissipation capacity of damping devices.

Rather than aiming for a globally optimal solution, these studies focused on deriving multiple practically constructible SDSs and evaluating their structural characteristics. By analyzing SDSs generated through a defined algorithm independently of the designer's individual skills, the fairness and objectivity of the results were ensured. In this paper, a set of SDSs is derived for a 16-story steel building equipped with both BRBs and ODs, and their structural characteristics are investigated and discussed.

2. Building Examined and variables

2.1. Building Examined

Figure 1 shows the structural floor plan and elevations of the 16-story steel office building to be designed. Although the proposed method for deriving SDSs is not limited to

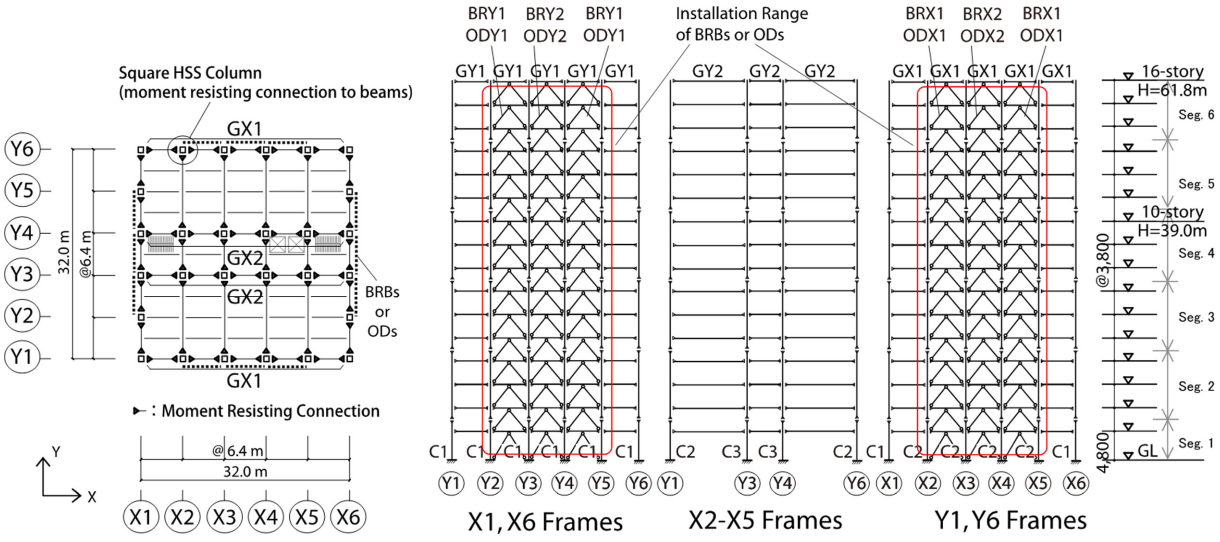


Figure 1. Floor plan and elevations of building examined.

this specific building, the outline of this example is first introduced to help explain the design variables, constraints, and modeling approach discussed later.

In Fig. 1, the ▲ symbols at beam ends in the plan indicate moment connections. All beam-column joints are modeled as rigid, and the columns are assumed to be square steel tubes. As shown in the frame elevation, the columns have splices located at mid-story height of the second floor and every third floor above. The structural segments between these splices are referred to as simply "segments," and members with the same designation (i.e., beams, columns, and dampers) within each segment are grouped to share identical cross-sectional dimensions or performance properties. Damping devices are either buckling-restrained braces (BRBs) or oil dampers (ODs), and are arranged in a chevron configuration, as shown in the elevations. Dampers can be placed in groups of three spans along each of the four perimeter frames, with the two outer spans of each group treated as a single damper group. Therefore, within each segment of one frame, there are two damper groups. The design options for each damper group consist of discrete performance values for BRBs or ODs.

2.2. Design Variables

The discrete design variables for the beam and column members are their cross-sectional dimensions and plate thicknesses, while those for the damping devices are their performance parameters. A detailed explanation of the design variables can be found in the authors' previous studies (Takagi, J., et al. (2021, 2023)). Table 1 summarizes the combinations of discrete design parameters for the damping devices.

where, K^e_{1BRB} and N^e_{yBRB} represent the initial axial stiffness and yield axial force of the BRB, respectively. The post-yield axial stiffness K^e_{2BRB} is assumed to be 2% of K^e_{1BRB}. K^e_{OD} denotes the series stiffness composed of the attachment stiffness and internal stiffness of the OD, and C^e_{OD} is its damping coefficient. C^e_{1OD} and C^e_{2OD} represent the damping coefficients before and after the relief mechanism is activated, respectively. N^e_{rOD} denotes the relief force. The superscript e indicates that these parameters are defined in the axial direction of individual damping members, distinguishing them from parameters

Table 1. Performance parameters and equivalent steel volume of damping devices

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
N^e_{yBRB} (kN)		500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500
K^e_{1BRB} (kN/mm)	0	95	190	285	380	475	570	665	760	855	950	1045	1140	1235
V^e_{BRB} (m^3)		0.15	0.18	0.21	0.24	0.27	0.30	0.33	0.36	0.39	0.42	0.45	0.48	0.51
C^e_{1OD} (kNs/mm)		6.25	12.50	18.75	25.00	31.25	37.50	43.75	50.00	56.25	62.50	68.75	75.00	-
C^e_{2OD} (kNs/mm)		0.42	0.37	0.36	0.75	0.73	0.72	1.10	1.09	1.08	1.46	1.45	1.44	-
K^e_{OD} (kN/mm)	0	101.3	101.3	101.3	200.0	200.0	200.0	287.7	287.7	287.7	362.2	362.2	362.2	-
N^e_{rOD} (kN)		400	400	400	800	800	800	1200	1200	1200	1600	1600	1600	-
V^e_{OD} (m^3)		0.35	0.35	0.35	0.51	0.51	0.51	0.67	0.67	0.67	0.83	0.83	0.83	-

at the story level, which are used in the multi-degree-of-freedom (MDOF) model described later.

The yield axial force of BRBs is treated as a discrete variable, ranging from 0 to 6500 kN in increments of 500 kN, and the relationship between K^e_{1BRB} and N^e_{yBRB} is assumed to be as given in Eq. (1).

$$K^e_{1BRB} = \alpha N^e_{yBRB} \tag{1}$$

where, the parameter α is defined as the average ratio of the axial yield force to the series stiffness of the BRB system, where the series stiffness is calculated from the initial axial stiffness of a commercially available BRB and the axial stiffness of the connection members, within the range of design options. The value of α is defined as 0.19 (1 /mm).

The combination of C^e_{1OD}, C^e_{2OD}, K^e_{OD} and N^e_{rOD} is treated as a set of design variables. These parameters are based on practical data and standard connection components. In the design of damping members, one performance combination for either a BRB or an OD is selected for each group. The performance options include zero, which indicates that no damping member is installed at the corresponding location. By including zero in the set of options and treating different types of damping devices in a unified manner, the design method aims to identify rational combinations and placements of damping members.

V^e_{BRB} and V^e_{OD} denote the equivalent steel volume of the BRB and OD, respectively, and include the steel volume of the connection components. Since chevron braces are used, the values represent the equivalent steel volume of a single damping member placed as one of the two members per span. The equivalent steel volumes for the available BRB and OD options, as shown in Table 1, range from 0.15-0.51 m^3 and 0.35-0.83 m^3, respectively. When comparing the average values across the design options, the OD is approximately 1.8 times as large as that of the BRB. These settings for the equivalent steel volumes of damping members are intended as one example to facilitate the derivation of SDSs and the analysis of their structural characteristics; the proposed design method itself is independent of these particular settings.

3. MSLS Method

3.1. Algorithm

An SDS is defined as a locally optimal solution that satisfies various design constraints for both gravity and seismic design, and minimizes the total steel volume, which is the sum of the steel volume used in the main frame (columns and beams) and the equivalent steel volume of damping members. In other words, the objective function of the local optimization is the minimization of the total steel volume, which effectively corresponds to minimizing the cost of the entire superstructure, including the damping devices. The discrete design variables consist of the cross-sectional dimensions of the beam and column members, as well as the placement and performance of the damping devices.

Figure 2 illustrates the concept of the multiple start local search (MSLS) method. Optimization problems with strict constraints and high computational costs tend to be complex and often converge to locally optimal solutions, making it difficult to find a globally optimal solution. In this study, deterioration in the objective function is not allowed during the search process, and multiple locally optimal solutions are derived. The best among them is evaluated as the SDS. While this approach does not guarantee the global optimum, the objective is to obtain and evaluate SDSs.

A solution that satisfies all design constraints is referred to as a "feasible solution." The initial solutions are selected from multiple feasible solutions generated by random variable assignments, and are chosen based on their relatively low total steel volume. Figure 3 illustrates the algorithm for deriving a locally optimal solution from one initial solution. Among the locally optimal solutions derived from multiple initial solutions, the one with the smallest total steel volume is defined as the superior design solution. Once the initial solution enters the iterative neighborhood search process, it is regarded as a temporary solution. In each iteration step, multiple neighboring solutions of the temporary solution are generated, and the feasible solution with the smallest total steel volume is selected as the new temporary solution to proceed for the next step.

To generate the initial solutions, random solutions are created by assigning random values to the design variables, including the cross-sections of beam and column members and the type and performance of damping devices. However, to actively explore rational configurations of damping members, all damping devices in random solutions are assumed to be ODs, chosen with equal probability from the options listed in Table 1. BRBs are excluded at this stage because their average equivalent steel volume among the options is smaller than that of ODs, and BRBs are more likely to replace ODs during the MSLS search process. In the constraint checking procedure for neighboring solutions, constraints with lower computational cost, such as width-to-thickness ratios and column-to-beam strength ratios, are checked first. If a solution satisfies these constraints, more computationally intensive constraints involving structural analysis are performed.

Constraint evaluations are conducted in two stages: (a) constraint checks using static elastic analysis of the frame model, and (b) constraint checks for major earthquakes based on RHA using an MDOF model. In stage (a), allowable stress design (ASD) and story drift limitations are evaluated under sustained loads and design seismic loads corresponding to moderate earthquakes. In stage

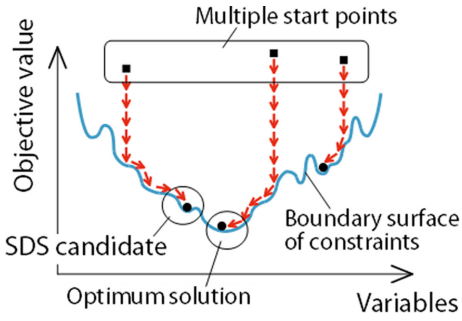


Figure 2. MSLS search concept.

(b), the seismic performance and the damping effect is assessed through RHA. The 3D frame model used in (a) is utilized to obtain information such as story stiffness, which is required for constructing the MDOF shear model.

3.2. Neighborhood Search

In each neighborhood search step, shown in Fig. 3, multiple neighboring solutions are generated from the current temporary solution. If feasible neighboring solutions with reduced total steel volume are found, the one with the smallest total steel volume is selected as the new temporary solution for the next step. For cross-sectional dimensions of structural members, discrete variables such as width and plate thickness are randomly increased or decreased by 1 with a 1/3 probability or kept unchanged. For the BRB and OD damping members, performance parameters, defined as yield strength for BRBs and damping coefficient for ODs, are similarly adjusted by ±1 or kept unchanged. Additionally, type switching (i.e., from BRB to OD or vice versa) is explored with a probability of 1/10. If the same variable has previously been switched to the new type, the performance parameter is randomly selected from the previous value ±1 with equal probability. Otherwise, it is randomly selected from the full design range of the new type. The number of neighboring solutions generated in each step equals the number of design variables. The total number of neighborhood search steps is set to 10,000, based on convergence behavior observed in the late search stages, where changes in the temporary solution became very small.

3.3. Design Constraints

The two-step seismic design procedure for moderate and major earthquakes is commonly used in the seismic

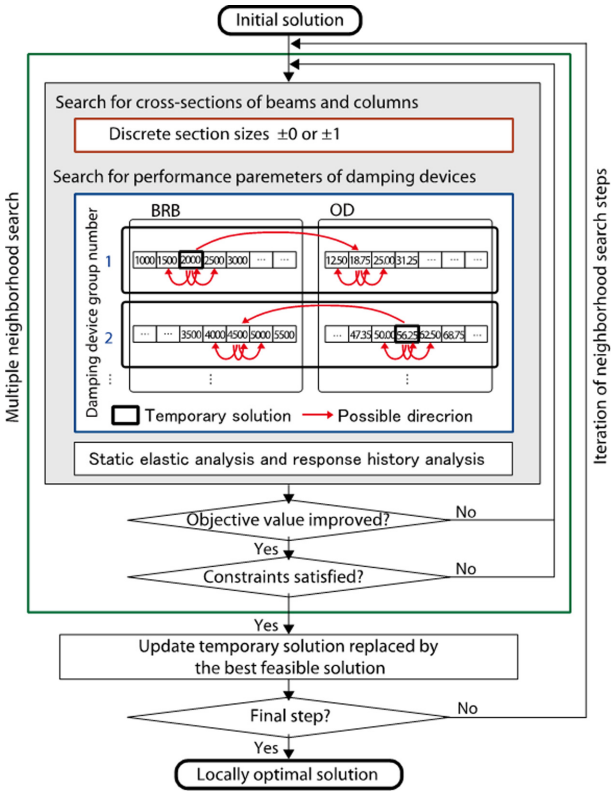


Figure 3. MSLS algorithm for an initial solution.
Note: Among the locally optimal solutions obtained from multiple initial solutions, the one with the smallest total steel volume is defined as the SDS.

design practice in Japan, and is also used in this research. The procedure is briefly overviewed in the authors' past studies (Takagi, J., et al. (2021)). The SDS must satisfy both: allowable stress design constraints under sustained and seismic design loads corresponding to moderate earthquakes (NILIM et al. (2020), AIJ (2019)), and constraints evaluated by RHA for major earthquakes (JSSI (2013)). Design constraints include specifications such as width-to-thickness ratios and CBR, as detailed in the authors' previous study (Takagi, J., et al. (2021, 2023)). In the ASD, the stresses generated in beam, column, and BRB members must be within the respective allowable limits, and inter-story drift ratio (IDR) must be less than 0.5%. The temporary load combines sustained loads (considering gravity and imposed loads for seismic design) with a design seismic load based on the A_i distribution and a standard shear force coefficient of $C_o = 0.2$, adjusted using the vibration characteristic factor R_t derived from the approximate natural period (NILIM et al. (2020)).

For major earthquake conditions, the maximum inter-story drift ratio (IDR) must remain below 1%, and floor acceleration below 10 m/s², as specified by JSSI (2013). The input ground motions consist of three very rare (Level-2) earthquake ground motions with random phases, matching the surface acceleration response spectrum

derived by considering amplification factors G_s for soil type II (NILIM et al. (2020). A 2% damping ratio proportional to the tangent stiffness is applied. Unless otherwise stated, response quantities from RHA represent the average of the three input ground motions. MDOF models are used for RHA.

Since MDOF analysis alone cannot directly assess plasticity in individual columns, the stress generated under the design seismic loads is multiplied by a factor a_c (= 3.5) to avoid significantly large plastic deformation under major earthquakes. This approach also helps assess the influence of additional axial force from ODs. Based on preliminary analyses of SDSs using the 3D frame model, $\alpha_c = 3.5$ is adopted.

3.4. Objective Function

The objective function of the MSLS method is the minimization of the total steel volume. The equivalent steel volume of damping members is included. The equivalent steel volume V^e_{BRB}, defined in Eq. (2), includes the BRB and its connecting components (collectively referred to as "BRB members") and serves as an index of the cost of the BRB.

$$\text{When } N^e_{yBRB} = 0,\ V^e_{BRB} = 0$$

$$\text{When } N^e_{yBRB} \neq 0,\ V^e_{BRB} = b_{1BRB} N^e_{yBRB} + b_{2BRB} \quad (2)$$

where, N^e_{YBRB} denotes the yield axial force of the BRB. The parameters $b_{1\mathrm{BRB}}$ and $b_{2\ \mathrm{BRB}}$ are constants derived from estimated prices of commercially available BRBs and calculated steel volumes of connecting components. Based on previous studies (Takagi, J., et al. (2021)), these constants are set to $b_{1\mathrm{BRB}}=6.0\times10^{-5}$ m^3/kN and $b_{2\ \mathrm{BRB}}$ =0.12 m^3. Similarly, the equivalent steel volume for ODs V^e_{OD} is defined in Eq. (3).

$$\text{When } N^e_{rOD} = 0,\ V^e_{OD} = 0$$

$$\text{When } N^e_{rOD} \neq 0,\ V^e_{OD} = b_{1OD} N^e_{rOD} + b_{2OD} \quad (3)$$

where, N^e_{rOD} denotes the relief force of the OD. The parameters $b_{1\mathrm{OD}}$ and $b_{2\mathrm{OD}}$ are constants derived in a manner similar to those for the BRB. These constants are set as $b_{1\mathrm{OD}}$ =4.0×10^{-4} m^3/kN and $b_{2\mathrm{OD}}$ =0.19 m^3. The design domains of C^e_{1OD} and C^e_{2OD} are as shown in Table 1. As indicated in the table, the equivalent steel volume V^e_{OD} varies depending on N^e_{rOD}, which reflects the physical size of the damper associated with the relief force. However, V^e_{OD} is not affected by C^e_{1OD} or C^e_{2OD}.

4. Analysis Models

4.1. 3D Frame Model

The 3D frame model is employed for two purposes: (1) to obtain information on story shear stiffness and other parameters necessary for constructing the MDOF model, and (2) to evaluate design constraints for ASD. While the modeling of the main frame is consistent for both purposes, the modeling of damping devices, particularly ODs, differs depending on the objective. An overview of the modeling approach for the main frame is provided in the authors' previous studies (Takagi, J., et al. (2021, 2023)). The modeling of damping members within the 3D frame for the purpose of MDOF parameter extraction is described in the next section. For the constraint evaluation in ASD, ODs are neglected, and BRBs are modeled as axial springs with stiffness K^e_{1BRB} based on Table 1.

4.2. MDOF Model

Figure 4 illustrates the configuration of the MDOF model. The Masses represent floors and are connected horizontally by multiple springs. These springs consist of the following components: MF spring: Elastic springs representing the main moment-resisting frame (beams and columns), with stiffness K_{MF}. BRB spring: Bilinear elastic–plastic springs representing the BRBs, with stiffness K_{BRB}. OD spring: Springs representing oil dampers, composed of elastic and viscous components.

The BRB spring consists of two stiffness values: the initial stiffness K_{1BRB} and post-yield stiffness K_{2BRB}. The yield strength is denoted as F_{yBRB}. The OD is modeled using the Maxwell model, and the OD spring consists of an elastic spring with series stiffness K_{OD} (combining connecting elements' and internal stiffness) and a dashpot with damping coefficient C_{OD}. The damping coefficients before and after relief are represented by C_{1OD} and C_{2OD}, respectively, and the relief force is denoted as F_{rOD}. The MF spring is modeled as linear elastic, based on preliminary analyses of SDSs, which showed that the plastic deformation of beam and column members had a limited effect. For RHA, the Newmark-β method with $\beta = 1/4$ is used, with a time integration step of 1/500 seconds.

The story stiffness and damping parameters of the MDOF model described above are derived from two sources: (1) the structural information obtained from the 3D frame analysis model, and (2) the axial-directional stiffness and damping properties of individual damping devices, including their connection components, as listed in Table 1.

The horizontal stiffness of the main frame, K_{MF}, is

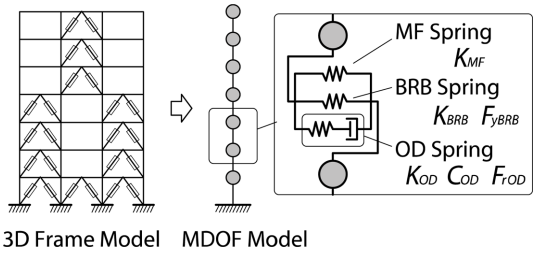


Figure 4. Composition of MDOF model.

determined from the story shear forces and inter-story drifts obtained by applying seismic loads with the A_i distribution to the frame model excluding the damping members. The relationship between the stiffness of individual BRBs and ODs in the frame model and their corresponding representation in the MDOF model is defined by Eqs. (4) and (5), respectively.

$$K_{BRB}=\sum\gamma_G^2\gamma_F K_{BRB}^e \tag{4}$$

$$K_{OD}=\sum\gamma_G^2\gamma_F K_{OD}^e \tag{5}$$

where, γ_G and γ_F are correction factors. γ_G is defined as the cosine of the angle between the damping member and the horizontal plane, and γ_F accounts for the reduction in lateral stiffness of the damping members due to frame deformation.

The factor γ_F is calculated for each story using Equation (6). In this equation, the summation symbol Σ denotes the total contribution of BRBs and ODs, respectively, within the corresponding story of the frame in the direction of the seismic load.

$$\gamma_F=\frac{(\sum\gamma_G N_{DFBRB}^e+\sum\gamma_G N_{DFeqOD}^e)/\delta_{DF}}{\sum\gamma_G^2 K_{BRB}^e+\sum\gamma_G^2 K_{eqOD}^e} \tag{6}$$

where, δ_{DF} denotes the inter-story drift of the corresponding story when seismic lateral forces are applied to a frame model that includes elastic brace members with initial stiffness K_{1BRB}^e at the BRB locations and equivalent stiffness K_{eqOD}^e at the OD locations. N_{DFBRB}^e and N_{DFeqOD}^e represent the axial forces developed in the braces under the same conditions. The equivalent stiffness of the OD, K_{eqOD}^e, is defined by Eq. (7), according to Reference (JSSI (2013)). In this equation, ω_{MF} is the fundamental angular frequency of the structural model composed of the main frame without braces.

$$K_{eqOD}^e=\frac{C_{OD}^e\omega_{MF}}{1+(C_{OD}^e\omega_{MF}/K_{OD}^e)^2} \tag{7}$$

The numerator of Eq. (6) represents the effective lateral stiffness of the braces within the frame. By dividing this by the sum of the lateral stiffnesses of the individual members in the denominator, the factor γ_F is defined as an index that quantifies the effectiveness of the braces in contributing to the frame's lateral stiffness. This factor γ_F reflects the reduction in effectiveness due to axial deformation along the brace-aligned direction of the columns to which the braces are connected.

The yield shear force of the BRBs, F_{yBRB}, and the relief force of the ODs, F_{rOD}, in a story are defined by Eqs. (8) and (9), respectively.

$$F_{yBRB}=\sum\gamma_G N_{yBRB}^e \tag{8}$$

$$F_{rOD}=\sum\gamma_G N_{rOD}^e$$

5. Evaluation of SDSs

The design solution in which the maximum IDR (R_{MAX}) obtained from RHA is constrained to 1%, and the maximum floor acceleration (A_{MAX}) is constrained to 10 m/s², is referred to as the baseline solution. Based on this, two additional solutions were derived: the 1.5% solution, in which the R_{MAX} constraint was relaxed to 1.5%, and the 600gal solution, in which the A_{MAX} constraint was made more stringent at 6 m/s^2. These variations were intended to quantitatively evaluate the influence of the constraints on the resulting design solutions and to verify the effectiveness of the proposed method in yielding rational solutions tailored to different requirements.

Figures 5 and 6 illustrate the amount of steel volume per unit floor area and the configuration of damping devices for each design solution, respectively. Table 2 summarizes the demand-capacity ratios (DCRs) and structural characteristics under the various constraint conditions. The DCR is defined as the maximum ratio of the demand value or response to the corresponding limit, with values closer to 1 indicating that the constraint is

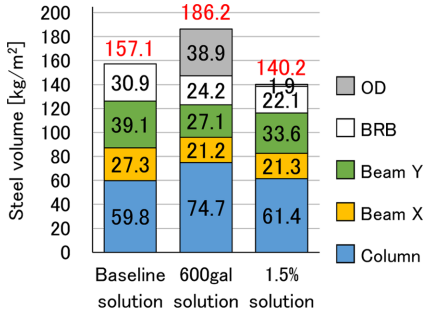


Figure 5. Steel volume.

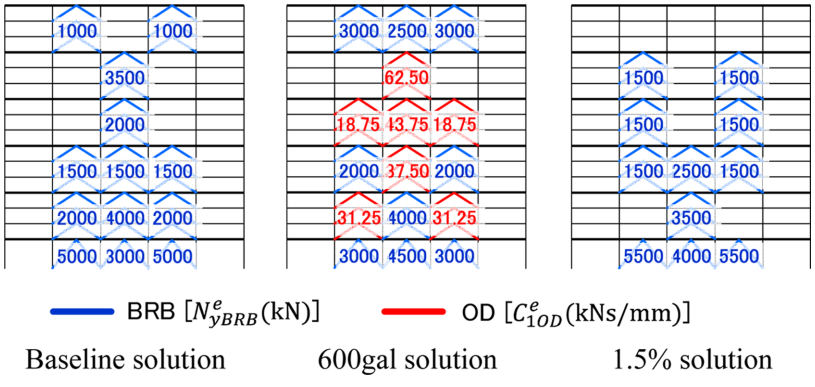
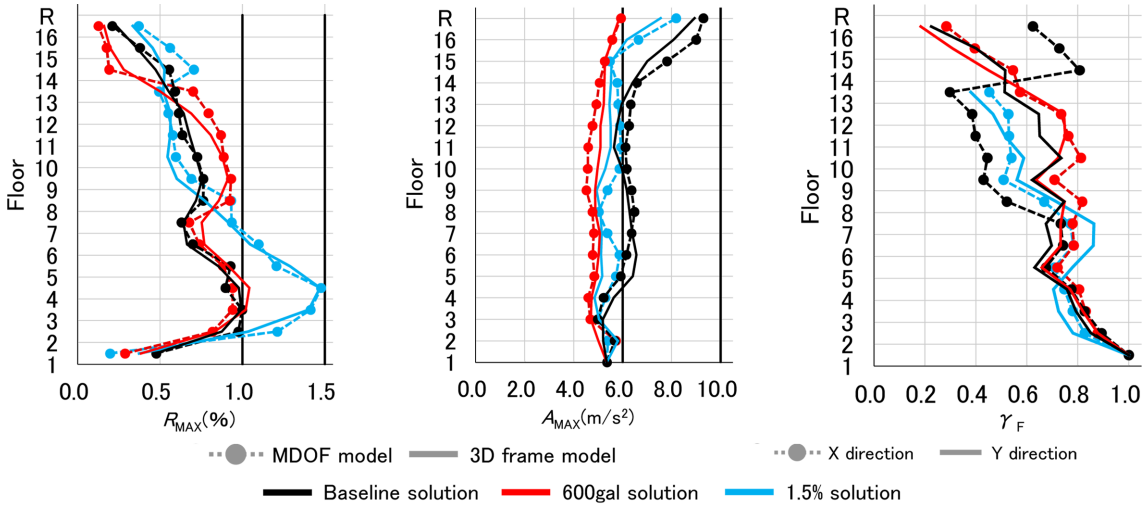


Figure 6. Configurations of damping devices in Y1 frame.

Table 2. Demand-capacity ratios and structural properties in SDSs

	CBR	The demand-capacity ratios							Structural characteristics		
		Allowable stress design					RHA				
		Column*1	Beam X	Beam Y*2	BRB	IDR	R_{MAX}	A_{MAX}	T_f(s)	T_{eq}(s)*3	h_{eq}
Baseline solution	0.76	0.99	0.53	0.64(0.85)	0.86	0.46	0.99	0.93	1.91	1.60	0.07
600gal solution	0.33	0.99	0.74	0.81(0.99)	0.93	0.76	0.99	0.97	2.31	1.91	0.12
1.5% solution	0.67	0.99	0.66	0.63(0.80)	0.98	0.52	0.98	0.82	2.31	1.95	0.09

*1 The demand-to-capacity ratio when the stress induced under the seismic design load is multiplied by a factor of 3.5
*2 The value in parentheses indicates the demand-to-capacity ratio of long-span beams under the sustained load
*3 Fundamental period of the equivalent SDOF system considering the stiffness of damping devices



Maximum IDR (%) Maximum floor acceleration

Figure 7. Maximum response (X dir.).

Figure 8. γ_F distribution.

more governing in the design. The results demonstrate that under multiple constraints, the response values tend to approach their limits, confirming that the optimization method facilitates rational design and the identification of governing design conditions.

In Table 2, T_f denotes the fundamental natural period of the main frame composed of columns and beams. T_{eq} and h_{eq} represent the equivalent natural period and equivalent viscous damping ratio, respectively, for a single-degree-of-freedom (SDOF) system incorporating the stiffness of damping devices, calculated based on the literature (JSSI (2013)). Figures 7 and 8 present the responses of R_{MAX} and A_{MAX}. Only the responses in the X-direction are shown. The differences in responses between the MDOF model and the 3D frame model are limited. Figure 8 shows the vertical distribution of the reduction factor γ_F for the SDSs. γ_F is a reduction factor that evaluates the effectiveness of braces, and its value depends on the vertical displacement at the brace connection points caused by axial deformation in the columns under the seismic lateral loads. Consequently, γ_F tends to decrease on the upper floors. The value of γ_F near the top floor is approximately 0.2, and without incorporating this factor, the responses of the shear model would not be consistent with those of the 3D frame model. This highlights the utility of γ_F in the multi-degree-of-freedom shear-type model.

In the baseline design solution, the constraints on R_{MAX} and A_{MAX} are predominant, and the total steel quantity is 157 kg/m^2. Approximately 20% of the total steel corresponds to the equivalent amount used for BRBs, while ODs are not utilized. Given the target performance of the baseline design based on Reference (JSSI (2013)), a BRB-oriented design may be more cost-effective than one using ODs.

In contrast, the 600gal solution incorporates ODs and results in a 19% increase in total steel quantity compared to the baseline. In this case, ODs are mainly installed in the upper stories, where the A_{MAX} constraint is more stringent, whereas BRBs are concentrated in the lower stories, where the R_{MAX} constraint is dominant. The increased damping provided by the ODs effectively suppresses acceleration responses. Due to the lower equivalent stiffness of ODs compared to BRBs, the effective period T_{eq} of the 600gal solution is longer than that of the baseline.

Although BRBs are present in the top story of the 600gal solution (as shown in Fig. 6), they remain mostly elastic throughout the RHA and are intended to suppress deformation and acceleration in the upper levels. In the

1.5% solution, where the R_{MAX} constraint is relaxed, the total steel quantity is reduced by 11% compared to the baseline, and no damping devices are installed in the higher stories. The horizontal stiffness of the main frame in this case is smaller than that of the baseline, resulting in a longer T_{eq}. The analysis indicates that a design without dampers in the upper stories can be rational due to response reduction associated with period elongation. The influence of the R_{MAX} constraint on the required stiffness of the main frame is significant; to suppress the maximum IDR, an increase in the lateral stiffness of the main frame is necessary.

6. Conclusions

A multiple start local search (MSLS) algorithm was proposed to handle various discrete design variables, including the cross-sectional dimensions of beams and columns in the main frame, as well as the layout and mechanical properties of buckling-restrained braces (BRBs) and oil dampers (ODs). By incorporating nonlinear response history analysis into the MSLS algorithm, the seismic energy dissipation capacity of the damping devices is evaluated. The proposed method performs local optimizarion of both the main frame and damping system simultaneously to derive superior design solutions (SDSs) for steel buildings. The obtained SDSs represent rational structural configurations that locally minimize the total steel volume, including the equivalent steel amount for damping devices. The SDSs satisfy the constraints of allowable stress design (ASD) under sustained and moderate seismic design loads, as well as the dynamic response constraints under major earthquakes. A method was developed for constructing multi-degree-of-freedom (MDOF) models and estimating the deformation of individual damping devices based on inter-story drift ratios (IDRs) in the response history analyses, and its validity was confirmed.

Application of the method to a 16-story steel office building allowed the derivation of SDSs and the evaluation of their structural characteristics. Under standard design constraints, BRBs were predominantly employed. When the constraint on floor acceleration responses was tightened, BRBs and ODs were found to be distributed across the lower and upper stories, respectively. Furthermore, the analysis revealed that suppression of maximum inter-story drift ratios (IDRs) during strong ground motions requires an increase in the lateral stiffness of the main frame. These results provide quantitative insights into the structural behavior and optimal configuration of multiple-type damping devices under various performance constraints.

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