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Research article

Effectiveness of Roof Structures as Dynamic Vibration Dampers in Buildings under Dynamic Loading

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A B S T R A C T

Buildings in earthquake-prone regions are vulnerable to dynamic responses that can cause severe structural damage if not properly controlled. One emerging approach for seismic response mitigation is the utilization of roof structures as dynamic damping systems. By appropriately tuning the mass, stiffness, and damping characteristics, roof structures can function as dynamic vibration absorbers through interaction with the main structural system. This study evaluates the effectiveness of roof structures acting as dynamic dampers in reducing the seismic responses of buildings. The research is conducted in two stages. The first stage involves a static analysis of U-shaped metallic dampers using the finite element method to determine stiffness and energy dissipation characteristics based on hysteresis curves obtained from cyclic loading. The second stage consists of a dynamic analysis in which the building structure and roof are modeled as a two-dimensional frame system, with metallic dampers installed between the building and the roof. Damper parameters are adopted from the static analysis results, while the roof mass is analytically determined to ensure its effectiveness as a dynamic damper. Dynamic analyses under earthquake excitation are performed to evaluate the reduction in structural displacement. The results indicate that roof-based damping systems can significantly reduce peak dynamic responses, particularly roof displacement and inter-story drift, demonstrating their potential to enhance the seismic performance of buildings in earthquake-prone regions.

1. INTRODUCTION

Buildings located in earthquake-prone regions exhibit a high level of vulnerability to dynamic responses induced by seismic excitations. Earthquake loads generate significant inertial forces within structures, which can increase displacements, accelerations, and internal forces in structural elements. If these responses are not adequately controlled, severe structural damage or even building collapse may occur. In addition to material losses, structural failure caused by earthquakes poses serious risks to human life and can adversely affect socio-economic stability. Therefore, controlling seismic response has become a critical issue in the planning and design of earthquake-resistant buildings [1].

Indonesia is a country with high seismic activity due to its location at the convergence of several major tectonic plates and its position along the Pacific Ring of Fire. This geological condition results in a relatively high frequency of earthquakes, including large-magnitude events. Numerous major earthquakes in Indonesia have demonstrated that many buildings, particularly multi-story structures and existing buildings without adequate seismic response control systems, have suffered severe damage. Consequently, seismic response mitigation strategies are essential to improving the seismic performance of buildings in earthquake-prone areas [2].

Conventional approaches to earthquake-resistant building design generally focus on enhancing structural capacity by increasing the strength, stiffness, and ductility of structural elements. Structural systems such as shear walls, moment-resisting frames, and bracing systems are commonly employed to resist lateral seismic loads. Additionally, strengthening techniques such as concrete or steel jacketing are often applied to existing buildings. Although these methods can improve structural capacity, conventional approaches are often less effective in reducing large dynamic responses. Increasing structural stiffness may also result in higher seismic forces acting on the structure and can lead to permanent damage to primary structural elements following strong earthquake events [3].

With the development of performance-based seismic design concepts, the focus of structural planning has shifted from merely preventing collapse to also limiting damage levels and facilitating rapid post-earthquake functional recovery. In this context, vibration control systems have emerged as an increasingly attractive alternative. These systems function by absorbing or dissipating seismic energy, thereby reducing the dynamic response of structures without requiring significant increases in structural element capacity [4].

One of the most extensively studied vibration control systems is the Tuned Mass Damper (TMD). A TMD is a passive device consisting of an auxiliary mass, elastic elements, and damping components that are tuned to resonate with the dominant frequency of the structure. When the primary structure vibrates under dynamic loading, the TMD produces an out-of-phase response that reduces the primary structure's vibration amplitude. Numerous numerical and experimental studies have demonstrated that TMDs are effective in reducing maximum displacements, accelerations, and inertial forces induced by earthquakes, thereby enhancing the seismic performance of buildings [5-6].

Beyond conventional TMDs installed as additional devices, recent research has explored the utilization of certain building components as integral parts of dynamic damping systems. One emerging approach is roof isolation, in which the roof structure is dynamically decoupled from the main structure via isolation or damping elements. Several retrofit studies have shown that roof isolation can reduce structural modal responses, particularly in the first and second modes, and improve seismic performance without requiring major modifications to the primary structural elements [7].

Nevertheless, the direct utilization of the roof structure itself as the primary component of a dynamic damping system remains relatively limited. Most previous studies have focused on external damping devices such as viscous dampers, friction dampers, base isolation systems, or TMDs that are separated from the building's structural system [8-10]. In fact, roof structures possess considerable mass. They are inherently connected to the main structure, making them potentially effective as dynamic damping elements if their mass, stiffness, and damping parameters are appropriately optimized [11].

Several studies have shown that installing hysteretic damping devices, such as steel metallic dampers, between the roof structure and the main structure can enhance seismic energy dissipation capacity [12-15]. Energy dissipation through inelastic deformation of the dampers allows a significant portion of seismic energy to be absorbed before it is transmitted to the primary structural elements, thereby minimizing structural damage [16]. However, comprehensive investigations into the optimization of roof structures as integrated dynamic-damping systems, particularly for multi-story buildings in earthquake-prone regions, remain limited and require further research.

Based on the above background, this study aims to investigate the feasibility of roof structures as dynamic dampers for seismic loading. The objective of this research is to evaluate the effectiveness of a modified roof structure. In this mass, stiffness, and damping mechanisms are optimized using metallic damping devices to reduce the dynamic response of buildings. The responses analyzed include structural displacements, accelerations, and internal forces induced by earthquake loading. The results of this study are expected to provide an effective and efficient alternative design solution for enhancing the seismic performance of buildings, particularly as a retrofit strategy with minimal structural intervention in earthquake-prone areas.

2. METHODOLOGY

In general, the research methodology adopted in this study is outlined as follows.

2.1. Two-Degree-of-Freedom (2-DOF) Dynamic Damper Concept

Based on an analytical approach derived from the vibration theory of a two-degree-of-freedom (2-DOF) mass–spring system, as illustrated in Figure 1, the upper mass functions as a dynamic damper for the 2-DOF structure when the natural frequency of the primary structure is equal to that of the roof system, i.e., $\omega_1 = \omega_2$. When the stiffness of the connecting spring k_2 is known, the mass of the upper structure (m_2) can be appropriately selected to operate as a dynamic vibration-damping system capable of reducing the vibration response of the primary mass (m_1) at its fundamental natural frequency.

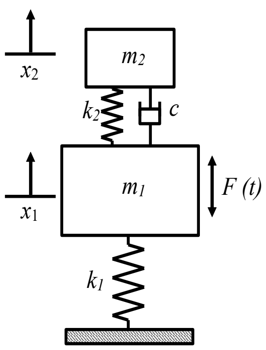

Figure 1. Two-degree-of-freedom (2-DOF) building structural model with a dynamic vibration damper

When this concept is extended to building structures, as long as the building's fundamental natural frequency can be determined, given the stiffness of the damping element between the main and roof structures, the roof mass can be properly designed so that the roof system effectively acts as a dynamic damper under dynamic loading.

2.2. Static Analysis of Metallic Dampers for the Evaluation of Stiffness and Damping Properties

A nonlinear finite element–based computational program was developed to evaluate the stiffness and strength of a U-shaped steel damper [12]. The damper was discretized using 20-node three-dimensional hexahedral elements, and both geometric and material nonlinearities were considered. Geometric nonlinearity was addressed using the updated Lagrangian formulation with the Jaumann stress rate to capture large displacements and rotations. In contrast, material nonlinearity was modeled using the von Mises yield criterion with an associated flow rule and isotropic hardening. The nonlinear response was obtained through a displacement-controlled loading scheme. In the numerical model, contact interactions and frictional forces between the sliding plates and the deformable U-shaped plate, as well as residual stresses, were neglected. The developed computational framework has been applied to various structural systems under different loading scenarios [12-14], and the numerical results have been validated through comparisons with theoretical predictions and experimental data, demonstrating good agreement.

2.2.1. Geometry and Material Properties

A static analysis of the metallic damper models under dynamic loading is conducted to determine their equivalent stiffness and damping characteristics. The selected damping device is a U-shaped metallic damper installed as a supporting element between the main and roof structures. Four configurations of U-shaped metallic dampers are employed as supporting elements, as illustrated in Figure 2.

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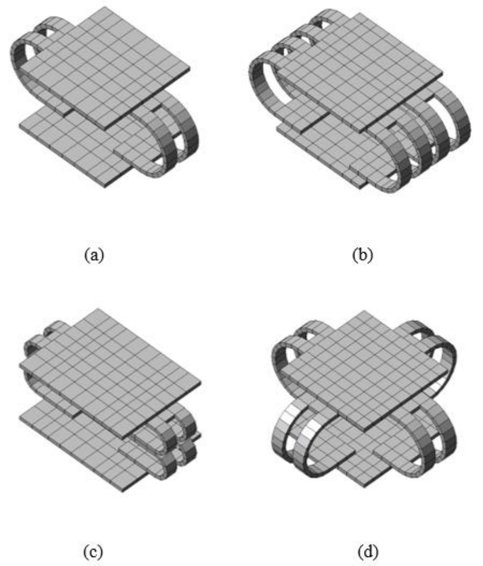

Figure 2. Numerical model of the U-shaped metallic damper

The dampers are numerically modeled using the finite element method (FEM) with three-dimensional solid hexahedral elements. The analyses are performed using a finite element–based computational program that accounts for both geometric and material nonlinearities. Metallic Damper-a (MD-a) is adopted as the baseline model in this stage. Subsequently, MD-b is developed to enhance stiffness in the horizontal (x-axis) direction. MD-c is introduced to increase stiffness in the vertical (y-axis) direction. Finally, MD-d is modeled to improve stiffness in both the horizontal (x-axis) and longitudinal (z-axis) directions.

The basic geometry of the U-shaped damper is illustrated in Figure 3, and the dimensions of each model are summarized in Table 1.

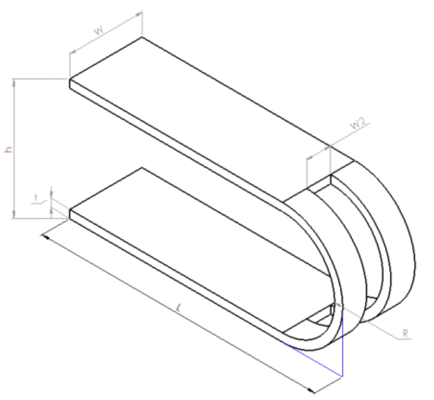

Figure 3. Metallic Damper Dimension

Table 1. Metallic Damper dimensions for all models

Parameter	MD-a	MD-b	MD-c	MD-d
Length (L)	150	150	150	150
Radius (R)	75	75	37.5	75
Width (W)	90	90	90	90
Height (H)	150	150	150	150
Thickness (t)	10	10	10	10
Gap Width (W2)	30	30	30	30

The material properties used for the metallic damper are presented in Table 2.

Table 2. Material properties of the metallic damper

Elastic Modulus (N/mm^2)	Possion's Ratio	Yield Stress (N/mm^2)	Shear Modulus (G)	Stress-strain relationship
210000	0.3	270.1	7900	Bi-Linear

1.1.2. Loading and Boundary Condition Modeling

The loading conditions and boundary conditions adopted in the numerical modeling are described as follows. As illustrated in Figure 4, the applied load is applied to the damper model in the horizontal (x-axis) direction. This loading condition allows the upper plate of the damper to translate along the x-axis, while vertical displacement (y-axis) is assumed to be restrained. In contrast, the lower plate is modeled as fully fixed, with no displacement permitted in either the horizontal (x-axis) or vertical (y-axis) directions.

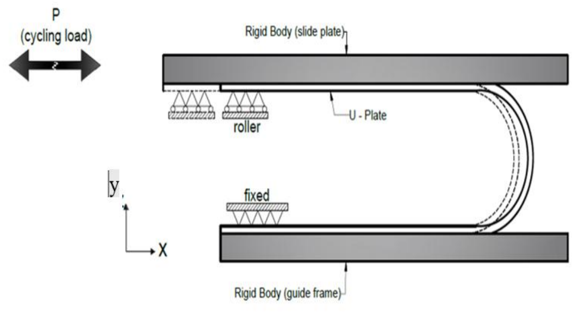

Figure 4. Loading model of the U-shaped metallic damper in the x-axis direction

Figure 5 illustrates the hysteresis curve obtained from the static analysis. Dynamic parameters, such as stiffness (K), are derived from this curve as defined in Eq. (1):

$$K = \frac{P\,el}{\delta\,el} \quad (1)$$

Meanwhile, the damping coefficient (c) is determined using Eq. (2):

$$c = \frac{\Delta W}{\pi \omega X^2} \quad (2)$$

In these equations, ΔW represents the energy dissipated by the damper, calculated from the enclosed area of the hysteresis loop; X^2 denotes the square of the maximum deflection; and ω denotes the excitation frequency of the damper.

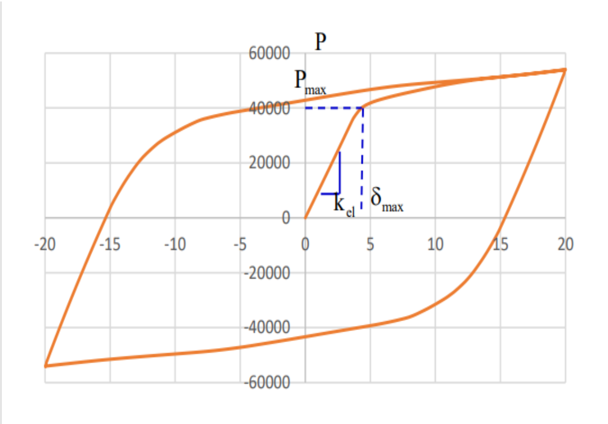

Figure 5. Representative hysteresis curve obtained from the analysis

2.3. Structural Modeling and Dynamic Analysis

The stiffness (K) and damping (c) parameters derived from the static analysis were subsequently implemented in the dynamic analysis. This analysis was carried out using a MATLAB R2024b program to assess the structural response under dynamic loading conditions. The dynamic behavior of the building structure was evaluated using four different metallic damper configurations to enable a comparative assessment of structural responses subjected to dynamic excitation.

The first dynamic analysis is conducted on the building structure with a roof system that does not incorporate a U-shaped metallic damper, as shown in Figure 6. The earthquake load is applied at node 7, and the corresponding displacement response is also evaluated at this node. Subsequently, the second dynamic analysis is performed on the building structure equipped with a roof system incorporating a U-shaped metallic damper, as illustrated in Figure 7. The damper's stiffness and damping properties are obtained from the results of Stage 2. As in the model without a damper, the earthquake load is applied at node 7, and the corresponding displacement response is evaluated at this node.

The structural members in the building have solid rectangular cross-sections. The frame members have dimensions of 0.1×0.1 m, while the bracing members have dimensions of 0.05×0.1 m. All members are made of low-carbon steel with an elastic modulus of $E = 220{,}000$ N/mm².

The dynamic load applied in this study is the El Centro earthquake record, as shown in Figure 8.

3. RESULT AND DISCUSSION

3.1. Static Analysis for the Development of the Metallic Damper Model

Based on static analysis using a nonlinear computational program, hysteresis curves were obtained for the four U-shaped metallic damper models used as seismic damping devices for the roof structure. The resulting hysteresis responses are presented in Figure 9. From these hysteresis curves, the equivalent linear stiffness and energy dissipation—subsequently converted into damping coefficients using Eq. (2)—were determined and are summarized in Table 3. The reported linear stiffness and damping values correspond to dynamic loading applied only in the x-axis direction. In contrast, the linear stiffness of the metallic dampers in the y-axis direction is assumed to be sufficiently large.

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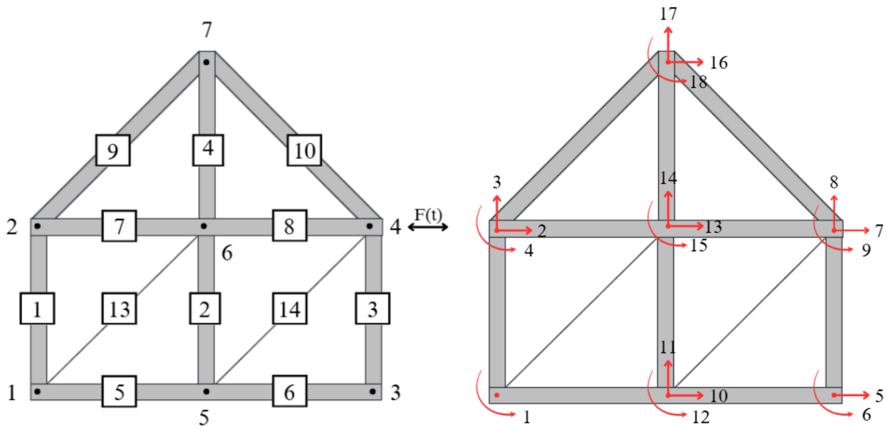

Figure 6. (a) Element and nodal discretization, (b) degree-of-freedom (DOF) distribution of the 2D frame structure without a metallic damper

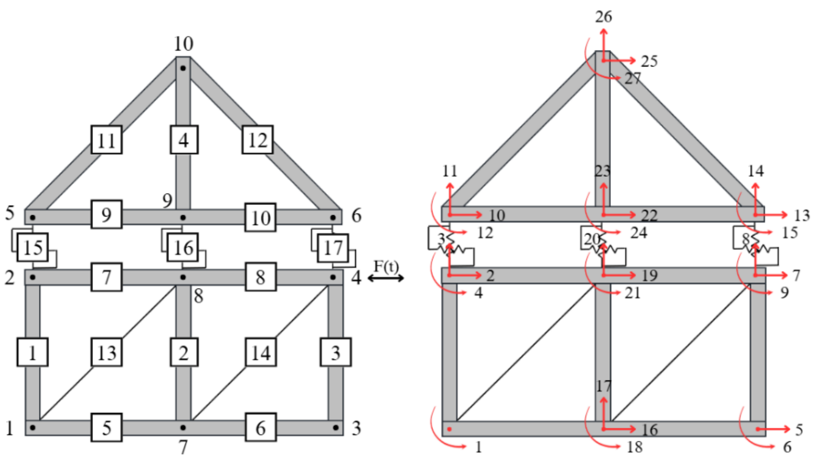

Figure 7. (a) Element and nodal discretization, (b) degree-of-freedom (DOF) distribution of the 2D frame structure with metallic dampers

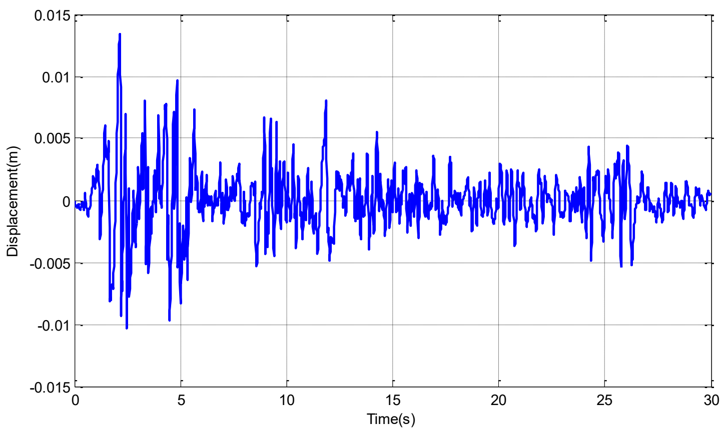

Figure 8. El Centro earthquake ground motion

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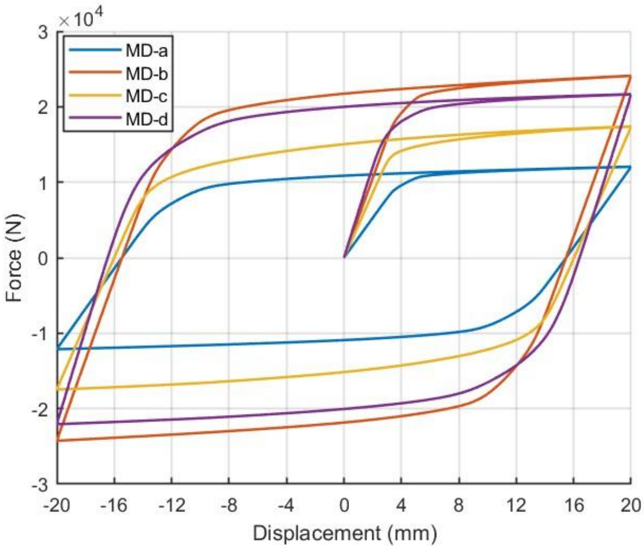

Figure 9. Comparison of hysteresis curves for four metallic damper models under x-direction loading

Table 3. Comparison of stiffness, energy dissipation, and damping properties of U-shaped metallic dampers

Model	P_{maks} (N)	P_{el} (N)	δ_{el} (mm)	K (kN/m)	ΔW (kN · m)	Ω (rad/s)	Δ_{maks} (m)	c (kN.s/m)
MD-a	12056.67	7775.08	2.96	2629.64	0.877	3.14	0.02	222.335
MD-b	24113.34	15550.05	2.96	5259.24	1.754	3.14	0.02	444.669
MD-c	17404.19	10962.55	2.56	4286.34	1.259	3.14	0.02	319.288
MD-d	21665.2	9938.37	1.64	6065.52	1.660	3.14	0.02	420.912

Table 4. Dynamic parameters of the building structure

	MD-a	MD-b	MD-c	MD-d
Mass of the building without roof (m_1)	1312.62 kg			
Fundamental natural frequency of building without roof (ω_1)	406.47 rad/s (64.69 Hz)			
Stiffness of MD to support roof structures (K_2)	2629640 N/m	5259240 N/m	4286340 N/m	6065520 N/m
Damping values of MD to support roof structures (c_2)	222335 N.s/m	444669 N.s/m	319288 N.s/m	420912 N.s/m
Mass of roof structure ($m_2 = 3*K_2/\omega_1^2$)	47.75 kg	95.5 kg	77.83 kg	110.14 kg
Mass ratio ($\mu=m_2/m_1$)	0.0364 (3.64%)	0.0727 (7.27%)	0.0593 (5.93%)	0.839 39%)

3.2. Determining Mass of Roof Structure for Four Metallic Damper Configurations

In the initial stage, the fundamental natural frequency of the building structure without the roof was determined using a computational program as ω_1 = 64.69 Hz. For the roof to function as a dynamic damper for the building structure, the roof system's natural frequency must be tuned to be close to the main structure's fundamental natural frequency. Based on the tuning condition $\omega_2 = \omega_1$, the relationship $\sqrt{3K_2/m_2} = \omega_1$ is obtained, which leads to $m_2 = 3K_2/\omega_1^2$.

If the mass of the main building structure is denoted as m_1, the mass ratio between the roof mass and the main structural mass is defined as $\mu = m_1/m_2$. The values of the mass ratio μ The roof structures supported by four different metallic damper stiffness configurations, the results are 3.64% for MD-a, 7.27% for MD-b, 5.93% for MD-c, and 8.39% for MD-d, respectively. Detailed calculation results are presented in Table 3

3.3. Dynamic Analysis of the Building Structure

The El Centro displacement input and the corresponding displacement responses at DOF 7 of the building structure, both with and without the U-shaped metallic damper installed at the roof level, are presented in Figures 10, 11, 12, and 13, respectively.

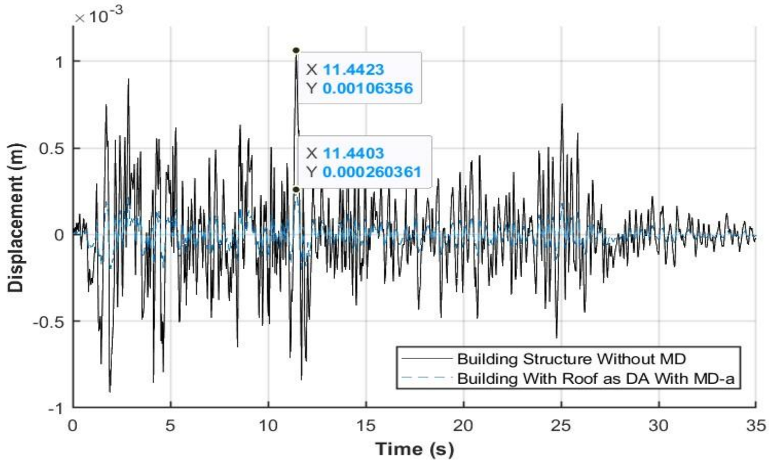

Figure 10. Comparison of the building response without a metallic damper and with a roof structure ($\mu =$ 3.64%) acting as a dynamic damper supported by MD-a

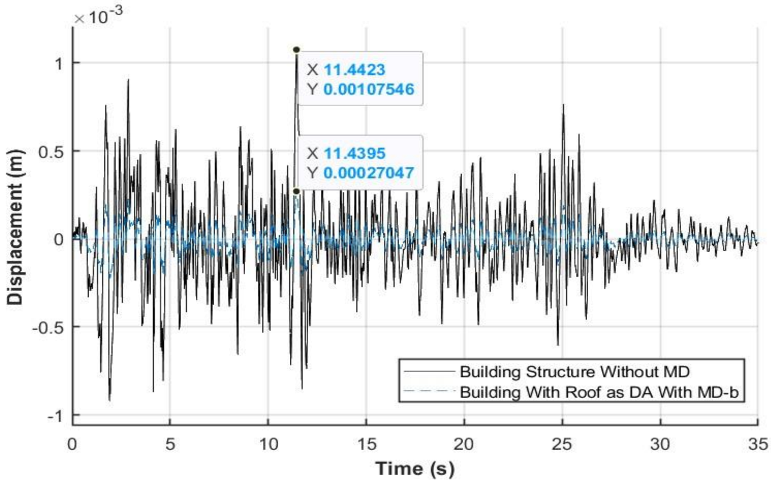

Figure 11. Comparison of the building response without a metallic damper and with a roof structure ($\mu =$ 7.27%) acting as a dynamic damper supported by MD-b

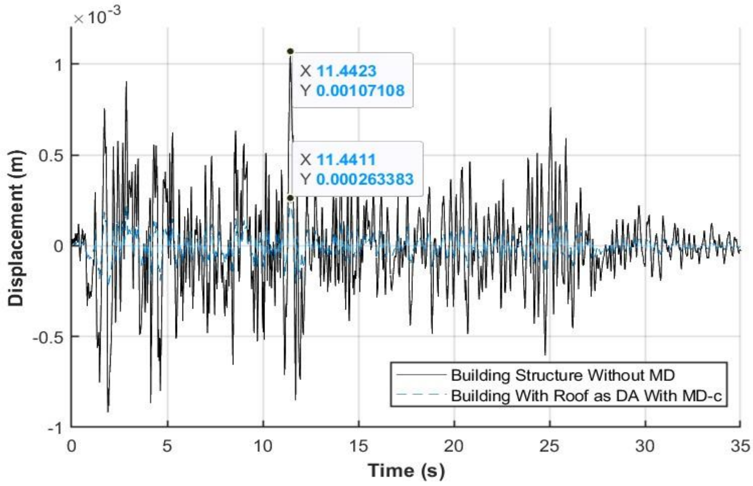

Figure 12. Comparison of the building response without a metallic damper and with a roof structure ($\mu =$ 5.93%)acting as a dynamic damper supported by MD-c

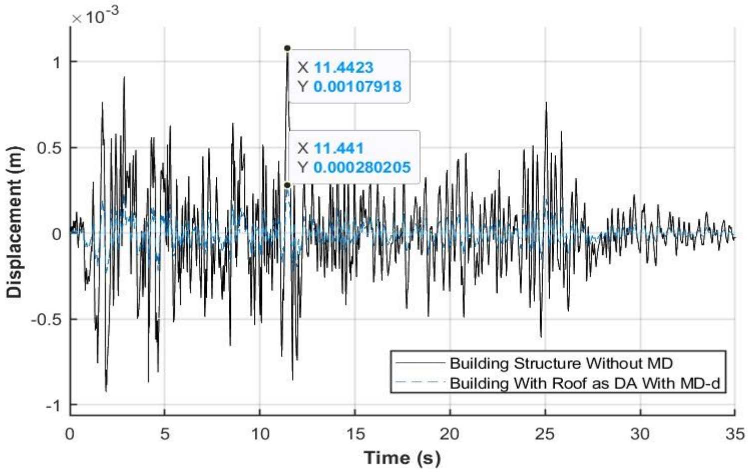

Figure 13. Comparison of the building structure response without a metallic damper and with a roof structure ($\mu = 8.39\%$) acting as a dynamic damper supported by MD-d

Table 5. Comparison of maximum displacements of the building structure without a metallic damper and with a roof structure supported by a metallic damper under variation of mass ratios (μ)

Model	Building Structures with Roof Structure					
	K (*N/m*)	c (*Ns/m*)	Mass of Roof (kg)	Ratio of Mass (μ)	$\delta_{maks}(m)$ without MD (mm)	$\delta_{maks}(m)$ Roof as Dynamic Damper with MD (mm)
MD-a	2629640	222335.2815	47.748	3.64%	1.063	0.260
MD-b	5259240	444669.4656	95.496	7.27%	1.075	0.270
MD-c	4286340	319288.5598	77.83	5.93%	1.071	0.263
MD-d	6065520	420912.1285	110.136	8.39%	1.079	0.280

Based on the displacement response results of the building structure for the U-shaped metallic damper configurations MD-a, MD-b, MD-c, and MD-d, as well as the corresponding mass ratio (μ) variations of each roof structure, as presented in Table 3.3, it can be concluded that the structural displacement response is significantly reduced.

4. CONCLUSION

A roof structure supported by U-shaped metallic dampers can act as a dynamic damper for the main building structure. The model is shown to effectively reduce the structural response at the building's fundamental natural frequency. Determination of the mass ratio (μ) between the main building structure and the roof structure, based on the stiffness of the U-shaped metallic damper, is essential to enable the roof structure to function as an effective dynamic vibration damper. Simulation results indicate that the smallest mass ratio (μ), together with the lowest damper stiffness, provides the greatest reduction in building displacement response among the other damper configurations and mass ratio combinations considered.

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Conflicts of interest

The authors declare that they have no conflicts of interest.

Generative AI and AI-assisted

AI was used for language editing, and the results were carefully verified and revised by the authors to ensure accuracy, originality, and integrity.

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