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Research article

Numerical Study on the Effectiveness of U-Shaped Steel Metallic Dampers Applied to Braced Building Structures under Dynamic Loading

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A B S T R A C T

The increasing demand for seismic-resilient structures has encouraged the development of advanced energy dissipation devices capable of reducing structural damage under strong ground motions. Among various passive control systems, metallic dampers have gained significant attention due to their stable hysteretic behavior, high energy dissipation capacity, and simplicity of installation. This study investigates the seismic performance of a building structure equipped with U-shaped steel metallic dampers installed within a chevron bracing system. The research is conducted through two complementary analytical stages. First, a detailed nonlinear finite element analysis is performed to evaluate the cyclic behavior of the U-shaped damper, accounting for both material and geometric nonlinearities. The resulting hysteresis curves are used to determine the elastic stiffness and energy dissipation capacity of the damper. In the second stage, the obtained mechanical properties are implemented into a dynamic numerical model of a multi-story building, where the damper is represented as spring element connecting the bracing system to the main structural frame. Linear time-history analyses are then conducted under earthquake ground motions to assess the dynamic response of the structure. The seismic performance of the damped structure is compared with that of an identical structure without metallic dampers in term of dynamic response. The results demonstrate that the proposed U-shaped metallic damper significantly enhances seismic performance by reducing structural demands and concentrating inelastic deformations within replaceable energy-dissipating components.

1. INTRODUCTION

Earthquake-induced damage to building structures remains a critical concern in structural engineering, particularly in regions with high seismicity. Conventional seismic design philosophies rely primarily on the inelastic deformation capacity of structural members to dissipate seismic energy. Although this approach can prevent collapse, it often leads to severe damage to primary load-resisting components, resulting in high repair costs and extended downtime after strong earthquakes. Consequently, modern seismic design has increasingly shifted toward the use of supplemental energy dissipation systems that can effectively control structural response while preserving the integrity of the main structural elements.

Among various passive energy dissipation devices, metallic dampers have attracted significant attention due to their simplicity, reliability, and stable

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hysteretic behavior. These devices dissipate seismic energy through controlled yielding of metallic components, allowing seismic demands to be transferred away from critical structural members. Previous studies have demonstrated that metallic dampers exhibit stable cyclic behavior, high energy dissipation capacity, and good fatigue resistance under repeated loading cycles [1-4].

In recent years, various configurations of metallic dampers have been proposed, including X-shaped, slit, shear-panel, and U-shaped dampers. Among them, U-shaped steel dampers have been shown to provide stable and repeatable hysteresis loops with minimal strength degradation, making them suitable for seismic applications. Experimental and numerical studies have indicated that the geometric parameters of U-shaped dampers—such as curvature radius, arm length, and plate thickness—strongly influence their stiffness, strength, and energy dissipation capacity [4-5].

Chevron bracing systems are widely used in steel structures due to their high lateral stiffness and efficient force transfer mechanism. However, conventional chevron bracing systems may experience concentration of inelastic demand in the braces and beam–brace intersections during strong earthquakes, potentially leading to brittle failure modes. Integrating metallic dampers into chevron bracing systems offers an effective solution by relocating inelastic deformation to replaceable damping elements while maintaining the elastic behavior of the primary structural members.

Despite the growing body of research on metallic dampers, comprehensive studies that integrate detailed nonlinear damper characterization with full-scale dynamic analysis of building structures remain limited. In particular, the combined evaluation of damper hysteretic behavior and its influence on global seismic response within a unified numerical framework requires further investigation.

Therefore, this study aims to evaluate the effectiveness of a U-shaped steel metallic damper installed in a chevron bracing system through a two-stage analytical approach. The first stage focuses on nonlinear finite element modeling of the damper to obtain its hysteretic response, stiffness characteristics, and energy dissipation capacity under cyclic loading. The second stage incorporates the derived damper properties into a dynamic structural model of a building subjected to earthquake excitation. The seismic responses of the damped and undamped structures are then compared to quantify the effectiveness of the proposed damping system. The findings of this study are expected to contribute to the development of performance-based seismic design strategies utilizing metallic energy dissipation devices.

2. RESEARCH METHODOLOGY

The research methodology consists of two main analytical stages:
(1) nonlinear finite element analysis of a U-shaped metallic damper under cyclic loading, and
(2) nonlinear dynamic analysis of a building structure equipped with the damper under seismic excitation.

2.1. Static Analysis of U-Shaped Metallic Damper

A computer program based on the nonlinear finite element method was developed to analyze the stiffness and strength of a U-shaped steel damper [6]. The damper was modeled using 20-node hexahedral elements. The program incorporates both geometric and material nonlinearities. Geometric nonlinearity is evaluated using the Updated Lagrangian formulation with the Jaumann stress rate, accounting for large displacements and rotations. Material nonlinearity is modeled based on the von Mises yield criterion, an associated flow rule, and an isotropic hardening rule. The numerical solution is obtained using a displacement-controlled loading scheme.

Several assumptions are adopted in the finite element modeling of the U-shaped steel damper. First, contact interactions between the sliding plates (upper and lower plates) and the deformable U-shaped plate are not considered. Second, frictional forces between the sliding and deformable plates are neglected. Third, residual stresses are not taken into account in the numerical simulation.

The developed computational program has been applied to analyze various structural systems under different study cases [7-8]. The numerical results have been validated through comparison with theoretical calculations as well as experimental data, demonstrating good agreement.

2.1.1. Geometry and Material Properties

Figure 1 illustrates four types of U-damper models used in this study. Model 1 represents the baseline configuration. Model 2 is designed to enhance stiffness in the *z*-axis direction. Model 3 is intended to increase stiffness in the *y*-axis direction. Model 4 is designed to improve stiffness in both the *x*- and *z*-axis directions. Basic configuration of the damper is presented in **Figure 2** and their dimensions are summarized in **Table 1**.

The material properties of the U-shaped plate are presented in **Table 2**. This table provides information on the mechanical characteristics of the material, which are used to evaluate its capacity to withstand applied loads or stresses.

2.1.2. Loading and Boundary Condition Modeling

The loading and boundary condition modeling of the U-shaped metallic damper is illustrated in **Figure 3.** When the U-shaped steel damper is subjected to cyclic loading in the horizontal direction along the *x*-axis, all nodal displacements at the bottom of the U-shaped steel plate are fully restrained in the *x*-, *y*-, and *z*-directions. In contrast, the nodes at the top of the U-shaped steel plate are allowed to move in the *x*-direction but are restrained in the *y*- and *z*-directions. When the U-shaped steel plate is subjected to cyclic loading in the vertical direction, all nodal displacements at the bottom of the U-shaped steel plate are fully restrained in all directions. Meanwhile, the nodes at the top of the U-shaped steel plate are allowed to move in the *y*-direction but are restrained in the *x*- and *z*-directions.

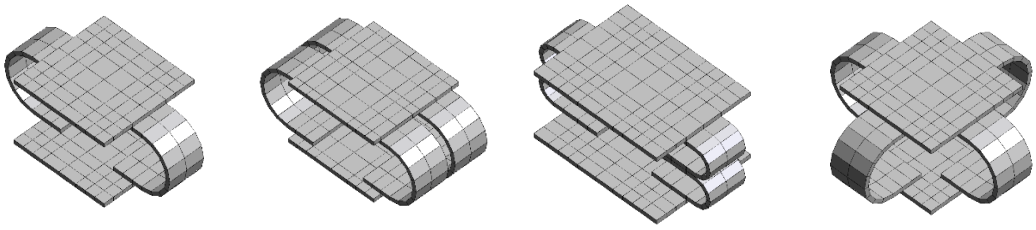
2.1.3. Calculation of maximum strength, elastic stiffness, and dissipation energy

A nonlinear finite element program was employed to evaluate the maximum strength, elastic stiffness, and energy dissipation of the damper. The computational results produce a hysteresis curve that represents the relationship between load and displacement at a selected reference point. The elastic stiffness, which is assumed to represent the equivalent stiffness of the damper, is determined from the ratio of the maximum elastic load (P_{el}) to the corresponding maximum elastic displacement (δ_{el}) as expressed in Eq. (2.1). The energy dissipation (ΔW) is calculated from the enclosed area of the hysteresis loop.

$$K = \frac{P\,el}{\delta\,el} \tag{2.1}$$

$$c = \frac{\Delta W}{\pi \omega X^2} \tag{2.2}$$

The parameter ΔW represents the area enclosed by the hysteresis curve, which corresponds to the amount of energy dissipated by the steel damper. Meanwhile, X^2 denotes the square of the maximum deflection of the steel damper, and ω represents the excitation frequency of the damper, which is assumed to be very small due to the quasi-static loading condition. Accordingly, the damping value for each model can be calculated using Eq. (2.2).



(a) (b) (c) (d)

Figure 1. Model of four metallic dampers (a). basic configuration, (b). double plates double plates in x-axis, (c). double plates in y-axis, (d) plates in x- and x-axis

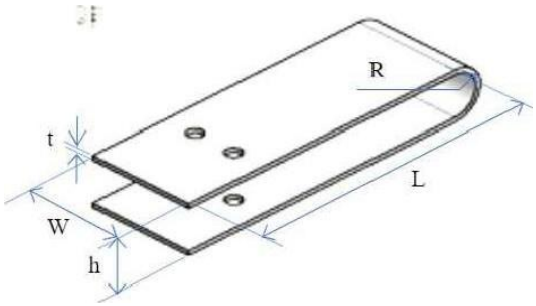


Figure 2. Basic configuration of U-plate

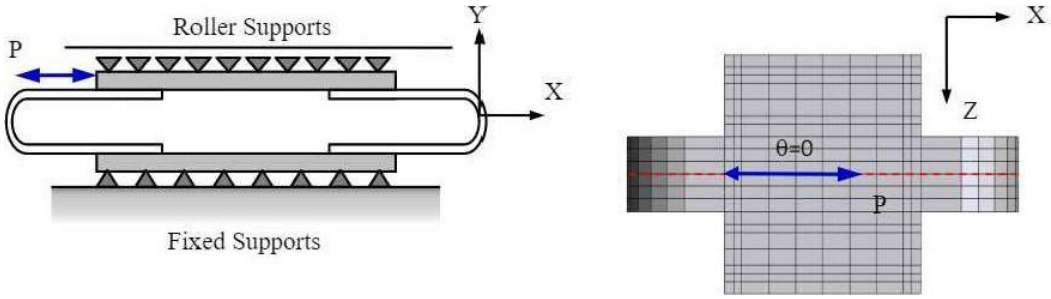


Figure 3 Modeling Boundary Condition and Loading

Table 1. Dimensions of U-Shaped Metalic Damper

Parameter	Model 1	Model 2	Model 3	Model 4
Panjang (L)	150	150	150	150
Jari-Jari (R)	75	75	37.5	75
Lebar (W)	90	90	90	90
Tinggi (H)	150	150	150	150
Ketebalan (t)	10	10	10	10

Table 2. Material Properties of Dampers

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

2.2. Structural Modeling and Dynamic Analysis

The stiffness (k) and damping (c) values obtained from the static analysis were subsequently used in the dynamic analysis, which was performed using a computational program developed in MATLAB R2024b to evaluate the structural response under dynamic loading. The dynamic analysis of the building structure was conducted using four different damper configurations in order to compare the structural responses when subjected to dynamic excitation.

2.2.1. Modelling of Building Structure

The building structure was modeled using two-dimensional frame elements, while the damper system was represented by linear spring elements, as illustrated in **Figure 4b**. For comparison purposes, a building structure equipped only with bracing elements and without dampers (see **Figure 4a**) was also modeled to evaluate its response under dynamic loading (see **Figure 5**).

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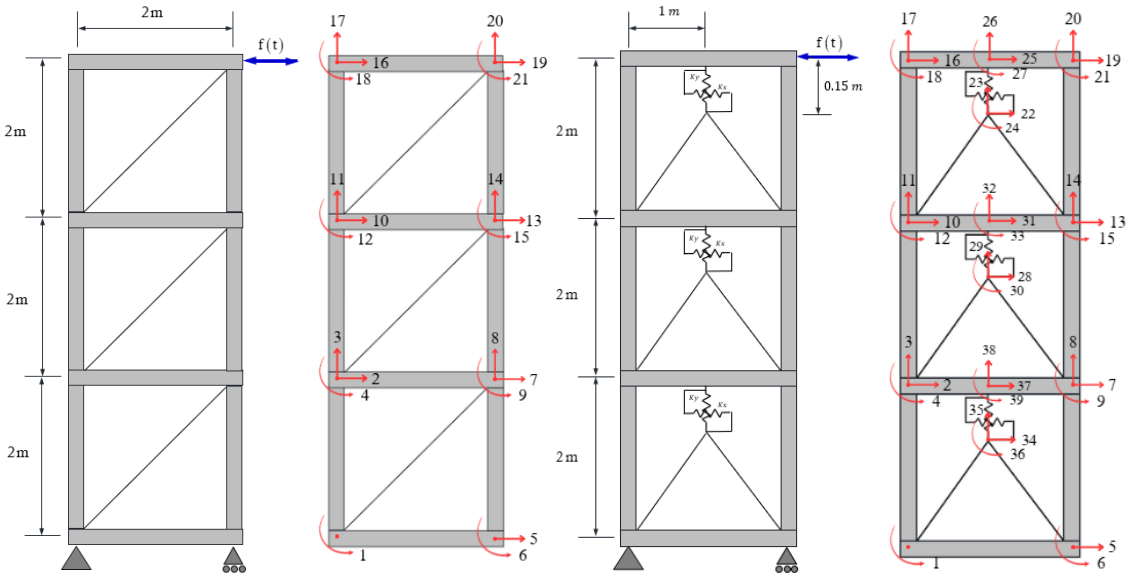


Figure 4. (a) Modeling of building structure without metallic damper, (b). Modelling of building structure with metallic damper

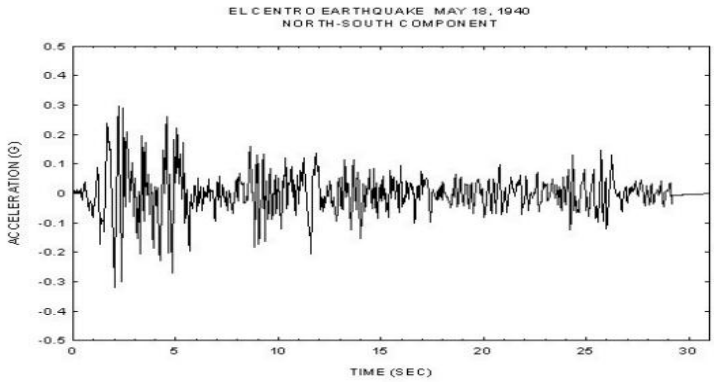


Figure 5. Dynamic loading of Elentro

2.2.2. Geometrical and Material Properties of Members of Building Structure

The geometry of the members used in the 2D frame was assumed to be uniform. The frame members were modeled with a square cross-section measuring 0.1 × 0.1 m, while the bracing members were modeled with a rectangular cross-section of 0.1 × 0.05 m. Both types of members were assigned the material properties listed in Table 3.

Table 3. Material properties of frame and bracing elements

Modulus Elastisitas (E)	Densitas (ρ)
$2.2\times10^{11}\ Pa$	$7800\ kg/m^3$

3. RESULT AND DISCUSSION

3.1. Static Analysis

3.1.1. Loading Given in X-Axis

From the nonlinear computational analysis, hysteresis curves were obtained, as shown in Figure 6a. Based on these curves, the elastic stiffness and

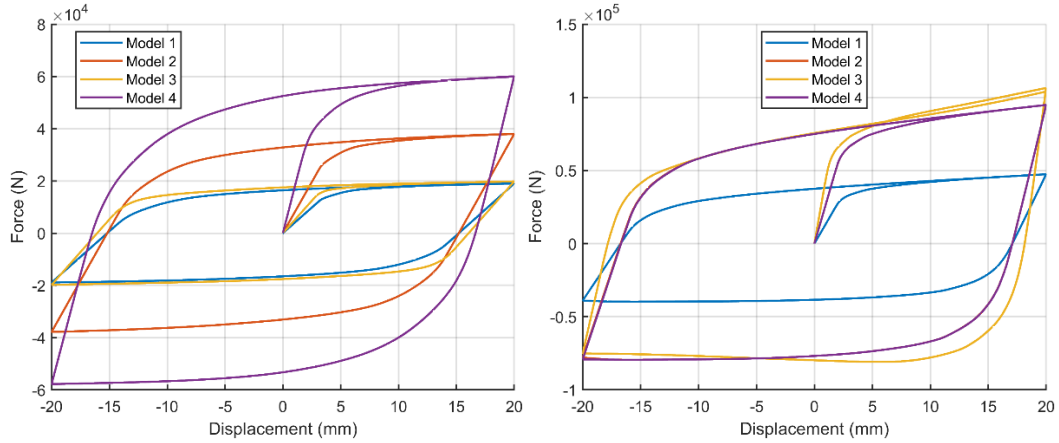
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energy dissipation values were determined. The energy dissipation was then converted into equivalent damping values using Eq. (2.2). The resulting stiffness and damping values for the four damper models are summarized in Tables 4, respectively.

3.1.2. Loading Given in Y-Axis

From the nonlinear computational analysis, hysteresis curves were obtained, as shown in Figure 6b. Based on these curves, the elastic stiffness and energy dissipation values were determined. The energy dissipation was then converted into equivalent damping values using Eq. (2.2). The resulting stiffness and damping values for the four damper models are summarized in Tables 5, respectively.



(a) (b)

Figure 6. (a) Hysteresis curves of metallic damper under loading in x-direction, (b). Hysteresis curves of metallic damper under loading in y-direction

Table 4. Comparison of Stiffness and Energy Dissipation of Dampers under Loading in the X-Axis Direction

Model	$P_{maks}(N)$	$P_{el}(N)$	$\delta_{el}(mm)$	$K_{el}(kN/m)$	$\Delta W(kN.m)$	$\omega(rad/s)$	$\delta_{maks}(m)$	$c(kN.s/m)$
1	18998.19	11724.7	3	3908.16	1.316	3.14	0.02	333.655
2	37996.37	23449.16	3	7816.23	2.633	3.14	0.02	667.308
3	19803.5	13260.94	2.68	4948.01	1.463	3.14	0.02	370.878
4	60038.24	24791.55	1.44	17241.28	4.360	3.14	0.02	1105.148

Table 5. Comparison of Stiffness and Energy Dissipation of Dampers under Loading in the Y-Axis Direction

Model	$P_{maks}(N)$	$P_{el}(N)$	$\delta_{el}(mm)$	$K_{el}(kN/m)$	$\Delta W(kN.m)$	$\omega(rad/s)$	$\delta_{maks}(m)$	$c(kN.s/m)$
1	47397.56	23498.08	1.72	13661.5	3.295	3.14	0.02	835.098
2	94791.14	46925.56	1.72	27281.97	6.588	3.14	0.02	1669.713
3	106379.9	39614.44	0.88	45016.57	7.147	3.14	0.02	1811.482
4	94797.94	47040.06	1.72	27353.9	6.585	3.14	0.02	1668.970

Table 6. Comparison of Structural Displacement with Damper

Variasi 1						
Model	K_x (N/m)	K_y (N/m)	C_x (Ns/m)	C_y (Ns/m)	δ_{maks} (without damper) **(mm)**	δ_{maks} (with damper) **(mm)**
1	3908160	13661500	333655.0635	835098.2195	35.444	49.767
2	7816230	27281970	667308.4821	1669713.956	35.444	30.999
3	4948010	45016570	370878.9007	1811482.641	35.444	26.453
4	17241280	27353900	1105148.001	1668970.642	35.444	30.982

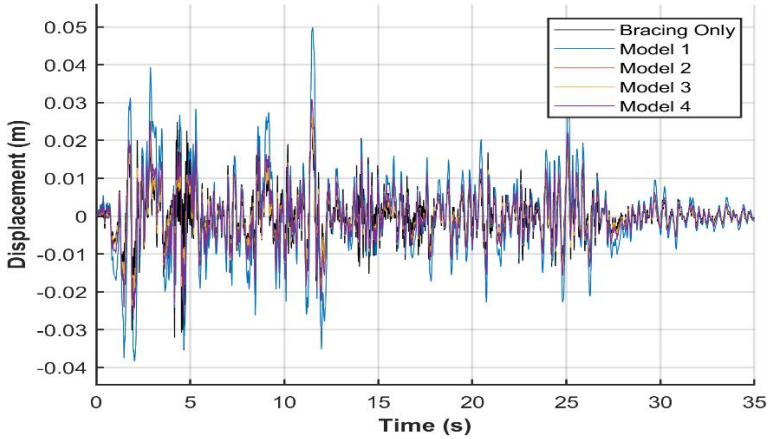


Figure 7. Comparison of Structural Displacement for Four Damper Configurations

3.2. Dynamic Analysis

A dynamic analysis was performed using a computational program based on the linear finite element method (FEM) to obtain the structural displacement response. A comparison of the displacement responses of the building structure without a metallic damper and with metallic dampers is presented in Figure 7. The results indicate that the structural responses of the building equipped with metallic dampers (Models 2, 3, and 4) are significantly reduced compared to the structure without a damper. Among the investigated configurations, Model 3 exhibits the most effective performance, reducing the structural displacement from 35.44 mm to 26.453 mm, as shown in Table 6. This reduction is attributed to the high energy dissipation capacity of Model 3 in the y-direction, which enables it to absorb and dissipate a significant portion of the input energy, thereby limiting structural deformation and vibration amplitude.

4. CONCLUSION

Several conclusions can be drawn from this study as follows:

- In terms of energy absorption capacity in the *x*-direction, Model 4 exhibits the highest energy absorption among all configurations, with a value of 4.360 kN·m.
- In terms of energy absorption in the *y*-direction, the metallic damper represented by Model 3 demonstrates the highest energy absorption capacity, reaching 7.147 kN·m.
- Regarding the reduction of structural response under dynamic loading, the building equipped with the Model 3 metallic damper shows the most effective performance, reducing the structural displacement from 35.44 mm (without damper) to 26.453 mm.

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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 result was carefully verified and revised by the authors to ensure accuracy, originality, and integrity.

REFERENCES

[1]. Aiken, I. D., Nims, D. K., Kelly, J. M., & Pall, A. S. (1993). "*Seismic response of steel frame structures with passive energy dissipation*

systems". Earthquake Spectra, 9(3), 383–401. https://doi.org/10.1193/1.1585722

[2]. Whittaker, A. S., Constantinou, M. C., Tsopelas, P., & Carter, B. (1999). "*Equivalent viscous damping provided by yielding steel dampers"*. Journal of Structural Engineering (ASCE), 125(3), 257–264. https://doi.org/10.1061/(ASCE)0733-9445(1999)125:3(257)

[3]. Tsai, K. C., Chen, H. W., Hong, C. P., & Su, Y. F. (2014). "*Design of steel triangular plate energy absorbers for seismic-resistant construction"*. Engineering Structures, 58, 28–40. https://doi.org/10.1016/j.engstruct.2013.10.01

[4]. Kasai, K., & Kibayashi, M. (2012). "*Cyclic behavior and design of steel dampers"*. Journal of Structural Engineering, ASCE, 138(12), 1423–1434. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000582

[5]. Farajiani, F., Elyasigorji, F., & Khosravikia, F**.** (2024). "*Seismic performance assessment of steel structures equipped with U-shaped metallic dampers"*. Buildings, 14(5), 1368. https://doi.org/10.3390/buildings14051368

[6] Kato, S., Kim, Y.B., Nakazawa, S., Ohya, T. (2006), *"Simulation of the Cyclic Behavior of J-Shaped Steel Hysteresis Devices and Study on the Efficiency for Reducing Earthquake Responses of Space Structures",* Journal of Constructional Steel Research, 61(10), 1457-1473

[7] Satria, E., Kato, S., Nakazawa, S; Kakuda, D. 2008), *"Effectiveness of Applying T-Joint Struts on Two-Way Single Layer Lattice Dome Structures"*, Annual Meeting of AIJ (Architectural Institute of Japan), Hiroshima, Japan, August, pp.889-890.

[8] Satria, E; Son, L;, Bur, M; Akbar, M.D (2021); *"Finite Element Analysis to Determine Stiffness, Strength, and Energy Dissipation of U-Shaped Steel Damper under Quasi-Static Loading"*, International Journal of Automotive and Mechanical Engineering, 18(3), pp. 9042–9050.