IOP Conference Series: Materials Science and Engineering

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To cite this article: Ji Woon Park *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **431** 122008

Bi-axial Seismic Behaviour of a Bridge Structure with a Shape Optimized Metallic Damper

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Abstract. This study performs a structural analysis to determine seismic behaviour of bridge structures with optimally designed metallic damper absorbing earthquake energy. Since the metallic damper utilizes the plastic deformation of steel to reduce vibration of the structures, this optimized metallic damper can be more economic, reliable and sustainable than the conventional bridge dampers such as friction or viscous dampers. The considered earthquake loads applied to the structure is assumed to work on two-dimensional directions. Also, the shape optimization of metallic damper is purposed to perform ideally under those bi-axial earthquake excitations. The optimizing process is based on the calculation of dissipated energy by the damper through finite element analysis of ABAQUS and the SQP algorithm by MATLAB. The MATALB algorithm controls the alteration of the damper's shape to maximize the amount of energy dissipation under the constraint of total mass of the damper. To evaluate the effect of the developed metallic damper using this optimized shape, this study applied the damper into a three-span bridge model and conducted earthquake analysis through SAP2000.

1. Introduction

As the demand for large structures such as nuclear power plants, storage tanks, and bridges increases, precise identification and proper handling of structural vibration problems are becoming more essential. In case of Korea, since 1988, when the earthquake-resistance design standard was first established in Korea, the number of buildings subject to the earthquake-resistant design has been increased. However, as have not been smoothly reinforced, the old structures, including old bridges, are vulnerable to earthquake [1]. These structures must be redeemed with seismic reinforcement. In the two aspects of energy dissipation and large-scale deformation, the most suitable way for seismic retrofitting of the vulnerable structures is installation of additional damping members. Viscous and magnetic (ie, MR damper) type dampers have been most widely used for this purpose [2, 3]. Nevertheless, these two types of dampers have high price, low durability, and the possibility of internal viscous fluid loss. Moreover, those dampers can only work in 1-direction. On the other hand, metallic dampers are characterized by relatively low cost, excellent durability, and ease of installation. As the metallic dampers dissipate hysteretic energy through the materials plasticity, the seismic energy can be absorbed with loading conditions in any direction.

The metallic damper reduces seismic vibration by the passive damping system. This type of damping system exhibits the damping ability through the plasticity of the member. However, when the vibration damping system has too high rigidity, there is a possibility of a transmission of large seismic energy to the superstructure [4]. Therefore, it is important to maintain the proper level of damping force and energy dissipation in order to design an efficient passive damper that prevents the large displacement of the structure under the earthquake. On this context, this study first presents the concept of a metallic damper which has the most efficient geometry. This optimized shape is economical and suitable for the damping purpose. Here, optimal design in engineering means a mathematical technique that finds the best performance while satisfying the objective function and various constraints. This paper introduces a developed optimal shape of the metallic damper with better performance than its initial geometrical set. Secondly, seismic analysis of a simple bridge structure was carried out by applying the shape optimized metallic damper with SAP2000 software. Although the introduced optimized damper is developed in uniaxial loading condition, this paper analyses the biaxial performance of the damper. By applying this one-directionally developed metallic damper into the simplified three-dimensional frame structure under 2-dimentional earthquake vibration, this study confirms the possibility of this damper in multi-directional use.

2. Shape optimization of an uniaxial metal damper

2.1. Concept of the presented metallic damper

During earthquakes, the metallic dampers yield and deform prior to the main structure. As the damper dissipates seismic energy through its plastic deformation, the main members, such as superstructures, avoid any damage or destruction [5]. Currently, steel shear damper or unbounded braces are most commonly used metallic dampers. However, both dampers are designed for buildings with relatively small resilience or deformation. Therefore, there is a need for a more efficient design of metallic dampers for large-scale structures or bridges.

The basic concept of the metallic damper that is proposed in this study is shown in figure 1. The concept was established to be installed between bridge piers and superstructure. The initial geometrical size and shape is suggested as a basic long-drawn rectangular shape. This has been presented with reference to another hysteretic damper for bridges using ultra-high performance fiber reinforced concrete (PVA-ECC) which was installed in Odawara City High-rise Bridges [6]. This reference damper and the presented damper of this study are similar in some characteristics. They are structurally simple, easy to design and install, and capable of dissipating all the vibration energy in the multi-axis directions. The presented metallic damper, however, is cheaper by using metal as the ductile material for energy dissipation. In addition, stable operation and easy maintenance can also be achieved through the use of metal materials which are easy to obtain and whose property is sufficiently guaranteed.

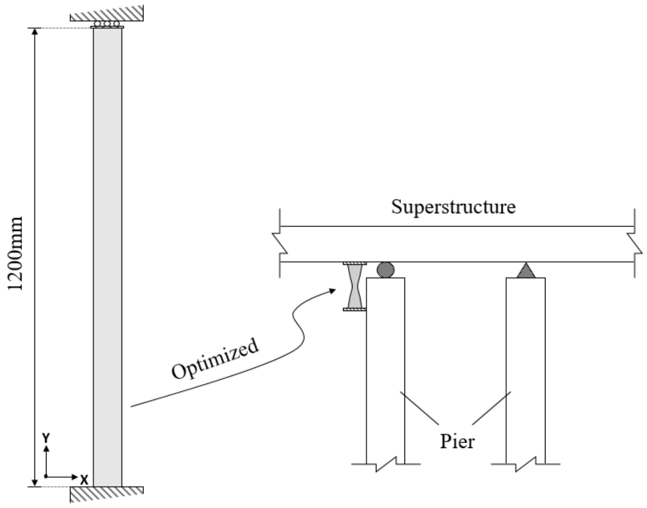

Figure 1. Initial size, shape, and installation concept of the developed damper.

2.2. Shape optimization

In the previous research, a shape optimization for the presented metallic damper was conducted for a uniaxial cyclic loading [7]. Some prior studies have been made on the optimization of other dampers, all of which are aimed at improvement of existing hysteretic dampers such as J-type metallic dampers or steel shear panel dampers [8-10]. However, the previous study of this present paper differs in that the maximization of the total dissipation energy is the primary goal of the optimization, as shown in figure 2. Here, the energy dissipation due to hysteresis is represented by E, and the coordinate vectors for determining the shape by x and y. The volume of each altered damper shape and the total allowable volume are V and V^0, respectively, which means that the alteration of the shape is restricted based on the use of the same volume of material during the optimization process. The shape is determined by three control points as illustrated in figure 3. The elastic-plastic analysis of each shape-changed damper is conducted repeatedly through ABAQUS, based on the fact that the FEM analysis of hysteretic dampers has proven to be very similar to the experimental results [6, 10-12].

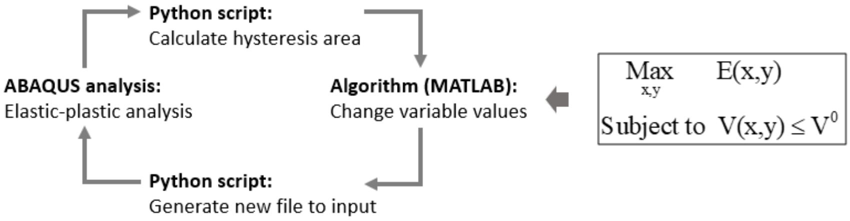

Figure 2. Flow and fundamental principle of the optimization process.

Both ends of the damper are fixed in the vertical direction, and it is assumed that a cyclic load is applied to the upper end in the horizontal direction. The material was assumed to be completely plastic and the general properties were selected with reference to a mild steel, which is ASTM-a36 Steel. As being said, modelling and finite element analysis were performed through ABAQUS and the hysteresis loop was extracted as a result through a Python script. Since the calculated area of the loop is equal to the amount of energy dissipated by the damper, the SQP algorithm is used to obtain the shape parameters that maximize this value. As a result, the energy absorption of the optimized damper increased up to 73% compared with the initial model. This increase in capability of the modified geometry is due to the efficient distribution of stress generation in the model as shown in figure 3.

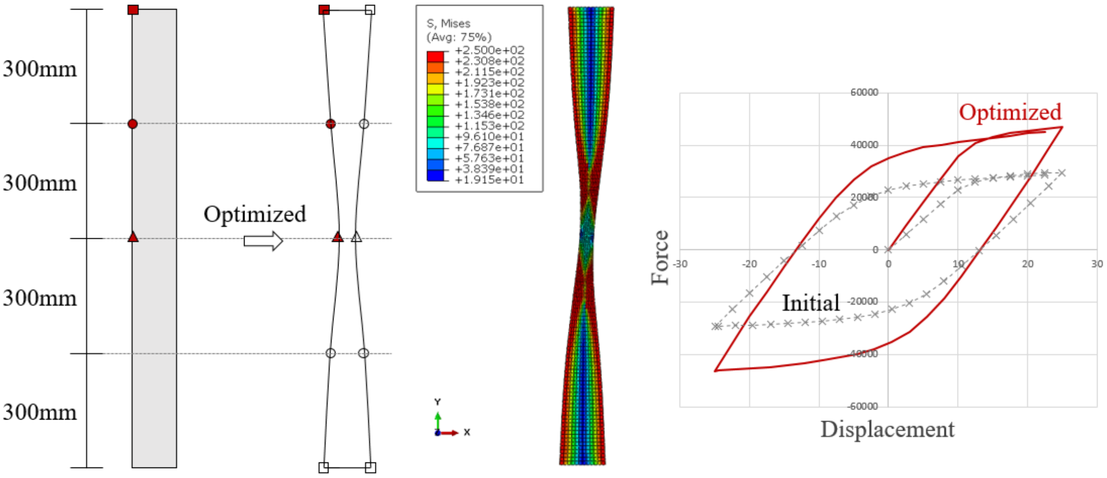

Figure 3. Optimization results of the metallic damper: developed geometry and improved energy dissipation capacity.

3. Seismic analysis of the developed damper

3.1. Structural analysis in 1-directional seismic loading

The hysteresis curve of the developed metallic damper was replaced with bilinear loops for the input data of SAP2000 modelling. With this bilinear assumption illustrated in figure 4, properties for nonlinear analysis cases are derived, such as stiffness, yield strength and post yield stiffness ratio. Through this assumption, the capability of the damper was reconfigured conservatively. The presumed values are quadrupled under the assumption that four developed dampers will be installed per one pier structure.

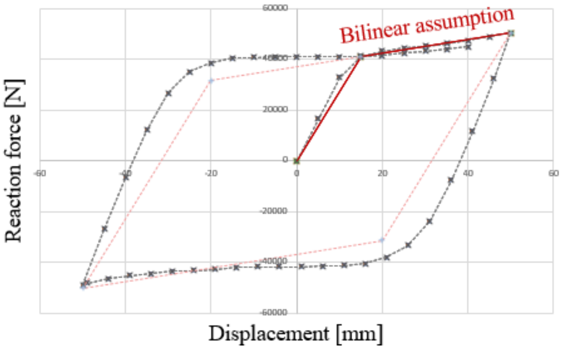

Figure 4. Bilinear assumption of the hysteresis curve.

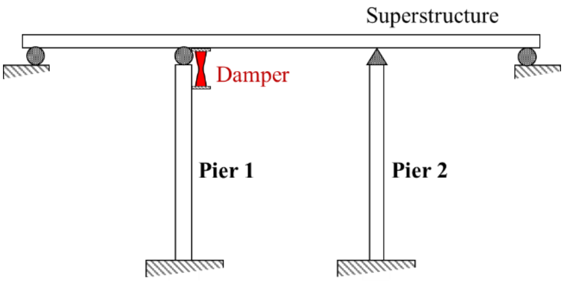

Figure 5. Overview of the target structure and installation position of the damper.

A structure for the analysis was established as a 3D frame bridge with two piers as described in figure 5. The total length of the superstructure is 125m. The damper was assumed to be installed between a bridge pier and the superstructure of the three span continuous bridge. Two identical bridge structures were analysed simultaneously with the difference in the presence of the developed damper (figure 6). The seismic analysis of the bridge structure was conducted using the non-linear modal history (FNA) case in SAP2000 and the El Centro earthquake data. Frame elements were used for the piers and the superstructure. A circular concrete section was applied as the section of pier with 2.2m diameter and a circular steel section as the superstructure with 1m diameter. The exact dimensions of the sections are merely simple assumptions.

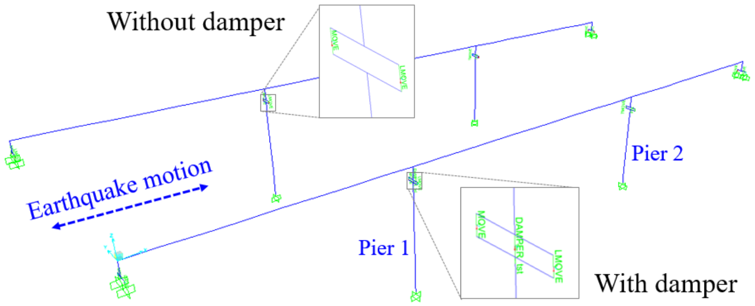

Figure 6. Modelling of the structure in SAP2000 for analysis in 1-directional seismic loading.

The damper showed an excellent performance reducing the vibration of whole structure. The installation of the developed damper significantly lessen the draft of the superstructure. Also, the maximum moment of pier 1 decreased by almost 28% as shown in table 1. Figure 7 shows how the moment changes with respect to the duration of earthquake motion and free vibration period. The increase of energy dissipation can be identified through the graph as the magnitude decreases in much faster manner with installation of the damper.

Table 1. Results of the 1-directional seismic loading analysis.

	Pier 1 max. moment	Pier 2 max. moment	Max. drift [1]
w/o damper	15554.56 kN-m	57252.74 kN-m	0.1045
w/ damper	13457.91 kN-m	41449.93 kN-m	0.0754
decrease	13.48 %	27.60 %	27.90 %

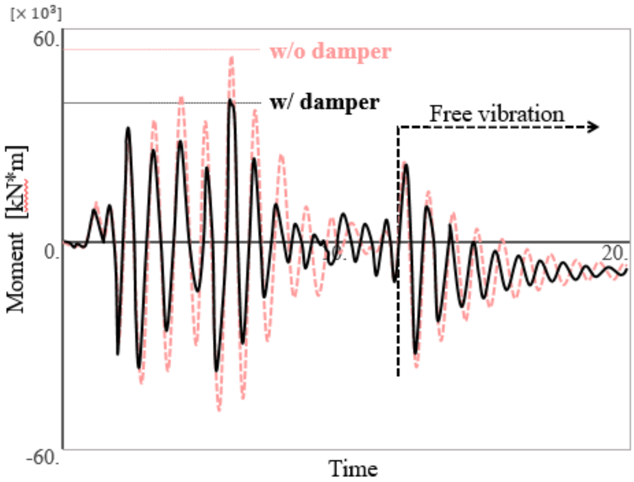

Figure 7. Change of moment with time at pier 2 from 1-directional seismic analysis’s results.

3.2. 2-directional seismic loading

To measure capability of the developed damper in perspective of multi-directional loading, another structural analysis was conducted. In this case, 2-directional seismic loading was applied to the structure and the damper. The earthquake loading was presumed to occur at an angle of 30 degrees from the axis of the superstructure. This particular angle is a mere supposition. Other conditions were equal to the previous case, therefore El Centro was applied again as the earthquake data. The direction of global axis and the applied motion at the modelling is described in figure 8.

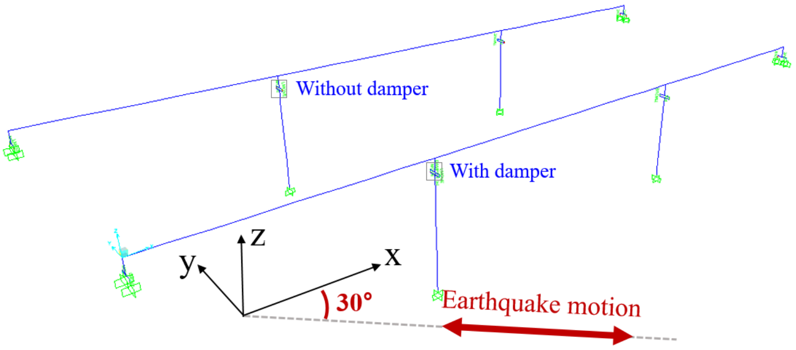

Figure 8. Modelling of loading condition in SAP2000 for analysis in 2-directional seismic loading.

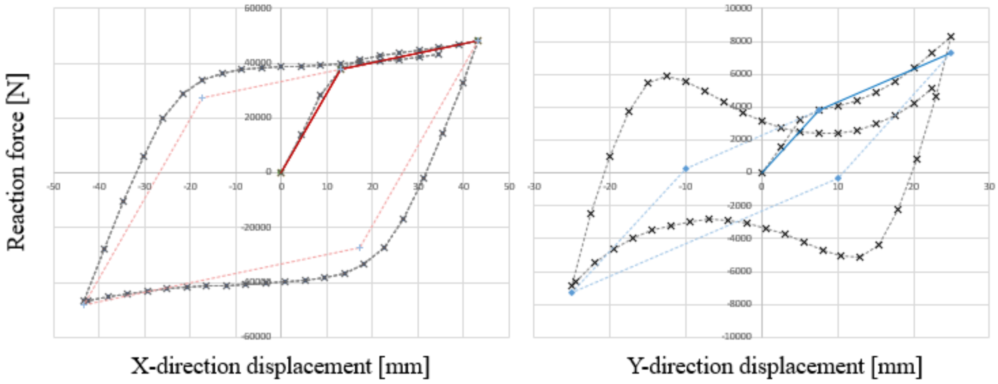

Figure 9. Bilinear assumption of the hysteresis curve for X and Y direction with 30-degree-tilted loading condition.

The oblique earthquake motion can be divided into two different orthogonal direction. Accordingly, the hysteretic characteristics of the damper were also considered in the same two divided directions, X and Y. Here, X and Y axis indicate the identical global axis at figure 8. As before, the hysteretic behavior is assumed bi-linearly, respectively to both curves in their own directions. The hysteretic curves and the bilinear assumptions of the damper are presented in figure 9, with the 30-dgree-tilted condition. By applying the presumed properties, the analysis was conducted under the 2-directional seismic loading condition.

The results of the analysis is arranged in table 2 and figure 10. Y-directional reaction moments of both piers were reduced significantly with the application of the developed metallic damper. In perspective of X-directional moments, although the moments of the pier 2 was almost identical, meaningful reduction was found in pier 1. This results confirms the effect of the damper in transverse direction to the super structure. Overall decrease of reactions at both two piers can be checked in figure 10.

Table 2. Results of the 2-directional seismic loading analysis.

	Pier 1		Pier 2	
	Max. moment Y	Max. moment X	Max. moment Y	Max. moment X
w/o damper	11670.11 kN-m	6794.89 kN-m	36776.95 kN-m	13625.15 kN-m
w/ damper	13475.63 kN-m	7250.24 kN-m	49572.02 kN-m	13548.19 kN-m
decrease	13.40 %	6.28 %	25.81 %	-0.57 %

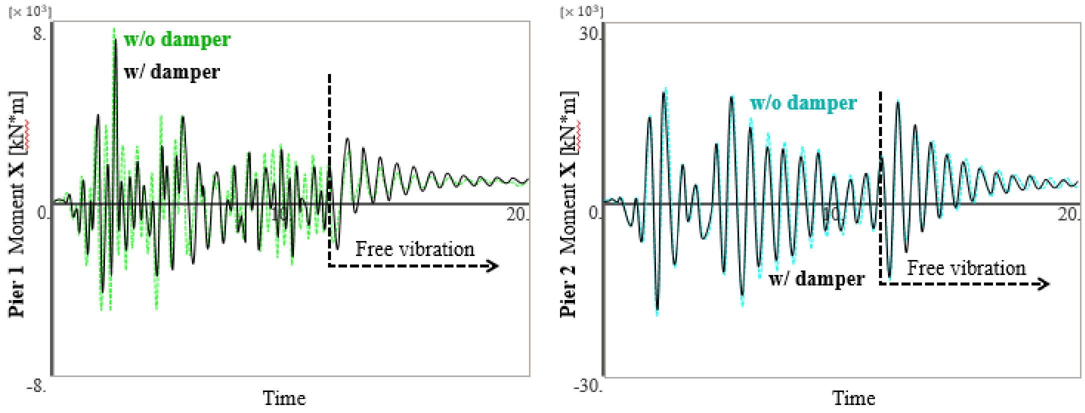

Figure 10. Change of X-directional moment with time at pier 1 and pier 2 from 2-directional seismic analysis's results.

4. Conclusion

In the previous study, shape optimization of a metallic damper is conducted to maximize the seismic energy absorption. The maximization was under some geometrical constraints and a condition of restricted amount of material use. Through this study, it have been found that the energy dissipation can be increased up to 73% higher than a basic rectangular model according to the shape change.

This developed damper was optimized only for one axial direction. However, considering the characteristics of the system using the plasticity of its material, the present study investigated the possibility of application in two-axis seismic loading. First, a seismic analysis of a simple bridge structure using the developed uniaxial damper was performed for one axial direction that is parallel to the axis of superstructure. Through this analysis, it was confirmed that the damper successfully improve the seismic behavior of the total structure. The moment load of the pier was reduced by 28%, and the lateral deflection of the structure was also reduced. Secondly, two-directional seismic load is applied to the identical structure with same initial conditions. The results of this analysis confirmed that the developed damper performs effectively even under the biaxial loading condition. The installation of the developed damper showed excellent performance and effectively reduced the vibration of the structure. In future research, optimization of more various damper shapes will be done along with comparative seismic analysis with other existing dampers, such as viscous dampers. Therefore, it is expected that the development of this damper will be more secured.

Acknowledgments

This research was supported by the EDucation-research Integration through Simulation On the Net (EDISON) Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2014M3C1A6038855).

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