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Shape optimization of metallic yielding devices for passive mitigation of seismic energy

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ABSTRACT

Bi-directional Evolutionary Structural Optimization (BESO) is a well-established topology optimization technique. This method is used in this paper to optimize the shape of a passive energy dissipater designed for earthquake risk mitigation. A previously proposed shape design of a steel slit damper (SSD) device is taken as the initial design and its shape is optimized using a slightly modified BESO algorithm. Some restrictions are imposed to maintain simplicity and to reduce fabrication cost. The optimized shape shows increased energy dissipation capacity and even stress distribution. Experimental verification has been carried out and proved that the optimized shape is more resistant to low-cycle fatigue.

1. Introduction

In the last two decades development of energy dissipation devices for mitigation of wind and earthquake has flourished. Various types of passive, semi-active and active devices have been proposed, tested and implemented [1]. With this technology, a large portion of input energy from wind or earthquake excitations is dissipated by designated devices. As a result, structural responses are suppressed, and major structural elements can be protected from damage. Particularly in earthquake applications, metallic devices which utilize yield deformation of metals remain among the most popular types selected by engineers. They are reliable, inexpensive to fabricate, easy to install and maintain. Metallic devices can be classified into flexural types, such as hourglass shape ADAS [2], triangular shape TADAS [3]; shear types such as YSPD [4] and axial types, such as the Buckling Retrained Brace [5]. Devices are mainly designed to be incorporated into lateral-load-resisting system in structural frames, but some are developed to be installed between beam and columns [6].

Design of metallic devices requires several desirable engineering characteristics:

1. possessing sufficient elastic strength and stiffness such that device is not excited to inelastic region under service loads;
2. having stable and large energy dissipative capability; and
3. having reasonable resistance against low-cycle fatigue.

With respect to low-cycle fatigue, current design standard in the United States requires devices to undergo five fully reversed cycles at maximum earthquake device displacement [7]. Generally, in order to increase the resistance to low-cycle fatigue, stress concentration has to be avoided.

Along with the revolutionary improvement of digital computers in recent decades, computational methods and numerical techniques have established their place as invaluable engineering tools. Among these, numerical optimization methods have attracted a great number of researchers and have been improved a lot. Particularly, the state-of-the-art shape and topology optimization techniques have been applied to a range of physical problems and have been proved to yield much better results than experimental designs [8,9]. The Evolutionary Structural Optimization (ESO) method, introduced by Xie and Steven [10] is a simple and effective topology optimization technique which can tackle shape optimization problems as well. This method iteratively improves the design domain by removing its inefficient parts. A Bi-directional

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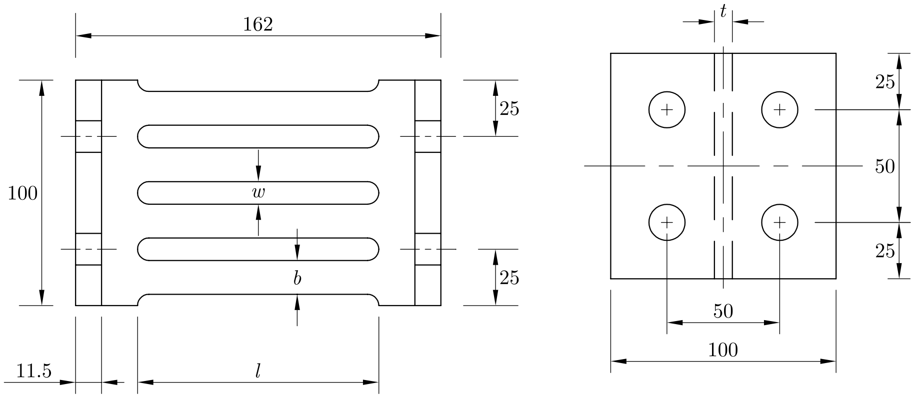

Fig. 1. The SSD device design proposed by Chan and Albermani [18].

version of the ESO method, called BESO, has been later proposed by Querin et al. [11,12] and Yang et al. [13]. In BESO, besides removal of inefficient parts, the efficient parts of the design domain will be improved by adding more material next to them. Since its introduction, the BESO algorithm has been improved significantly [14]. The improved BESO algorithm has been successfully applied to non-linear problems [15,16]. This method is also capable of optimizing both shape and topology of the designs [17].

In this paper, the BESO algorithm is modified to optimize the shape of an existing steel slit damper device design (SSD). The proposed algorithm applies some shape restrictions to the design to make the final shape easily manufacturable. An efficient device design should possess a high energy dissipation capability per unit volume. To gain this, the proposed algorithm maximizes the total plastic dissipation. It is also demonstrated that the optimum design resulted from the proposed optimization algorithm, show less stress concentration than the initial design.

In order to verify the numerical results and to address the shortcomings of the numerical models, physical experiments are carried out. It is demonstrated that experimental outcomes support the numerical results.

2. Optimization

Chan and Albermani [18] have proposed a class of simple designs for SSD devices supported by a series of experimental test results. Fig. 1 shows the typical shape of the device. The size of the slits (w) can be controlled by varying l and b. In this paper, a new class of design is proposed by optimizing the shape of the slits in Fig. 1. To achieve this, a shape optimization algorithm based on the BESO technique is proposed and utilized here. Some restrictions are imposed to maintain the simplicity of the shape and hence reduce its fabrication costs. These restrictions are discussed in detail in Section 2.4.

2.1. Numerical modeling

For numerical modeling, the flanges are considered solid and a plane stress rectangular mesh is used to model the web. A uniform web thickness of $t = 8$ mm is considered overall the design except for the elements on the far left and right sides of the domain. These elements which are in the vicinity of the flanges are modeled using thicker elements to simulate fillets (Fig. 2).

For the sake of fabrication, the holes are prevented from being too wide by setting the two strips of 15 mm width on the left and right sides as non-designable elements. Fig. 2 illustrates the designable and non-designable domains.

The left side of the model is fixed and a uniform vertical displacement is applied to the right side of the model. The loading cycle consists of three steps: an upward displacement of 10 mm, followed by a downward displacement of 20 mm, and finally an upward displacement of 10 mm up to the original location (Fig. 2). In this manner the elastic strain energy will be zero after a full cycle and the total strain energy would be equal to the total plastic dissipation.

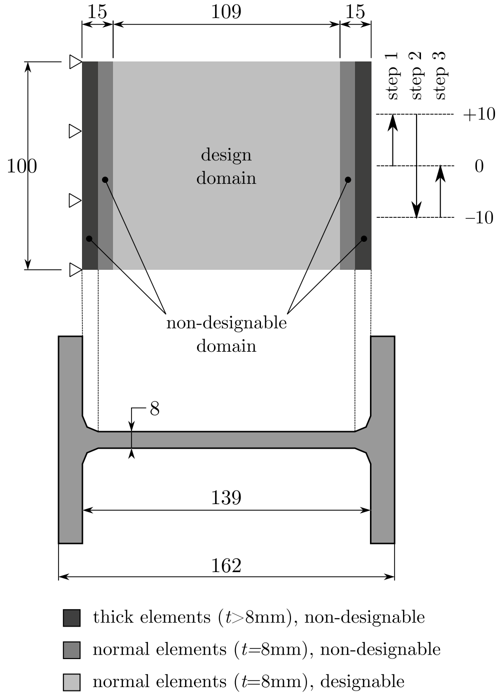

Fig. 2. The designable and non-designable domains.

2.2. Problem statement

To optimize the shape of the SSD, the total plastic energy dissipation is considered as the objective function which is to be maximized. In order to prevent the optimization algorithm from catching the extreme full or empty domain designs, it is necessary to include an additional constraint to restrict the amount of usable material [19]. Here we use a volume constraint which forces the algorithm to use a certain amount of material in the design domain. Alternatively, one can impose a restriction on the maximum force instead of using a volume constraint [15]. The optimization problem can be expressed as

$$\begin{array}{rl} \max\limits_{x_1,x_2,\ldots,x_N} & E_P \\ \text{subject to} & V = \bar{V} \\ \text{and} & \text{shape restrictions} \end{array} \tag{1}$$