Shape optimum design of shear panel damper made of low yield steel

†*Y. Liu[1], Y. Nishio[2], M. Shimoda [3]and M. Shimazu [4]

[1] Department of Mechanical Engineering, Sojo University, Japan.
[2] Graduate School of Mechanical Engineering, Sojo University, Japan.
[3] Department of Advanced Science and Technology, Toyota Technological Institute, Japan
[4]Department of Architecture, Sojo University, Japan.

*Presenting author: liuyang60212@gmail.com
†Corresponding author: liu@mec.sojo-u.ac.jp

Abstract

In this paper, a shape optimization approach is presented for a shear panel damper made of low yield steel to improve the deformation ability. A minimization problem of maximum cumulative equivalent plastic strain, an index of the deformation ability of the shear panel damper is formulated subject to a constraint of total absorbing energy. The response surface methodology as well as the design of experiment technique is applied to the optimization process. In this study, finite element analysis with isotropic/kinematic hardening model is adopted to simulate the cyclic elasto-plastic behavior instead of experimental approach, and the numerical solutions are validated by comparing with previous experimental results. With the numerical analysis, the shape parameters effects are investigated and second order polynomials are fitted to obtain the regression equations for the maximum cumulative equivalent plastic strain and the total absorbing energy. The final optimal shape is determined by using the established regression equations. The shape optimization approach can substantially improve the deformation capacity of the shear panel damper.

Keywords: Shear panel damper, Shape optimization, Deformation ability, Energy absorption, Response surface method

Introduction

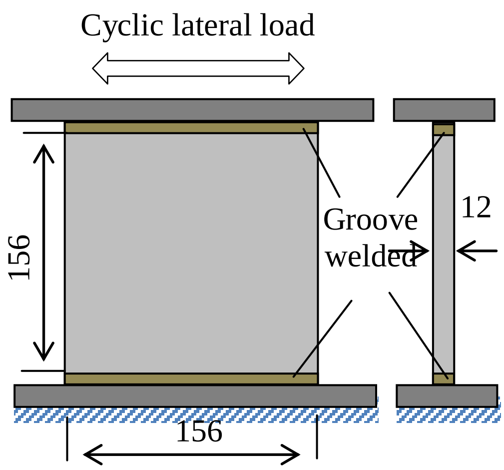
Shear panel damper (SPD) made of low yield steel has high level of passive energy dissipation capacity as a consequence of inelastic deformation of the low yield steel, and has been received considerable interest in the last two decades. When installed into building and bridge structures, it is expected to partially divert the input seismic energy into the SPDs and effectively reduce the seismic responses of the structures under strong earthquake loads. To be a type of hysteretic damper, properly design of the SPD (stiffened or unstiffened) is strongly required to sustain high deformation capacity and repetition durability for low cycle fatigue under cyclic seismic loading, especially for the application in bridge structures, which demand large range of shear deformation. If the SPD is designed unreasonably, the clacks should initiate at edges or corners of the shear panel in the early stage of cyclic loading due to the stress concentration, and grow along with cycles, that will decrease the energy absorption capacity drastically. In focusing on improving the deformation capacity and repetition durability, recently, some experimental and analytical researches have been carried out by varying the panel shape or installing the stiffeners on the left and right sides of the SPD for the application in bridge structures [1][2][3]. However, most of researches are confined to be empirical methods or analytical researches dealing with direct problems, the shape optimization of obtaining the maximization of deformation capacity and total absorbing energy has not been studied.

The studies on optimization of elastic and elastoplastic structures have been extensively investigated during the past 30 years, and a number of useful algorithms and methodologies are developed (e.g. [4][5]). As a practical and effective optimum design methodology for nonlinear problem, the response surface methodology (RSM) combined with the design of experiment (DOE) technique is currently applied to nonlinear design optimization problems, such as optimization problems of crushing energy absorbing of the automobile body and box-type column structures [6]. In this paper, a shape optimum design of the SPD was studied by the response surface approximation methodology and the technique of design-of-experiment. Since deformation capacity of the SPD can be evaluated by the maximum cumulative

equivalent plastic strain at a cyclic shear deformation. Instead of experimental approach, the cyclic behavior of SPD subjected to cyclic loading is studied by sophisticated finite element method (FEM) with isotropic/kinematic hardening model, and a comparison between numerical simulation and experimental result was made and precision of the numerical simulation was confirmed. Then an orthogonal array is employed to arrange the design point using the technique of design of experiment, and numerical simulations of the SPDs with various shape parameters were carried out. Based on the numerical results, the influences of the shape parameters to responses of the maximum cumulative equivalent plastic strain and the energy absorbing behaviors are investigated to obtain the regression equations of the two objective functions. Finally, the response surface methodology was adopted to solve the shape optimization problem, and to obtain the optimal shape parameters of the SPD.
In our previous study, free edges on the left and right sides of the SPD were optimized to improve the deformation ability. The geometry of the reduced left and right edges was represented by cubic Bezier curves as a linear combination of Bezier polynomial [7]. In this study, a shape optimum design is carried out to determine the optimal shape parameters of holes in the panel when all of the free edges are invariable.

Numerical Analysis

The initial shape of SPD, which is a 156×156 mm square plate with uniform plate thickness of t_w=12 mm, is shown in Figure 1. The upper and lower edges of the panel are groove welded to plates. Cyclic lateral load was applied at the upper plate, and the loading history is shown in Figure 2, in which the increments of the shear displacement in each loading cycle are ±1δ_y, where δ_y=5 mm is the shear yield displacement corresponding to the 0.2% offset yield stress of the material.



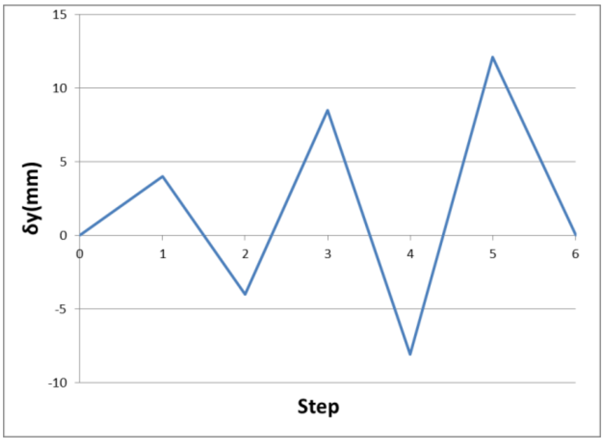


Figure 1. Initial shape and boundary conditions Figure 2. Loading history

The material properties of low-yield 100(LY100) steel were measured by tensile coupon test and the obtained stress-strain curves are shown in Figure 3. The yield strength defined 0.2% offset value of LY100 is 80.1 N/mm^2 and elongation reaches 60%, which is about three times of SS400 mild steel.
The cyclic elastoplastic behavior of SPD subjected to cyclic loading is simulated by ABAQUS with a combined isotropic/kinematic hardening model [7][8], which was employed as constitutive law to describe the material cyclic behavior accurately. The combined hardening model consists of two components: a nonlinear kinematic hardening component and an isotropic hardening component.

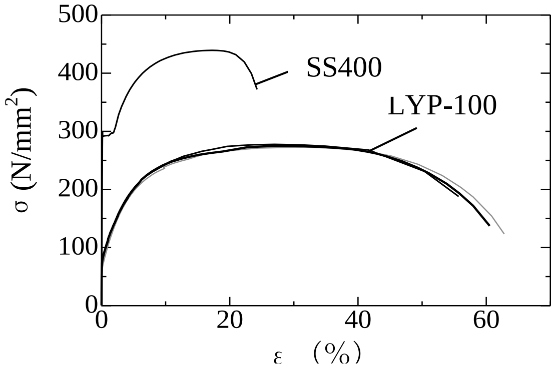
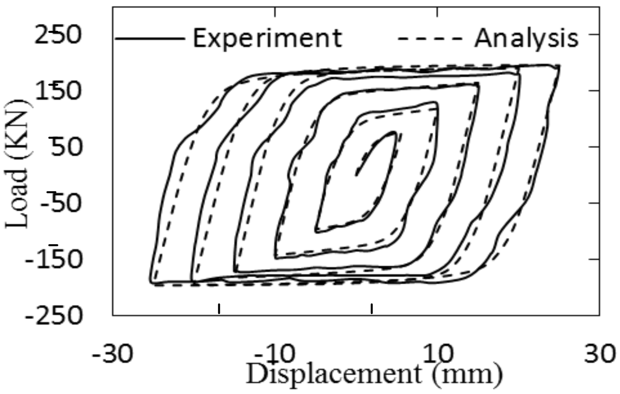


Figure 3. Stress-strain curves for SS400 and LY100 tension coupons

Figure 4 shows typical hysteretic curve of the shear load versus displacement of the initial shape of SPD compared with corresponding experimental curve. As shown in Figure 4, hysteretic curve obtained from the analysis agree generally well with those from the experiment. It is clarified that the present analysis with the combined isotropic/kinematic hardening model can accurately predict the cyclic elastoplastic behavior of the LY100 SPD. Figure 5 shows the accumulated equivalent plastic strain distribution by FEM simulation in the 4th cycle loading, and remarkable strain concentration at the panel corners can be observed.



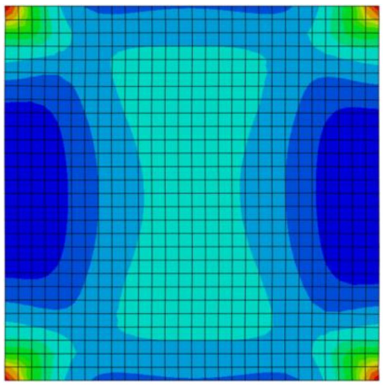


Figure 4. Hysteretic load-displacement curves   Figure.5 *CEPS* distribution of the initial SPD

DESIGN OPTIMIZATION

In this study, with the aim of minimizing the maximum cumulative equivalent plastic strain ($CEPS_{max}$) subjected to a constraint of total absorbing energy (E), the shape parameters r_1, r_2, θ of holes in the panel (as shown in Figure. 6) are taken as design variables. An orthogonal array in the design of experiment is employed to assign analysis points in simulating the cyclic elastoplastic behavior of SPD. Based on the numerical results of the cyclic elastoplastic analysis, the response surface approximation technique is applied to generate the regression equations of the $CEPS_{max}$ and the E in terms of the design variables that are evaluated to be significant at high levels for the response by means of analysis of variance. Then, the optimization problem is formulated as:

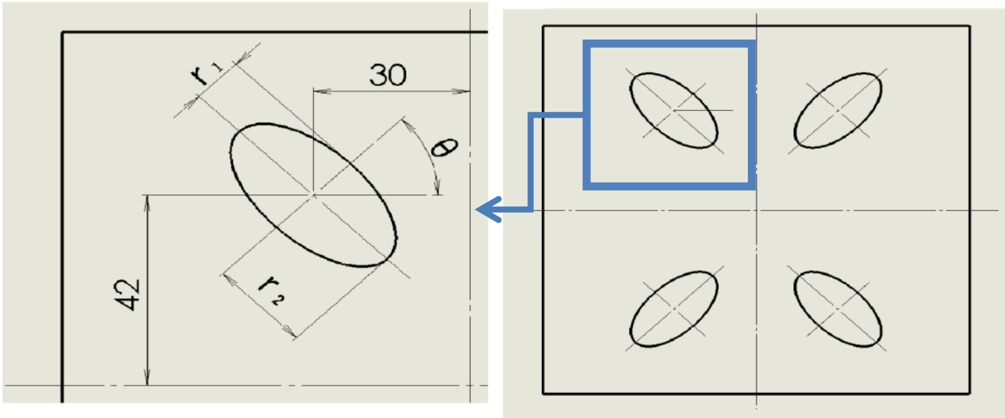


Figure 6. Shape parameterization

$$\begin{aligned} &\text{Design variables : } r_1, r_2, \theta \\ &\text{Objective function : Minimizing } CEPS_{max} \\ &\text{Constraint condititon : } E \geqq k \cdot E_{in} \end{aligned} \tag{1}$$

where $CEPS_{max}$ indicates the maximum cumulative equivalent plastic strain, and E_{in}, E indicate the total absorbing energy of the initial shape and the optimized shape respectively. k indicates the coefficient of the allowable lower bound and is taken as 80 % and 50% in this study.

Optimization process of the first iteration

The experimental design levels of the process variables in the first iteration are shown in Table 2. As shown in Table 2, an orthogonal array L_{27} is employed to arrange the design point, and results of $CEPS_{max}$ and E are obtained by the cyclic elastoplastic analysis at each design point under the same cyclic lateral load shown in Figure 2.
Based on the numerical solutions of the cyclic elasto-plastic analysis in the first iteration as shown in Table 2, the response surface regression procedure was employed to fit the polynomial Equation to the numerical analysis results, and the maximum cumulative equivalent plastic strain ($CEPS_{max}$), the total absorbing energy E are approximated in the form of orthogonal polynomials as:

$$\begin{aligned} CEPS_{max}(r_1, r_2, \theta) =& 0.750-1.641\times10^{-2}r_1+3.956\times10^{-4}r_1^2+3.955\times10^{-2}r_2-9.811\times10^{-4}r_2^2 \\ & -6.370\times10^{-4}\theta+4.664\times10^{-5}\theta^2-6.41\times10^{-3}r_1r_2+1.561\times10^{-4}r_1r_2^2 \\ & +2.431\times10^{-4}r_1^2r_2-7.227\times10^{-6}r_1^2r_2^2+1.996\times10^{-3}r_1\theta-2.309\times10^{-5}r_1\theta^2 \\ & -6.811\times10^{-5}r_1^2\theta+7.193\times10^{-7}r_1^2\theta^2-1.934\times10^{-3}r_2\theta+1.680\times10^{-5}r_2\theta^2 \\ & +5.989\times10^{-5}r_2^2\theta-4.419\times10^{-7}r_2^2\theta^2 \end{aligned} \tag{2}$$

$$\begin{aligned} E(r_1, r_2, \theta) =& 6418.812-66.951r_1-0.932r_1^2-155.879r_2+3.656r_2^2 \\ & +37.193\theta-0.429\theta^2+13.020r_1r_2-0.631r_1r_2^2 \\ & -0.481r_1^2r_2+2.094\times10^{-2}r_1^2r_2^2-4.410r_1\theta+4.466\times10^{-2}r_1\theta^2 \\ & +0.121r_1^2\theta-1.086\times10^{-3}r_1^2\theta^2-0.636r_2\theta+1.350\times10^{-2}r_2\theta^2 \\ & +4.486\times10^{-2}r_2^2\theta-8.311\times10^{-4}r_2^2\theta^2 \end{aligned} \tag{3}$$

Table 2. Design levels numerical solutions for SPDs

Design Point	r_1 (mm)	r_2 (mm)	θ(°)	$CEPS_{max}$	E (KJ)
1	10	10	15	0.6017	4.91
2	10	10	45	0.6017	4.91
3	10	10	75	0.6017	4.91
4	10	15	15	0.5615	4.50
5	10	15	45	0.5478	4.52
6	10	15	75	0.5707	4.44
7	10	20	15	0.5312	4.06
8	10	20	45	0.5408	4.15
9	10	20	75	0.6918	3.85
10	15	10	15	0.5509	4.36
11	15	10	45	0.5388	4.36
12	15	10	75	0.5275	4.41
13	15	15	15	0.4737	3.91
14	15	15	45	0.4737	3.91
15	15	15	75	0.4737	3.91
16	15	20	15	0.4567	3.44
17	15	20	45	0.4587	3.40
18	15	20	75	0.5001	3.29
19	20	10	15	0.5711	3.72
20	20	10	45	0.5266	3.75
21	20	10	75	0.4706	3.89
22	20	15	15	0.4972	3.27
23	20	15	45	0.4133	3.27
24	20	15	75	0.4375	3.37
25	20	20	15	0.4152	2.75
26	20	20	45	0.4152	2.75
27	20	20	75	0.4152	2.75

Table3 Design levels and optimization result (k=0.8)

		1st	2nd	3rd	4th	5th	6th
Design levels	r_1(mm)	10 15 20	5 10 15	7 12 17	7 12 17	7 12 17	10 12 14
	r_2(mm)	10 15 20	8 13 18	5 10 15	5 10 15	6 11 16	8 10 12
	θ (°)	15 45 75	30 45 60	34 44 54	44 54 64	44 54 64	44 54 64
Optimization result	r_1(mm)	10.2	12.3	12.3	11.9	12.4	12.4
	r_2(mm)	13.0	10.3	10.1	10.9	10.1	10.2
	θ (°)	45.0	43.9	54.0	54.0	54.0	54.0
	$AEPS_{max}$	0.5555	0.5398	0.5430	0.5495	0.5367	0.5348
	E (KJ)	4.66	4.63	4.68	4.65	4.66	4.65

To obtain more precise approximated response surface, analysis points are selected for the 1st, 2nd, 3rd, 4th, 5th and 6th iteration of the optimization process, and the optimum results of the 6 iterations are shown in Table 3. The obtained optimal shape of SPD is shown in Figure 7. Figure 8 shows accumulated plastic distribution, which is simulation result of the cyclic elastoplastic behavior of the optimized SPD subjected to cyclic loading. The numerical estimation of $CEPS_{max}$ in the optimized SPD is 0.5348, which decreased by 25% comparing with the initial shape. It is obvious that the optimal shape can substantially increase the deformation capacity of SPD. Furthermore, when the coefficient of the allowable lower bound k is set to k=0.5, the obtained optimal shape of SPD is shown in Figure 8, and the $CEPS_{max}$ was reduced to 0.3662, which is 48.2 % down than value of the SPD with the initial shape.

Conclusions

In this study, a shape optimum design of shear panel damper made of low yield steel was carried out to determine the optimal shape parameters of holes in the panel. The combination between the response surface method and the design of experiment technique and the cyclic elastoplastic behavior simulation of shear panel was employed as the optimization methodology. It was confirmed that the shape optimization approach can effectively obtain the optimal shape of the shear panel damper. In the optimal shape, the maximum cumulative equivalent plastic strain is decreased significantly, that can substantially improve the deformation capacity of the shear panel damper.

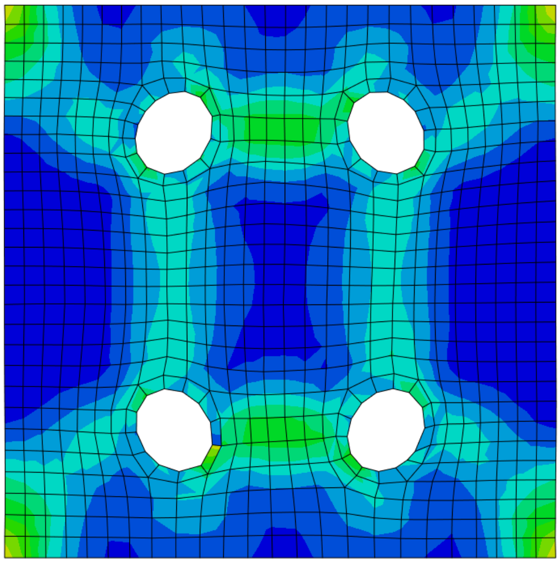


Figure 7. Optimal shape of SPD (k=0.8)

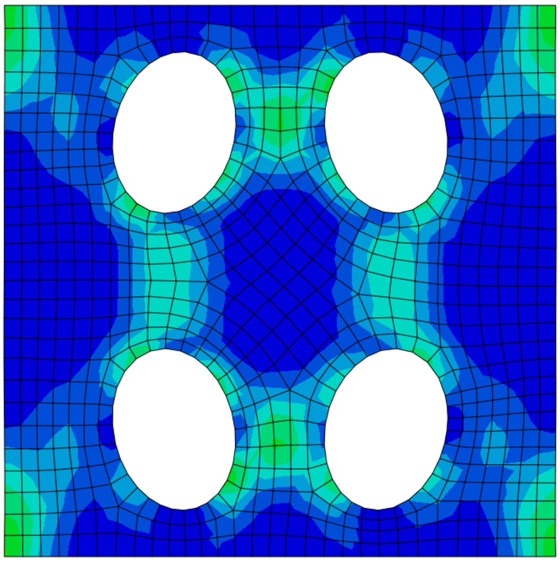


Figure 8. Optimal shape of SPD (k=0.5)

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