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OPTIMIZATION OF ENERGY DISSIPATING STEEL PLATE FUSES

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Abstract

Steel plate devices are widely used for providing energy dissipation in earthquake resistant structures. Recent development of self-centering structures, such as controlled rocking frames, which offer minimized downtime and repair costs following severe earthquakes, relies on the energy dissipation capability of steel plate fuses. The cyclic response of steel plate fuses varies depending on different design factors related to the fuse link geometry or its material property. This paper presents a numerical study on the cyclic response of steel plate fuses with butterfly-shaped and straight shear links. Finite element models are first developed and validated against past experimental studies. A sensitivity study using the design-of-experiment method is performed to statistically determine the effects of different design factors on the cyclic response of steel plate shear links. Seven design factors related to the material or geometry of steel plate fuses are considered as input factors. The cyclic response of fuses is examined in terms of initial stiffness, yield strength, ultimate stiffness, effective damping, maximum strength, and ductility. From the results of the sensitivity analysis, it is shown that the overall cyclic behavior of steel plate fuses is most significantly influenced by the fuse link end-width and thickness. The fuse link length and mid-width are influential on some of the cyclic response characteristics. In addition, an optimization study is performed to determine the optimal ranges for the design factors that result in simultaneous response optimization conditions, such as maximized energy dissipation and ductility. Predictive equations are also developed and validated for the cyclic response characteristics of steel plate shear links. The optimization results indicate that thick and moderately long fuses with shear links of large end-widths are optimal considering simultaneous optimizations of different response variables.

Keywords: steel plate fuse; earthquake resistant; seismic energy dissipater; optimization; finite element analysis

1. Introduction

Energy dissipation devices are essential in seismic design of ductile structures. Sacrificial energy dissipating devices or accessible and easily replaceable fuse elements are incorporated in structures to minimize repair costs and downtime in major seismic events [1,2]. The damping, ductility, and reusability of steel have made it ideal for wide applications in energy dissipating devices (e.g., [3,4]). Particularly, developments of self-centering rocking frames rely on the energy dissipation of steel plate fuses (e.g., [5,6]).

Several studies have investigated the energy dissipation and hysteretic response of steel shear plates and dampers [3,7,8]. Among others, Ma et al. [9] experimentally tested butterfly-shaped fuses (with diamond-shaped openings) and slit fuses (with rectangular openings). By creating openings or cuts in the plate, the buckling and ductile behavior of the plate is improved since a flexural mode can govern as opposed to the predominant shear mode response of a solid plate. Further, an individual shear link is more compact than a solid plate. Chan and Albermani [10] developed and tested a new steel slit damper (SSD). The device exhibited stable hysteresis with excellent energy dissipation and ductility. Ghabraie et al. [11] found that diamond-shaped cuts were optimal based on a topology optimization of SSDs in terms of energy dissipation. Deng et al. [12] studied the shape optimization of steel shear panel dampers by minimizing the maximum equivalent plastic strain in simulated models.

In this paper, cyclic response sensitivity and multi-response optimization studies of steel plate shear links are presented. Three-dimensional finite element (FE) models are developed and validated for steel plate fuses in ANSYS Mechanical APDL [13]. The design of experiment (DOE) method is employed to generate factor combinations. Simulation models are then developed and analyzed to provide a database for evaluating the influence of different design factors related to the shear link geometry (i.e., length, end-width, mid-width, thickness, and the band zone length) and material (i.e., modulus of elasticity and yield strength of steel) on the cyclic response of shear links. Significant factors found from the sensitivity analysis are then used to develop response surface models for optimization studies based on a desirability approach.

2. Finite Element (FE) Modeling

Fig.1 shows the three-dimensional FE model that is generated and analyzed using ANSYS Mechanical APDL [13]. SHELL181 elements with reduced integration are used in the modeling. Material behavior is represented by a Chaboche model combined with non-linear isotropic hardening (NLISO). Based on the coupon tests reported in Lee et al. [14], the elastic modulus and yield stress of steel material are taken as 200 GPa and 295 MPa, respectively. Mesh density of the steel plate fuse models is controlled using mesh control features in ANSYS Mechanical APDL [13]. Automated free meshing with the element size of 3.5 mm is used for the fuse model.

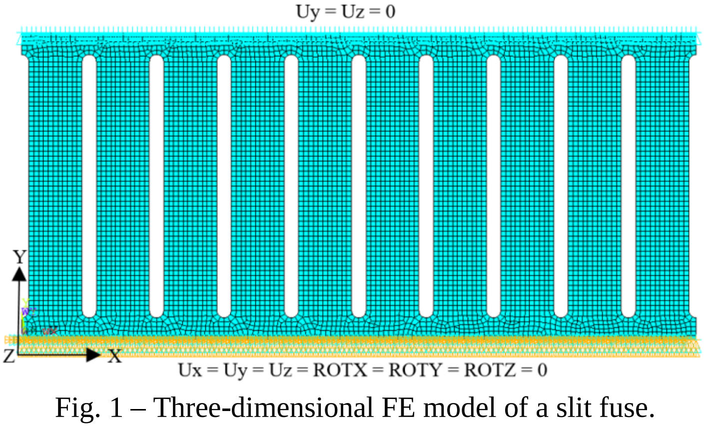

Fig. 1 – Three-dimensional FE model of a slit fuse.

A displacement-controlled loading is applied to the top edge of the fuse model. The loading protocol consists of symmetrical cyclic drift ratio with incrementally increasing amplitudes [14]. Nonlinear static analyses with a full Newton-Raphson solution scheme are performed in ANSYS [15]. Geometric and material nonlinearities are included in the displacement-control analysis. To avoid convergence issues, the minimum number of sub-steps is set to 10 and 25 for small and large amplitude load steps, respectively. A validation study, reported in [15], confirms the accuracy of the FE simulation in predicting the cyclic response and limit states of steel plate fuses.

3. Sensitivity Analysis

A sensitivity analysis of the cyclic load-displacement response of steel plate fuses is performed to assess the effects of different design factors using a statistical DOE method and the validated FE models. Seven potentially influential factors on the cyclic response characteristics are considered. Five of the factors are related to the fuse geometry (including the fuse length, L; mid-width, a; end-width, b; thickness, t; and band zone length, c) and two factors are material-related (i.e., steel yield strength, F_y and modulus of elasticity, E). Two levels are considered for the input factors. Table 1 lists these factors along with their low (−) and high levels (+). The factor ranges are selected to be broad and practical based on previous experimental studies (e.g., [9,14]).

Table 1 – Factors and ranges considered for the sensitivity analysis

Factors	**Symbol**	**Low level (−)**	**High level (+)**	**Units**
Length	L	180	500	mm
Mid-width	a	15	36	mm
End-width	b	36	200	mm
Thickness	t	5	40	mm
Steel yield strength	F_y	245	340	MPa
Modulus of elasticity	E	185000	212000	MPa
Band zone length	c	5	75	mm

3.1 Factor Combinations: Experimental Design

The sensitivity analysis is performed using Design-Expert software [16]. A 2-level one-fourth fractional factorial design with a resolution of four, requiring 32 runs, is considered for the analysis. For each factor combination, a FE model is created and analyzed under cyclic loading. Further details are presented in [15].

3.2 Response Variables

Six different response variables are recorded from the cyclic load-displacement response. These response parameters, as the output of each simulation, include: (1) the initial stiffness, K; (2) yield strength, P_y; (3) ultimate stiffness, $K^{'}$; (4) effective damping, β_{eff}; (5) peak strength, P; and (6) ductility, μ (refer to [15]).

3.3 Results of Sensitivity Analysis

The percentage contributions of significant factors and interactions for each response variable are presented in Table 2. The positive sign indicates that the corresponding factor or interaction has a direct (positive) effect. A summary of the sensitivity analysis results [15] is provided below.

All the response characteristics are significantly influenced by the fuse link end-width and thickness while the length and mid-width are influential on some of the response parameters. It is observed that the cyclic response of steel plate fuses is not significantly affected by the variation of modulus of elasticity (from 185000 MPa to 212000 MPa), steel yield strength (from 245 MPa to 340 MPa), and the band zone length (from 5 mm to 75 mm).

Table 2 – Percentage contribution of factors and interactions with respect to each response variable

Response variable											
Initial Stiffness		Yield Strength		Ultimate Stiffness		Effective Damping		Peak Strength		Ductility	
Factor	Contribution %	Factor	Contribution %	Factor	Contribution %	Factor	Contribution %	Factor	Contribution %	Factor	Contribution %
b	22	*b*	29	*b*	24	*t*	29	*t*	43	*t*	30
t	15	*t*	29	*t*	20	*b*	-12	*b*	23	*L*	-26
L	-15	*bt*	18	*Lt*	-8	*bt*	-11	*bt*	16	*c*	-9
bt	13	*a*	5	*L*	-7	*a*	8	*a*	4	*b*	6
Lb	-12	*ab*	5	*bt*	6	*at*	7	*at*	3	*Lt*	-5
Lt	-9	*L*	-2	*c*	5	F_y	5	*L*	-3	*ab*	-3
aE	-7			*Lc*	-4	tF_y	5	*Lt*	-2	*Lc*	3
				aE	-3	bF_y	-4			*LE*	-3

The initial stiffness of steel plate fuses is mainly affected by the end-width, thickness, length and their interactions. These factors account for about 92% of the total variability in the initial stiffness response. Further, a negative effect for the length and its interactions with the thickness and end-width is observed on the initial stiffness of steel plate fuses.

The yield strength of a steel plate fuse is mainly controlled by the fuse link end-width, thickness, mid-width, and length. These parameters account for approximately 87% of the total variability in the response. The influence of end-width and thickness and their interaction is noticeable among all these factors having a combined percentage contribution of approximately 75%. Further, except for the fuse length, all other factors have a positive effect on the yield strength response.

The ultimate stiffness of a steel plate fuse is mostly sensitive to end-width, thickness, and length. These parameters with their interactions account for about 65% of the total response variability. The effect of end-width, thickness and their interaction on the ultimate stiffness is observed to be positive while the effect of length and its interaction with the thickness is negative.

The important factors that significantly impact the effective damping response are the thickness and the end-width having a combined contribution of more than 50%. Thicker steel plate fuses with a smaller end-width are observed to have higher effective damping. The effective damping is increased by about 5 times for thicker fuses with a smaller end-width.

The factors that mostly influence the load capacity of steel plate fuses are the thickness, end-width, mid-width, and length. These factors with their interactions account for 94% of the total variability in the response. Among these, over 80% of the load capacity variability is controlled by the thickness, end-width and their interactions. Further, the length and its interaction with thickness show a negative effect on the load capacity response while all the other factors have positive effects. In addition, with increasing the end-width for thick fuses, the load capacity is increased significantly.

The most significant parameters and interactions influencing the ductility of steel plate fuses are the thickness, length, end-width, the band zone length. Overall, the percentage contribution of these parameters and their interactions is found to be about 85% of the total variability in the ductility response. Further, it is observed that shorter and thicker fuses possess greater ductility.

4. Developing Response Surface Models

4.1 Factors and Response Characteristics

Four design factors, which are the most influential factors on the cyclic response of steel plate fuses [15], are considered for the response surface study. These factors include the fuse length, L; mid-width, a; end-width, b; and thickness, t. A central composite design (CCD) is used to generate factor combinations for the response surface study. The factor combinations are created using Design-Expert software [16] and are presented in reference [17].

4.2 Results and Predictive Equations

Using least-squares regression analyses, predictive equations are developed to quantitatively express a relationship between the response variable y, (e.g. initial stiffness, K) and the input design factors, x_i (e.g. length, L). A quadratic polynomial relationship [Eq. (1)] is adopted to relate each response to the design factors (x_i).

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + \varepsilon \tag{1}$$

In this equation, the β's are unknown regression coefficients and ε is a random error term (residual) that shows the difference between the actual (y_l) and predicted response values ($\hat{y}_l$), i.e. $\varepsilon_l = y_l - \hat{y}_l$ for each factor combination or design point ($l = 1, 2, \ldots, n$). The least squares method is used to determine the regression coefficients, where the β's minimize the sum of the squares of the errors ($\sum_{l=1}^{n} \varepsilon_l{}^2$).

Based on the predictive equations, 3D surface plots can be used to explore the variation of each response. For instance, Fig. 2 presents the variation of the initial stiffness response with respect to pairs of input parameters. The initial stiffness of steel plate fuses ranges from 0.49 kN/mm to 953 kN/mm. Thorough discussions along with predictive equations are presented elsewhere [17].

4.3 Validation of Response Surface Models

To validate the predictive equations, ten additional models of steel plate fuse links with randomly generated factors are simulated in ANSYS. By comparing the response quantities from ANSYS with those obtained using the predictive equations, it is observed that the average actual-to-predicted response ratio for the response variables is within a range from 0.92 to 1.02. Therefore, the accuracy of the predictive equations is acceptable. Details of this validation study is presented in Ref. [17].

5. Multiple-response Optimization

The developed response surface models are used to the study multiple-response optimization of steel plate fuses. An optimal condition may require simultaneous consideration of multiple response values. For this purpose, desirability functions are used.

5.1 Desirability Functions for Multiple-response Optimization

In this study, a multiple-response optimization method is considered as opposed to a univariate optimization. The simultaneous consideration of different response variables can be complex since the problem may involve conflicting objectives. Simultaneous optimization problems can be approached using a desirability function method [18]. First, a desirability function d_i is defined for each response with the most and least desirable condition of 1 and 0, respectively. Then, an overall desirability function, D is defined and maximized [19]:

$$D = (d_1 \times d_2 \times \ldots \times d_n)^{1/n} \tag{2}$$

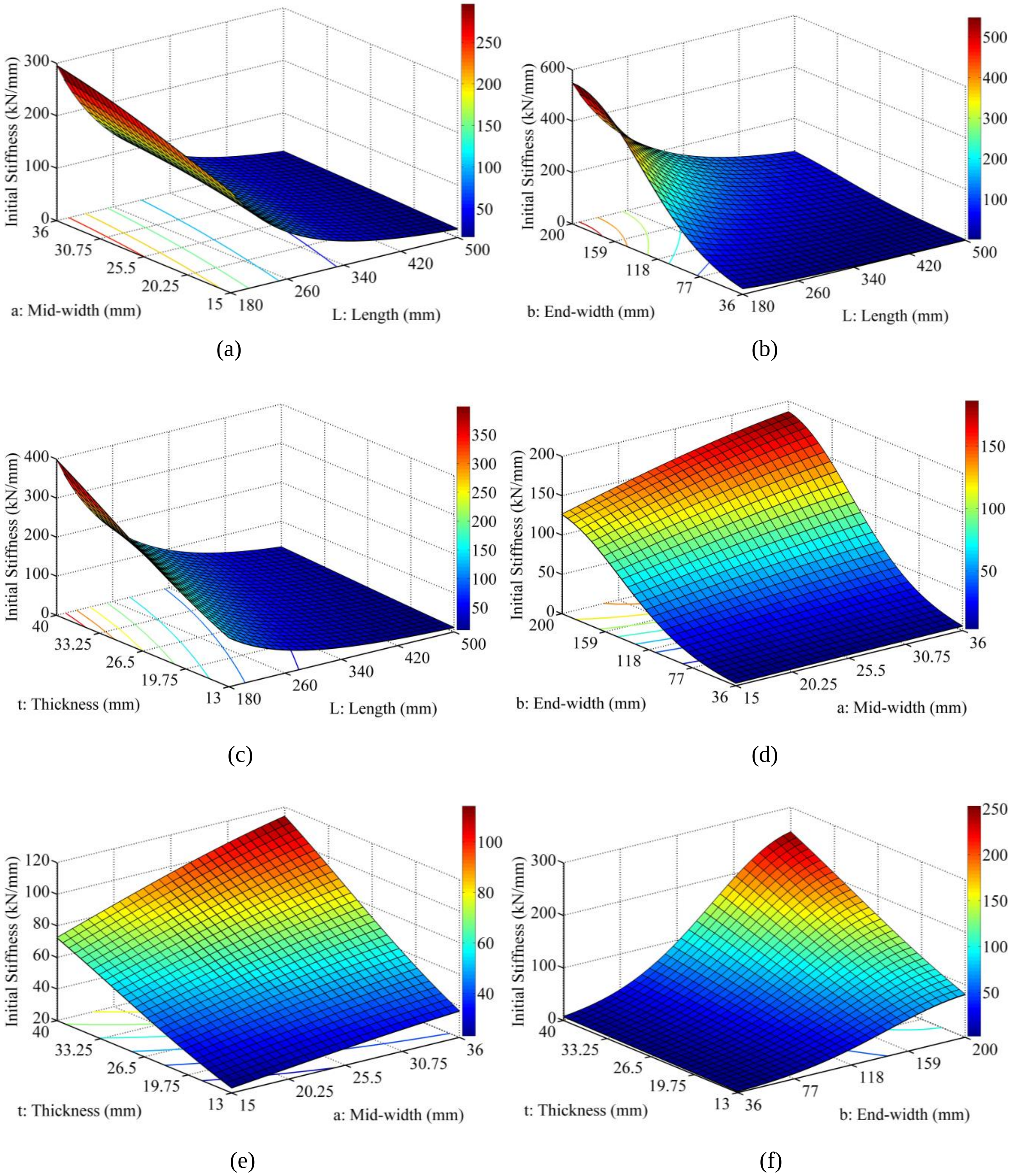

Fig. 2 – Variation of initial stiffness with respect to different pairs of design factors.

In Eq. (2), n is the number of responses in the optimization problem. The desirability function for each response variable is defined differently depending on the objectives of the optimization problem. When the objective of the problem is to maximize the response variable, the desirability function is defined as follows:

$$d = \begin{cases} 0 & y < L \\ \left(\frac{y-L}{T-L}\right)^w & L \le y \le T \\ 1 & y > T \end{cases} \tag{3}$$

where T and L denote the target and lower bounds, respectively. The shape of the desirability function can be altered by putting different levels of emphasis on the response variables using a weight parameter, w. This parameter varies from 0.1 to 10 [16]. A value of 10 indicates the most emphasis on the target. When the objective of the problem is to minimize the response variable, the desirability function will be in the form of Eq. (4):

$$d = \begin{cases} 1 & y < T \\ \left(\frac{y-U}{T-U}\right)^w & T \le y \le U \\ 0 & y > U \end{cases} \tag{4}$$

5.2 Optimization Objectives

Four optimization problems are considered. Table 3 shows the objectives of these optimization problems. These objectives involve improving the structural response characteristics of steel plate fuses in terms of maximizing the effective damping and ductility; maximizing the ultimate stiffness, effective damping and ductility; maximizing the initial stiffness, effective damping and ductility; and maximizing the peak strength, effective damping and ductility.

Maximizing the effective damping and ductility is common in all the optimization problems as highly ductile behavior and maximized energy dissipation capacity are critical for steel plate fuses. For a well-designed steel plate fuse, the lateral displacements under lateral loads should be reduced, which is achieved by increasing the initial stiffness [9]. Furthermore, steel plate fuses should have enough stiffness in the post yielding stage to prevent the occurrence of an undesirable softening condition [14]. Steel plate fuses are also expected to possess high load capacity. In all the optimization problems, weight, w, is set to 1.

Table 3 – Optimization objectives.

	Response					
	K	P_y	K'	β_{eff}	P	μ
In optimization 1				Maximize		Maximize
In optimization 2			Maximize	Maximize		Maximize
In optimization 3	Maximize			Maximize		Maximize
In optimization 4				Maximize	Maximize	Maximize

5.3 Results of Optimization Studies

In this section, firstly, the results of optimization problem 1 are presented in detail. Then, the results from other optimization problems will be summarized.

The first optimization problem determines the optimum ranges maximizing the effective damping and ductility. One optimal factor setting is found to be: length = 500 mm, mid-width = 25 mm, end-width = 200 mm, and thickness = 35 mm. The desirability function for the ductility response $(d)_\mu$, for instance, is 0.927:

$$(d)_\mu = \left(\frac{y-L}{T-L}\right)^w = \left(\frac{645.529-101.913}{688.463-101.913}\right)^1 = 0.927 \tag{5}$$

The overall desirability function, D, for the optimal factor combination is 0.589, which is determined using Eq. (4) as follows:

$$D = (0.927 \times 0.375)^{1/2} = 0.589 \quad (6)$$

Fig. 3 illustrates the change in the desirability function (D) with respect to each design parameter. The simultaneous maximization of effective damping and ductility is achieved with the optimal setting for each design factor as shown in these one-factor desirability plots. Herein, an *optimal range* is defined for each factor as a range resulting in at least 80% of the peak desirability (80% × 0.589 = 47%). As observed in Fig. 3(a), a desirability value equal to or higher than 47% is reached when the length of the steel plate fuse is varied from 246 mm to 500 mm. This indicates that moderate to higher length steel plate fuses are desirable for the simultaneous maximization of effective damping and ductility.

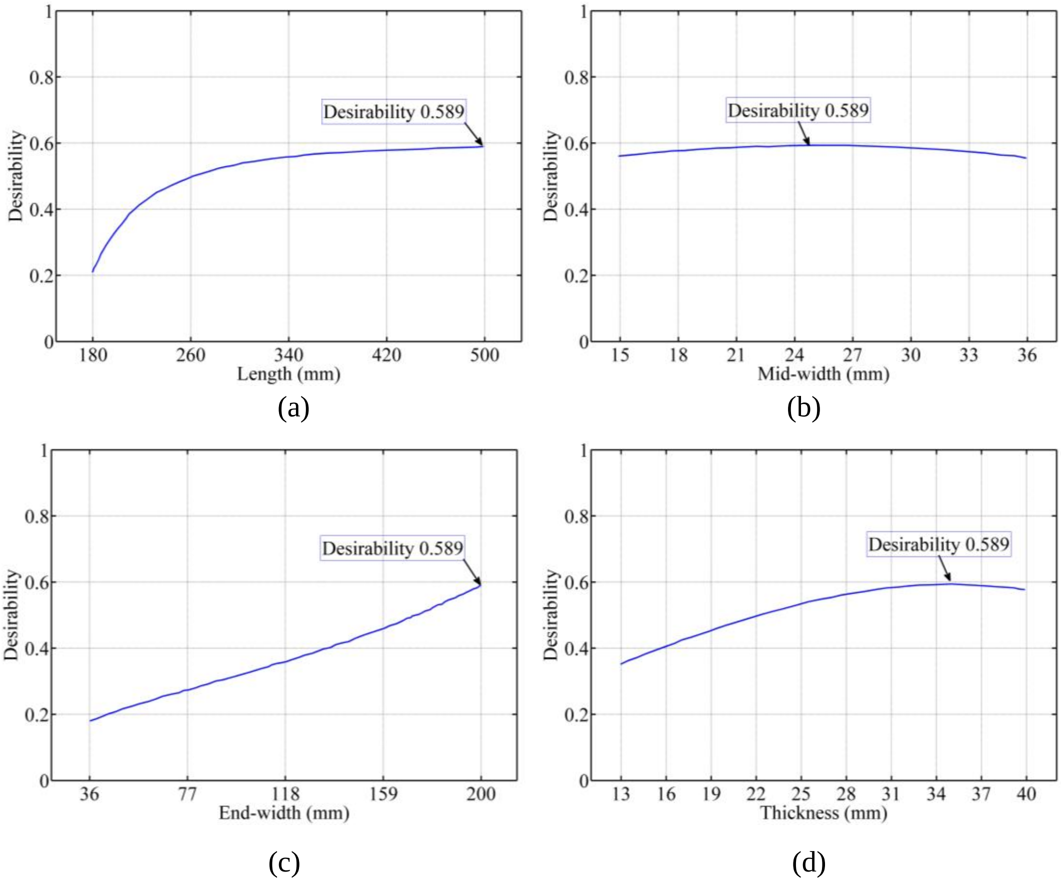

Fig. 3 – The variation of desirability function versus input parameters for optimization problem 1.

Fig. 3(b) shows that the influence of the fuse link mid-width on the optimal condition is insignificant. From Fig. 3(c), it is observed that greater values of end-width are beneficial in reaching the optimization objectives. The optimal range for the end-width is from 163 mm to 200 mm showing a desirability value of greater than or equal to 47%.

Fig. 3(d) shows that moderate to high thicknesses are desirable in achieving maximized effective damping and ductility. The optimal range for the fuse thickness is from 20 mm to 40 mm, which leads to a desirability of 47% or higher.

Table 4 summarizes these findings in a ranked order based on the variability of the optimal ranges for each factor in Fig. 3. For the first optimization problem, the most effective factor is found to be the end-width while mid-width is the least influential factor. These findings are further supported by the contour plots shown in Fig. 4.

Table 4 – Ranking of the most influential input parameters to least for optimization problem 1.

Rank	Input Parameter	ΔD	Optimal range		Unit	Higher Desirability
			Low	High		
1	End-width	0.41	163	200	mm	Moderate/high
2	Length	0.34	246	500	mm	Moderate/high
3	Thickness	0.24	20	40	mm	Moderate/high
4	Mid-width	0.04	15	36	mm	Low/moderate/high

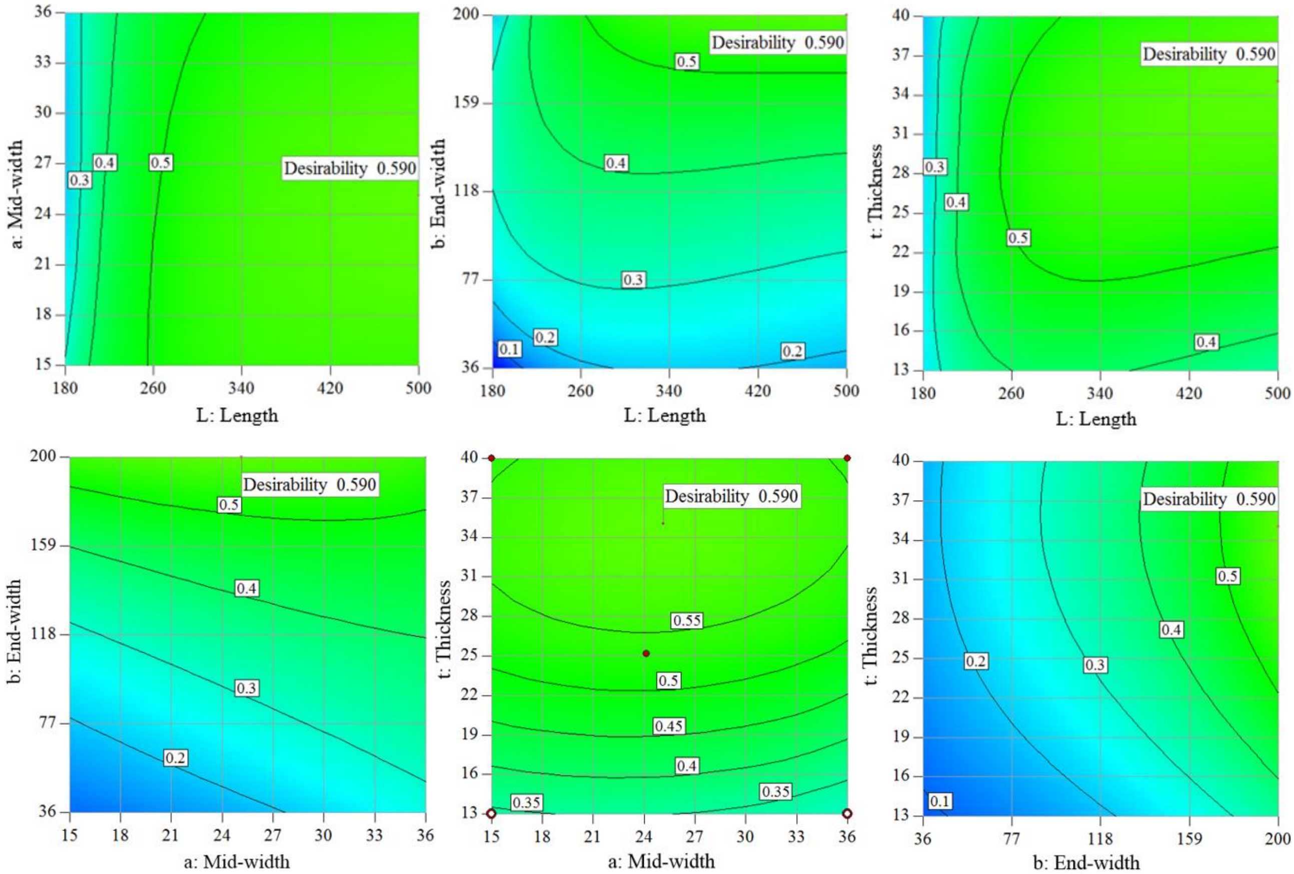

Fig. 4 – Contour plots of desirability for optimization problem 1.

Similar steps are taken to determine the optimal ranges in the other optimization problems. To summarize the results, Fig. 5 is presented. The order of the design factors on the vertical axis is based on the significance of their influence on reaching the optimal condition – from the least to the most significant influence. For instance, Fig. 5 shows that the fuse link end-width is the most influential factor on reaching the optimal conditions in all the optimization problems, while the mid-width is the least effective factor.

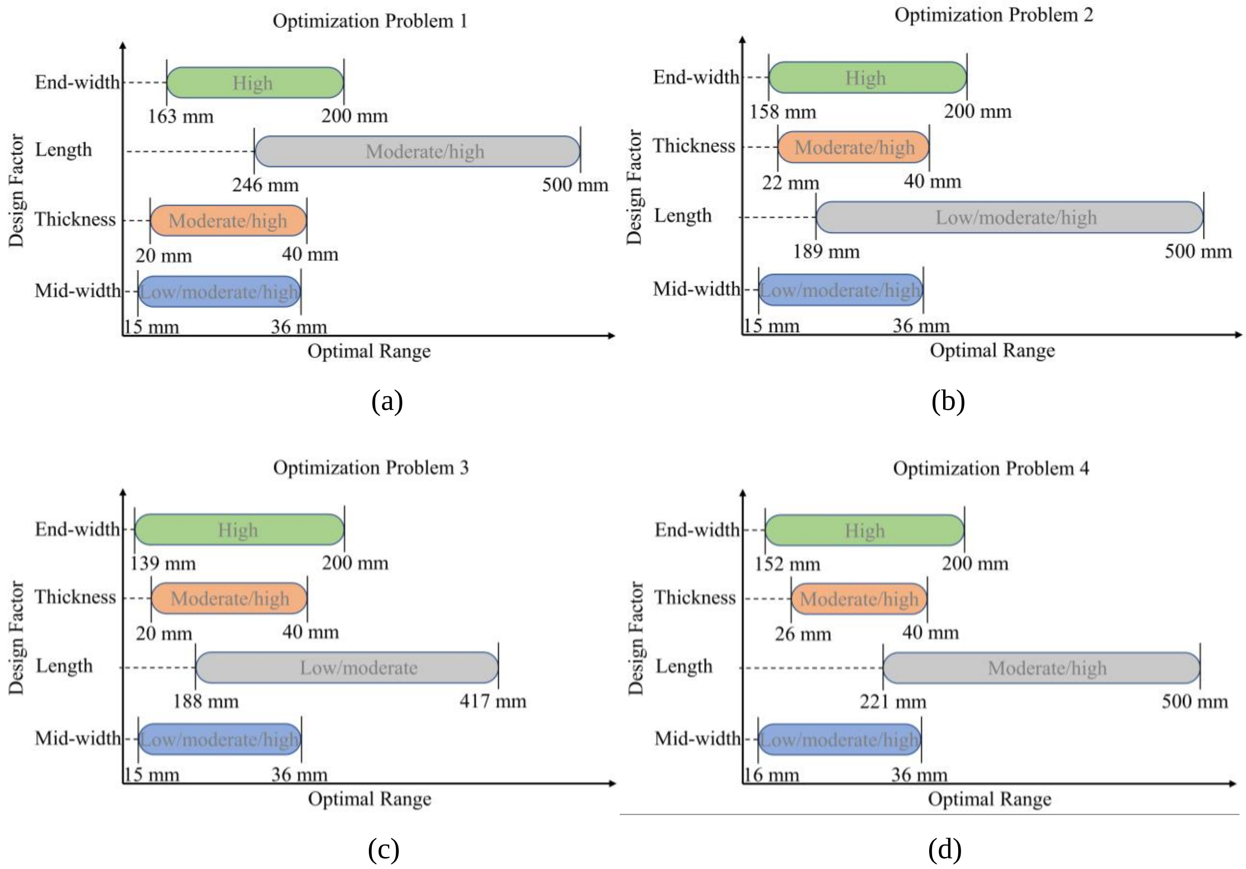

Fig. 5 – Optimal ranges for each factor obtained in: (a) optimization problem 1, (b) optimization problem 2, (c) optimization problem 3, and (d) optimization problem 4 (plots are not scaled).

In order to further assess the accuracy of the optimization results, four runs are performed in ANSYS with the optimal factor combinations obtained from the optimization studies. The confirmation study, which is reported in Reference [17], indicates that the predicted optimal response values agree well with the simulation results; thus, the optimization results are valid.

6. Conclusion

This paper summarizes a research on the sensitivity analysis and optimization of steel plate fuses. Experimentally validated finite element modeling is used along with the statistical design of experiment method. The sensitivity study is performed to determine the effect of different design factors on the cyclic response of steel plate shear links. Significant factors are identified and then used as input factors for developing response surface models. Using the predictive equations and a desirability approach, the multi-response optimization of steel plate shear links is presented. The following conclusions are summarized based on the results:

- The end-width and thickness of steel plate shear links influence all the cyclic response characteristics whereas the length and mid-width are influential on some of the response variables – given the ranges considered for the design factors in this study.

- The cyclic response is not sensitive to the variations in the steel modulus of elasticity, steel yield strength, and the band zone length of the fuse.
- Simultaneous maximization of ductility and effective damping is obtained for the fuse with moderate to high values of end-width, length, and thickness.
- To simultaneously maximize the ultimate stiffness, effective damping, and ductility, steel plate links should possess large end-widths and moderate to large thicknesses.
- To simultaneously maximize the initial stiffness, effective damping, and ductility of steel plate fuses, high values for end-width, moderate to high values for thickness, and low to moderate values for length are beneficial.
- For the simultaneous maximization of effective damping, peak strength, and ductility, the optimal design is found as: high values for the end-width in addition to moderate to high values for thickness and length.
- Overall, thick and moderately long fuses with links of large end-widths are optimal.

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