Force-displacement relationship of a butterfly-shaped beams based on gene expression programming

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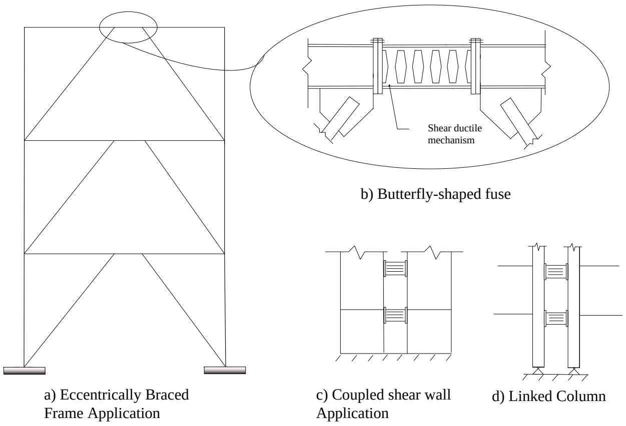
Abstract

Structural steel plates having engineered cut-outs to exhibit controlled yielding is recently proposed for desirable performance compared to conventional systems. Butterfly-shaped beams with hexagonal cut-outs inside of the beam's web is studied to better align the bending strength diagram along the link length with the corresponding demand shape of the applied moment diagram. In previous studies, it has been reported that these links have substantial energy dissipation capability and sufficient ductility which necessities further investigations. In this study, a set of 240 nonlinear finite element models are developed for creation of a database and subsequently calibrated with finite element software packages. The capability of the gene expression programming (GEP) is explored for prediction of force-displacement relationship of a butterfly-shaped beam. Two new models are developed based on the reliable generated database. Subsequently, the proposed models are validated with several conducted analysis and statistical parameters, for which the comparisons are shown in detail. The results represent that the proposed models are able to predict the force-displacement relationship of a butterfly-shaped beam with satisfactory accuracy.

Keywords: Structural fuses, Butterfly-shaped beam, Finite element analysis, Gene expression programming.

1. Introduction

Under severe earthquakes the ductile behavior of the structural elements allows inelastic drifts leading to the overall system's energy dissipation capability (Farzampour and Eatherton 2019; Luth et al. 2008; Saffari et al., 2013, Farzampour and Yekrangnia, 2014). In various structural applications, shear links could be implemented by strategically removing of the material to concentrate the inelasticity and damages in one part of the structure while the remaining parts are intact and undamaged (Atasever et al., 2018; Farzampour et al., 2019; Kim et al., 2016). Along the same lines, a promising type of a structural fuse for use in different structural applications is butterfly-shaped beams in which the steel web plate has cutouts inside leaving butterfly-shaped links to better align the capacity diagram with corresponding demand diagram (Castaldo et al., 2016). Figure 1 shows the implementation and details of the butterfly-shaped beam in different structural applications. Previous studies indicated that using butterfly-shaped shear links within the structures leads to reduction in inelasticity concentration at the critical areas (Farzampour and Eatherton (2018). This concept could be implemented for designing various high-rise and low-rise buildings as well as the fortification of the existing structures. Butterfly-shaped dampers are studied previously for beam-column connection protection from significant damages under earthquakes. This fairly new dampers are able to concentrate the plastic deformations in structural shear links while the columns and beams remain almost elastic. In addition, some studies showed that these fuses are able to withstand more than 30% shear angle ratios if the possibility of the buckling is prevented (Farzampour, 2019; Tsai et al., 1993).



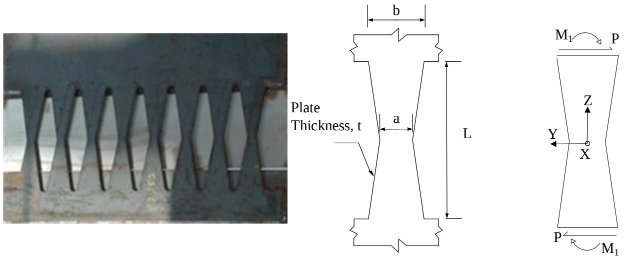
b) Butterfly-shaped fuse

a) Eccentrically Braced Frame Application

c) Coupled shear wall Application

d) Linked Column

a)Examples of the of a butterfly-shaped fuse



b) The geometrical shape, and loading condition

Figure 1. Butterfly-shaped link and applications

2. Gene expression programming

As a progressive algorithm, gene expression programming (GEP) is competent of determining functions from the vast datasets via computer programs evolvement that adopt the role of a living organism. It is generally accepted that they are able to ascertain the links among variables and adapt them by varying their shapes and sizes (Bingöl and Kılıçgedik, 2018; Farzampour et al., 2018). By using genetic operators, population evolution occurs upon the selection of a population consisting of individuals. The algorithm is terminated if an acceptable fitness level is achieved. A comparison of the predicted and actual values distinguishes minimal errors and such procedure is repeated until a satisfactory solution is obtained (Nie et al., 2013). There are two GEP components; chromosomes and expression trees (ETs). Chromosomes represent a mathematical expression consisting of one or more genes. The head and the tail are two main components of the genes. Upon transforming every chromosome into an ET, a mathematical relation is deduced.

Numerous parameters should be considered amidst the GEP optimization process. The range of varying parameters include fitness function, genetic operators and relevant rates, linking function, random numerical constant status, function set, size of genes, quantity of genes, size of population and learning algorithm, etc. Despite some available guidelines on optimal parameter selection, the simplest and most efficient approach is to apply a trial and error process. According to the literature review, GEP generates more favorable results if there is an increase in the head size. Nevertheless, a head that is too large can hinder GEP performance.Therefore, several researchers recommended a head size of 5-30 (Azamathulla, 2012; Bingöl and Kılıçgedik, 2018). The detailed information is shown in Table 1.

Table 1. Load conditions for example 1

Parameter	Parameter description	Parameter setting
P1	Chromosomes	100
P2	Fitness function error type	RMSE
P3	Number of the genes	3
P4	Head size	20
P5	Linking function	Multiplication
P6	Function set	+, –, ×, /, Pow, Sqrt, Exp, Ln
P7	Mutation rate	0.00138
P8	One-point recombination	0.00277
P9	Two-point recombination	0.00277
P10	Inversion rate	0.00546
P11	Transposition rate	0.00546

3. Data preparation and reduced order models

The models are developed according to a comprehensive database obtained from the finite element analysis (FEA) (OpenSees software). The 240 models are generated subjected to the cyclic analysis for modeling purposes to establish a general database, based on which the force-displacement equations are derived accordingly. Table 2 shows the parameters of interest ranges. It is noted that a couple of material yielding stresses are considered for the corresponding yielding stress.

Table 2. The value parameters considered for establishing the GEP database

a/b	b/L	L/t	fy, ksi (MPa)
0.1	0.1	10	39 (269)
0.33	0.3	20	52 (358)
0.75	0.5	40	
1.0	0.7	60	
	0.9	80	
		100	

To ensure a satisfactory comparison, a couple of verifications studies are conducted. The first verification study is related to a beam with hourglass-shaped links. FE ABAQUS package is used to model the general fuse system, and obtain the cyclic pushover hysteretic results shown in Figure 2（Aschheim and Halterman, 2002).

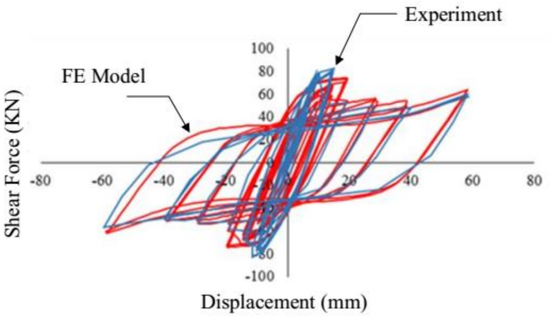
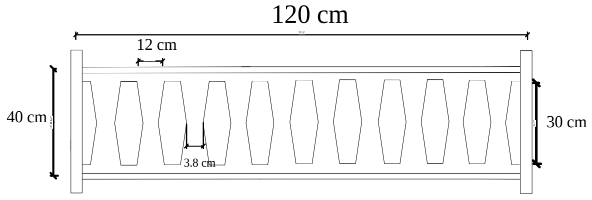
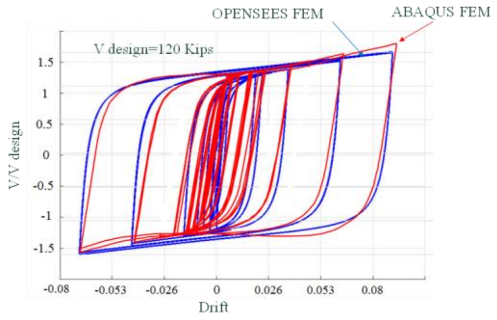


Figure 2. Verification of the finite element modeling methodology against laboratory specimens

For verifying the reduced order model with FE model, a cyclic load previously proposed by AISC (AISC 341-16) for EBF behavior investigations is applied at one end of the shown beam in Figure 3.a, while the other end was fixed. This loading protocol is chosen due to having similarity in behavior of the EBF system with the studied butterfly-shaped beam. The studied FE model is shown in Figure 3.a. For verifying the reduced order models with FEA. The hysteretic results of the reduced order model verification study from the FE analysis and reduced order model results are compared. It is shown that the reduced order model is able to capture the cyclic behavior of a typical butterfly-shaped beam with more than 98% accuracy, which is confirmed with Figure 3.b.



a) The model geometrical properties



b) Comparison of FEA with reduced order model
Figure 3. The reduced order model verification

4. Model development

The main purpose of this section is to propose a prediction equation for the force-deformation of butterfly-shaped beam that envelopes the hysteretic behavior subjected to cyclic loading. Figure 5. shows a cyclic envelope, which is specified by connecting the peak force responses at each displacement level. For each one of the 240 models, the envelope curve is derived and stored. The envelope curve subsequently is used for soft computational investigations and the force-displacement prediction equation in the next steps.

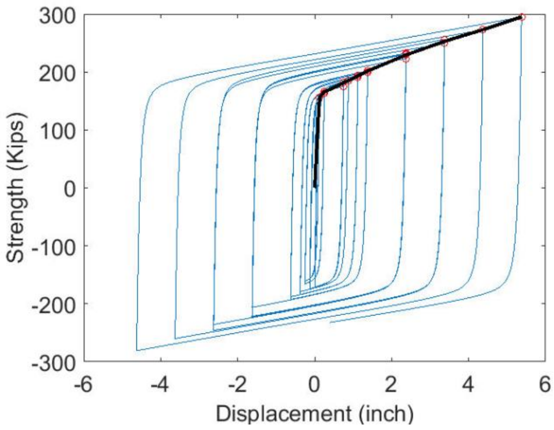


Figure 5. Example of a cyclic envelope based on hysteretic response

The considered parameters employed as the predictor variables are *a/b*, *b/L*, *L/t*, f_y and *d* in which the terms *a/b*, *b/L* and *L/t* are the geometrical ratios calculated based on the Figure 1, f_y is the yielding stress in ksi, and *d* is the vertical displacement of linking beam in inches. As a result, formulation of the shear force is formed as follows:

$$V = f(a/b, b/L, L/t, f_y, d) \tag{1}$$

$$V_I = \ln\left((f_y \frac{a}{b})^{(b/L)/(L/t)} \right) \times \left(100 f_y - f_y{}^{2(1.088-d)} \right) \tag{2}$$

$$V_{II} = v_1 v_2 v_3 \tag{3}$$

in which,

$$v_1 = (d + 8.06)\left(f_y - \frac{L/t}{\frac{-3638.88d + L/t}{-0.99 + f_y + (L/t)^d} - \frac{d\, f_y{}^{b/L}}{b/L + d}} \right)$$

$$v_2 = (b/L)\left(b/L - \frac{(43.47a/b + f_y)(f_y\, b/L)(\sqrt{L/t} + 6.02 f_y)}{(597137.17 - \frac{35573.57}{a/b})(\ln(L/t) + 5.08 + b/L} \right)$$

$$v_3 = \frac{(a/b - 8.05)\sqrt{a/b}(11.34 - a/b) + 0.032^{(d-0.736)} + d}{6.94 - \sqrt{f_y} - L/t}$$

5. Results and discussions

Several phases are conducted to select appropriate model, and accordingly the model accuracy is determined. Smith (1986) mentioned that models with correlation coefficient of R^2 more than 0.64, would have a strong correlation between the observed and predicted values, meaning that the models' prediction capability is satisfactory. However, the insensitiveness of the model evaluation capability corresponding to the additive differences is neglected if only R-values are considered. For addressing this issue, root mean square error (RSME) and mean absolute error (MAE) are employed to have more sensitivity to discrepancies between the observed and predicted values. RSME equation is shown in Eq. (4), which considers the summation of the error magnitudes in predictions. Along the same line, MAE equation shown in Eq. (5) indicates how large error values are expected compared to the predicted values on average. It is clear that the model performance is desirable if lower RSME and MAE values are achieved.

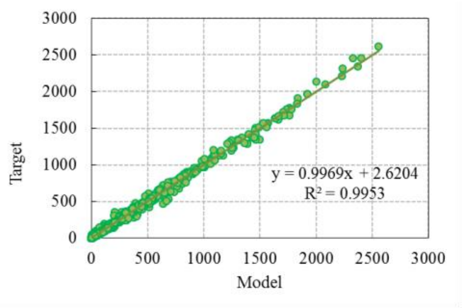
$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(Xo_i - Xe_i \right)^2} \tag{4}$$

$$MAE = \frac{1}{N} \sum_{i=1}^{N} \left| Xo_i - Xe_i \right| \tag{5}$$

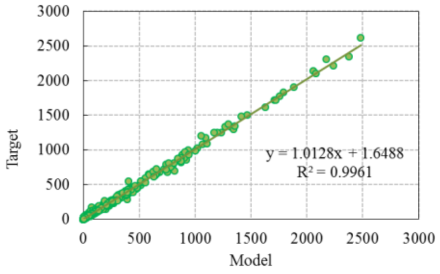
where N, X_{oi} and X_{ei} are the number of samples, observed and estimated values, respectively.

Figure 6. shows the scatter plot of the target (generated database) and predicted models (GEP). To visualize the correlation between possible variable pair consisting input variables, model and achieved variables, the scatter plots are implemented. Figure 6. shows that the testing and training datasets in which Target is the force values obtained from OpenSees, and model means predicted force values from GEP mode.

It can be observed from Figure 6 that the GEP model with high R values for both testing and training phases predicts the target values to an acceptable degree of accuracy. Having R^2 equal to one does not show a prefect prediction and it only indicates a linear correlation between the experimental and predicted data; hence, other statistical indexes (e.g. RMSE and MAE) for evaluation purposes should be implemented for verifying the accuracy of predictions.



(a) Training



(b) Testing

Figure 6. Scatter plot of predicted versus generated shear force using the GEP model for Eq. 3

6. Conclusions

The application of the relatively new soft computing approach of GEP to predict the force-displacement relationship of butterfly-shaped beams was described in this study. For this purpose, 240 finite element models were generated using OpenSees platform to establish a database after verification of the modeling methodologies. Two GEP models were proposed accordingly to predict the force-displacement of butterfly-shaped beams with general geometrical properties based on the generated database. The results of the GEP-based models were able to accurately predict the butterfly-shaped beams shear force at a specified displacement value. The model's validity is tested for parts of the results beyond the training data and it is shown that GEP prediction model satisfies the various criteria related to external validations.

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