Force–Displacement Relationship of the Butterfly-Shaped Beams Based on Gene Expression Programming

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Abstract
Structural steel plates with engineered cut-outs to exhibit a controlled yielding mechanism is recently proposed for desirable structural performance compared to conventional systems. Butterfly-shaped beams with hexagonal cut-outs inside of the beam’s web are implemented 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 a substantial energy dissipation capability and sufficient ductility which necessitates further investigations and structural behavior prediction studies. In this study, a set of 240 nonlinear finite element models are developed for the creation of a database and subsequently calibrated with finite element software packages. The capability of the gene expression programming (GEP) is explored for the prediction of the 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 analyses 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 · OpenSees

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 2018b; Luth et al. 2008; Mansouri et al. 2016b; Mirzai et al. 2018, Mirzai and Hu 2019; Saffari et al. 2013, Farzampour and Yekrangnia 2014; Mirzai et al. 2020). In various structural applications, shear links could be implemented by strategic material removal 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 and Eatherton 2018a; Kim et al. 2016; Zeynali et al. 2018; Farzampour et al. 2018; Paslar et al. 2020; Lee 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 have cutouts inside leaving butterfly-shaped links for better aligning the capacity diagram with corresponding demand diagram (Kim and Kim 2017; 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 a reduction in inelasticity concentration at the critical areas (Farzampour and Eatherton 2018a, b; Farzampour and Eatherton 2019a, b; Farzampour et al. 2019). 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 (Farzampour and Eatherton 2019a, b) for beam-column connection protection from significant damages under earthquakes. These new dampers are able to concentrate
the plastic deformations in structural shear links while the columns and beams remain almost elastic. In addition, several studies showed that these fuses are able to undergo 30% shear angle ratios if the possibility of buckling is prevented (Farzampour and Eatherton 2019a, b; Tsai et al. 1993; Esteghamati and Farzampour 2020). Figure 1b shows a typical butterfly-shaped shear link, and the general loading condition and geometrical properties, and the moment demand versus moment capacity of these links.

Along the same lines, different studies showed that straight shear links and butterfly-shaped shear links are capable of controlling the structural response of multi-story buildings under earthquakes, and then be accessible for replacement purposes (Farzampour and Eatherton 2019a, b; Farzampour et al. 2019). These links represent...
high ductility and stiffness; however, they are subject to brittle limit states, especially buckling (Farzampour 2019). The structural shear links employed in various applications could act as structural fuses since they are able to yield and limit the demand forces on the surrounding structural elements. For addressing various limit state issues, the effect of various geometrical properties are studied previously to indicate appropriate design ranges for specific applications (Farzampour and Eatherton 2018b). It is shown that compared to other types of links, the butterfly-shaped links are capable of having hinges far from the sharper areas, full hysteric behavior, significant buckling resistance, and applicable for space-constrained areas.

Hysteretic dampers such as the added damping and stiffness (ADAS) and triangular-plate added damping and stiffness device (TADAS) have tapered fuses bent about their minor axis (Whittaker et al. 1991; Tsai et al. 1993). Similarly, tapered fuses can be bent about their major axis (in-plane bending) to create larger stiffness. In-plane implementation of the fuses has been shown to have substantial energy dissipation capability, ductility, and large distribution of yielding. To control the drift response of mid-rise buildings in-plane fuses have been implemented with similar shapes compared to butterfly-shaped fuses for the purposes of desirable energy dissipation and reducing the demands on the framing members (Li and Huo 2010).

In recent years Gene expression programming (GEP) has been for many engineering problems (Ebrahimzade et al. 2018; Gandomi and Alavi 2012; Gandomi et al. 2014b; Gündüz 2012; Mahdavi Jafari and Khayati 2018; Mansouri et al. 2016a). This method is implemented in this study to investigate the structural prediction of butterfly-shaped beams’ behavior. This new data-driven method uses the individual population to extract the best solution according to one or several gene operations (Mansouri et al. 2017a). It is noted that the tangible discrepancy in the previously employed method of Genetic Programming (GP) and GEP is related to the nature of the used programs. The GP considers parse tree program length, while in GEP, the programs are in the format of linear strings with fixed length (Mansouri et al. 2017b), which are represented as the chromosomes.

In this paper, the GEP method is employed to assess the force–displacement relationship of butterfly-shaped beams. The validated reduced-order models are developed and a database is generated using the OpenSees platform. A total of 240 models are used to establish the database for further analysis related to the various geometrical properties. The results of the developed models are culminated in deriving force–displacement relationships for a typical butterfly-shaped beam with general geometrical properties.

2 Gene Expression Programming

As a progressive algorithm, gene expression programming (GEP) is generally accepted that they can ascertain the connection among parameters (Bingöl and Kılıçgedik 2018; Mansosuri and Farzampour 2018; Gandomi et al. 2014a; Nie et al. 2013).

The algorithm, shown in Fig. 2, is terminated if an acceptable fitness level is achieved. The tail only includes leaf nodes related to ET, and the head contains both leaf and internal nodes. In canonic GEP, the gen number and size of the head and the gene are considered as the input parameters for the algorithm (Güneyisi et al. 2013; Güneyisi and Nour 2019; Ipek and Güneyisi 2020). It is noted that that for multigenic chromosomes, all ETs are connected by their root node with a linking function. The linking function is considered as the additional operator in this study for the GEP system (Onen 2014; Azamathulla 2012; Bingöl and Kılıçgedik 2018; Zakaria et al. 2010). Table 1 lists the GEP optimized parameters.

![Fig. 2. The gene expression programming (GEP) algorithm (Gandomi et al. 2013)](image-url)
3 Data Preparation and Reduced-Order Model Establishment

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 and associated ranges.

To ensure a successful comparison, verification studies are conducted initially. 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. Twenty-nodded solid element with reduced integration capability is used as the selected element type to reduce the chance of shear locking and hour-glassing effects (Shin et al. 2017). A bilinear material property with yielding strength of 379 MPa and an elastic modulus of 200 GPa and strain-hardening of 1.38 GPa is considered. According to the geometry of the test, the story shear should be evaluated as the 1.42 times beam shear obtained from FEA, and the story drifts should be estimated by the beam chord rotation divided by 1.34. The beam chord rotation is defined as the transverse displacement by the beam’s clear span length. Figure 3 compares shear-story drifts responses with the corresponding laboratory test of the beam with hourglass-shaped links. In addition, it is reported that the buckling limit state has occurred at the 2% drift ratio, which is precisely captured from the FE models. From the FE model, the beam strength before and after buckling was 73.2 kN and 52.7 kN. The reported strength from the laboratory test specimen before and after buckling was 76 KN and 57.4 kN, which shows that the FE modeling methodology was able to capture the actual behavior and limit states of the beam with shear links inside within less than 5% difference.

In the second verification study, the reduced-order model from OpenSees is verified with FE package results. The modeling methodology with OpenSees is conducted by validating the cyclic behavior against the FE model. A butterfly-shaped beam is modeled based on the conventional

![Fig. 3 Verification of the finite element modeling methodology against laboratory specimens](image)
EBF system IBC (2012) and redesigned with a set of a flexural dominated links and a total length of 120 cm following previous studies (Farzampour et al. 2019). The geometrical properties of the model are shown in Fig. 4, the material model is based on the yielding stress of 250 MPa, modulus of elasticity of 2.0E + 5 MPa and the strain-hardening ratio of 0.0005. For verifying the reduced-order model with the 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 Fig. 4, 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 Fig. 4a, b, and the corresponding reduced-order model is shown in Fig. 5a, b, respectively.

Figure 5a shows the schematic illustration of the Opensees reduced-order model. For this model, the beams are modeled with element elastic elements, since the contribution of the upper and lower plates to the inelastic total behavior is negligible. The butterfly-shaped links are modeled with a displacement-based beam element (dispBeamColumn) with distributed plasticity and 5 integration points. The length of the beam is equal to 120 cm, and the height of the beam is equal to 40 cm. The links are modeled with taper shaped varying width shown in Fig. 5a, and the boundary condition for nodes is pinned which is schematically determined in Fig. 5a. The material model is Giuffré-Menegotto-Pinto Model with Isotropic Strain Hardening (Steel02 in Opensees) with the yielding point of 248 MPa, modulus of elasticity of 2e5 MPa and the strain-hardening ratio is 0.0005 (CR1, CR2, a1, a2, a3, a4, and sigInt are 0.925, 0.15, 0.005, 1.0, 0.005, 1.0 and 0 respectively). In addition, the applied cyclic loading protocol is shown in Fig. 5c. For verifying the reduced-order models with FEA. The hysteretic results of the reduced-order model verification study show 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 Fig. 5b.

4 Model Development

The main purpose of this section is to propose a prediction equation for the force–deformation of a butterfly-shaped beam that envelopes the hysteretic behavior subjected to cyclic loading. Figure 6. 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
Fig. 5  The verification of the reduced-order beam model

(a) The schematic representation of the FBF model in OpenSees

(b) The verification of the reduced-order model in OpenSees with FEA model with $V_{\text{design}}$ of 530 kN

(c) Loading protocol
computational investigations and the force–displacement prediction equation in the next steps.

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

\[
V = f(a/b, b/L, L/t, f_y, d)
\]  
(1)

in which \( V \) (pound) is shear force of the butterfly-shaped beam. Here are two proposed prediction models:

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

(2)

\[
V_{II} = v_1 v_2 v_3
\]

(3)

in which:

\[
v_1 = (d + 8.06) \left[ f_y - \frac{L/t}{-363.884d + L/t + 0.996f_y + (L/t)^2} \right]
\]

\[
v_2 = (b/l) \left( \frac{4.37a/b + f_y}{b/L} \right) \left( \sqrt{L/t + 6.02f_y} \right) \left( \frac{597137.17 - \frac{35573.57}{a/b}}{a/b} \right) \left( \ln (L/t) + 5.08 + b/L \right)
\]

\[
v_3 = \frac{a/b - 8.05}{6.94 - \sqrt{f_y - L/t}} \left( \sqrt{a/b(11.34 - a/b) + 0.032(0.736d)} + d \right)
\]

in which, the Eq. (2) is a simple and less precise force–displacement predicting equation, while Eq. (3) is more accurate and complex. In the next section, the accuracy of the proposed equations is evaluated and studied in detail.

5 Results and Discussions

Several phases are conducted to select the appropriate model with high accuracy. Smith (1986) showed that models with the \( R^2 \) correlation coefficient of 0.64 or more, 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, the root means square error (RSME) and the mean absolute error (MAE) are employed to have more sensitivity to discrepancies between the observed and predicted values. The RSME equation is shown in Eq. (4), which considers the summation of the error magnitudes in predictions. Along the same line, the MAE equation shown in Eq. (5) indicates how large error values are expected, compared to the predicted values in average. It is clear that the model’s performance would be more desirable if lower RSME and MAE values are achieved.

\[
RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (X_{Oi} - X_{Ei})^2}
\]

(4)

\[
MAE = \frac{1}{N} \sum_{i=1}^{N} |X_{Oi} - X_{Ei}|
\]

(5)

where \( N, X_{Oi} \) and \( X_{Ei} \) are the number of samples, observed and estimated values, respectively.

Figure 7 shows the scatter plot of the target (generated database) and predicted models (GEP). To visualize the correlation between possible variable pairs consisting of input variables, model, and achieved variables, the scatter plots are implemented. Figure 7 shows that the testing and training datasets in which Target is the force values obtained from OpenSees, and model mean predicted force values from GEP.

To adjust the weights on the GEP, a training set is used to minimize the overfitting. It is shown that if the accuracy over the training data set increases, and the accuracy of the validation data set stays the same or decreases, then the overfitting would occur. In addition, to confirm the actual predictive power of the model, the testing data set is implemented. It is necessary to further decrease the data points evaluated for several different estimators, and avoid cluttering issues leading to capturing the asymptotic behavior of each respective estimator. The asymptotic behavior is captured and the least-squares curve-fit is calculated for each metric of each estimator with 95 percent confidence bounds. For this purpose, GEP’s curve fitting...
is implemented to estimate the curve-fit and the confidence bounds which are shown in Figs. 8, 9, 10 and 11.

It can be observed from Fig. 7 that the GEP model with high $R^2$ 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 perfect 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 (Sadeghian and Fam 2015).

Besides, the curve-fitting chart shows how the models are fitting the data. For instance, Fig. 8 illustrates this chart for both the training and testing phases. It is determined that the GEP based shear forces with high fitting status are able to predict the target values with an acceptable degree of accuracy; hence, the prediction equation has high accuracy in estimating the ultimate shear forces for a beam equipped with butterfly-shaped shear links.

A unique number related to each one of the possible category values are assigned in categorical variable coding. In this process, which is also called dummy variable application, the dummy values are eventually substituted with actual category designations. To indicate how the target and model output data could cover the total range, the distributions in parallel scatter plots with dummy random points in Y-axis are developed and shown in Fig. 10, in which dummy values versus observed values based on the proposed Eq. (3) are determined. It is concluded that the target and model outputs are well covered over the entire range of target and model outputs, and the spread, as well as overlap of the actual and predicted values, are significantly close.

The proposed equations results for the training and testing set are represented in Table 3. It is concluded that based on Table 3, the accuracy of the proposed Eq. (3) with more complicated formulization compared to Eq. (2) is high due to close to one $R^2$ values indicating a better correlation between the results. For Eq. (3) The RSME and MAE for training and testing sets are close with less than 0.5% difference. However, this difference between the testing and training statistical parameters is between 10 and 20% for the model proposed in Eq. (2). The operator is able to decide to use either of the equations based on the application and the required accuracy for design purposes.

### 6 Conclusions

The application of the relatively new soft computing approach of GEP to predict the force–displacement relationship of butterfly-shaped beams is described in this study. For this purpose, 240 finite element models were generated using the OpenSees platform to establish a database. Two GEP models were developed 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 any specified displacement value. The model’s validity is tested for various parts beyond the training data, and it is shown that the GEP prediction model satisfies the various criteria. Furthermore, the validation phase determines the model efficiency for the general shear force estimation of butterfly-shaped beams. Several factors ($a/b$, $b/L$, $L/t$, $f_y$, and $d$) are represented within the model to consider the effect of the different geometrical and material properties of a typical butterfly-shaped beam. The accuracy of the proposed equations is shown to be high due to the close agreement in $R^2$, RMSE, and MAE between training and testing data sets. Therefore, it is concluded that the proposed models could be implemented for design and pre-planning purposes.

| Table 3 | The statistical data and accuracy of the proposed equations |
|----------------|------------------------------------------------------------|
| Model          | $V_{\text{target}}$ vs. $V_{\text{model}}$ |
|                | $R^2$ | RMSE | MAE |
|                | Training | Testing | Training | Testing | Training | Testing |
| I (Eq. 2)      | 0.83    | 0.82   | 136.37  | 156.17  | 72.43    | 79.32   |
| II (Eq. 3)     | 0.99    | 0.99   | 22.28   | 23.04   | 13.30    | 13.78   |
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