

Empirical Formulation for Compressive Capacity of Gusset Plates

MEISAM SAFARI GORJI and J.J. ROGER CHENG

ABSTRACT

Gusset plates play a critical role in the behavior and stability of bracing systems and truss bridges. While the behavioral characteristics of gusset plates have been widely investigated and analysis procedures have been developed, considerable uncertainty exists in the design equations, due primarily to the complexity of stress distribution in the connection area. Current design procedures rely heavily on highly simplified approaches, which typically result in inconsistent design factor of safety for various gusset configurations and boundary conditions. In this research, a powerful genetic programming (GP) tool is employed to develop an empirical formulation for compressive capacity of corner gusset plates using a comprehensive database collected from previously published test results and test-validated finite element models. The predictive model correlates the ultimate compressive strength of gusset plates with their mechanical and geometrical properties. A comparative study is performed to evaluate the performance of the derived expression compared to the results of the well-known effective length factor method. The results indicate that the GP-based equation accurately estimates the compressive capacity of gusset plates and its prediction performance is significantly better than that of the current procedures.

Keywords: gusset plate, compressive strength, buckling.

INTRODUCTION

The behavior of gusset plates in concentrically braced frames is quite complex, especially under compression, where the ultimate capacity depends largely on the boundary conditions and plate geometry. For this reason, it is difficult to evaluate the internal stress distribution in the gusset plates and determine their compressive strength. As such, in order to analyze and design these connections, designers have conventionally employed highly simplified approaches, which typically result in inconsistent reliability for various gusset configurations and boundary conditions. Current procedures to predict the buckling capacity of gusset plates are generally based on the column analogy method, also called effective length factor method, originally proposed by Thornton (1984). According to this method, it is assumed that the compressive capacity of the gusset plate is equal to that of an imaginary rectangular column below the effective width established by a 30° stress dispersion angle (Whitmore, 1952) and an average buckling length (Figure 1). The compressive strength of this imaginary column is then

determined using the column curves available in the codes assuming an effective length factor of $K = 0.65$, which corresponds to the fixed-fixed boundary condition (Thornton, 1984). While the Thornton method is based on a rational approach, several previous experimental and analytical studies have shown that this method can be conservative and inaccurate in many cases for a variety of reasons, including the following: (1) The column curves in the codes may not be appropriate for plates, (2) the out-of-plane restraint provided by the material outside the Whitmore width is neglected, (3) uncertainties exist in the value of K factor used for various gusset plate configurations and boundary conditions, and (4) the effect stress redistribution due to yielding prior to plate buckling is not appropriately captured (Dowswell, 2006). To account for the latter, Yam and Cheng (2002) proposed a modified Thornton method in which it was suggested that the effective width can be determined with a 45° stress trajectory angle instead of 30° angle.

Dowswell (2006) classified corner gusset plates into three types based on shapes and compactness and suggested an effective length factor for each category. While the suggested K values improved the estimations of compressive strength in many cases, the method still underestimates the buckling capacity of the gusset plates, especially for non-compact ones, where the mean value of test-to-predicted ratio was 3.08.

In 2009, the Federal Highway Administration (FHWA) issued a design guide for bolted and riveted gusset plates in truss bridges, where the compressive capacity of the gusset plates is determined using the early Thornton method (FHWA, 2009.) The guideline suggests several effective length factors ranging from 0.65 to 2 for various assumed

Meisam Safari Gorji, Postdoctoral Fellow, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada. Email: meisam.safari@ualberta.ca (corresponding)

J.J. Roger Cheng, Professor and C.W. Carry Chair in Steel Structures, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada. Email: roger.cheng@ualberta.ca

Paper No. 2018-14

buckling shapes and boundary conditions. However, since the ultimate compressive strength calculated using this method depends significantly on the selection of the K factor based on the buckling shape of the gusset, which is unknown in most cases, the estimated value is highly influenced by the engineer's judgement. While this design approach has served the profession rather well in the past, innovative solutions and design tools to achieve a more consistent factor of safety would be extremely beneficial to help facilitate the design process and possibly improve design economy.

The compressive behavior of gusset plate connections has been widely investigated by researchers in the past four decades, and a number of experimental and analytical databases were published by several researchers. These databases not only helped verify the validity of current design procedures, but also can serve as a basis for the development of new design methods in the future. A robust empirical model based on a reliable database can eliminate the highly simplified design assumptions and reduce errors in the prediction values. Such a predictive tool can be very useful as a cross check on the results of the existing methods, particularly, to examine if the new designs are consistent with the published test data. One such efficient tool is developed in this research using an advanced data mining technique called gene expression programming (GEP) (Ferreira, 2006).

RESEARCH OBJECTIVE

As mentioned previously, the primary objective of this research is to develop empirical formulations for predicting the compressive strength of corner gusset plate connections

using an evolutionary computing approach. The predictive model, which is developed based on a comprehensive database collected from the available literature, is expected to provide a valuable tool for design engineers and researchers.

DATA COLLECTION

Developing a reliable empirical model requires a comprehensive database that covers most important variables and key parameters affecting the compressive strength of gusset plate connections. A large database containing 41 experimental results and 164 test-validated finite element models covering a reasonably wide range of gusset plate geometries and mechanical properties was collected from a survey of past research conducted on the subject. The majority of experimental data used in this research were the results of a comprehensive testing program carried out by the senior author and his associates at the University of Alberta (Cheng and Hu, 1987; Yam and Cheng, 1993; Rabinovitch and Cheng, 1993; Cheng et al., 1994; Nast et al., 1999). The finite element data were adopted from several previously published analytical research on gusset plates in compression. Many of the aforementioned studies have been collected in previous research (Dowswell, 2006). It should be recalled that the primary focus herein is to investigate the ultimate strength of gusset plates in which the plate buckling is the governing failure mode. Although the total number of experimental and numerical data available on the subject was larger than that considered in this research, a number of gusset plates were excluded from the database, including the finite element (FE) models with purely elastic material models and

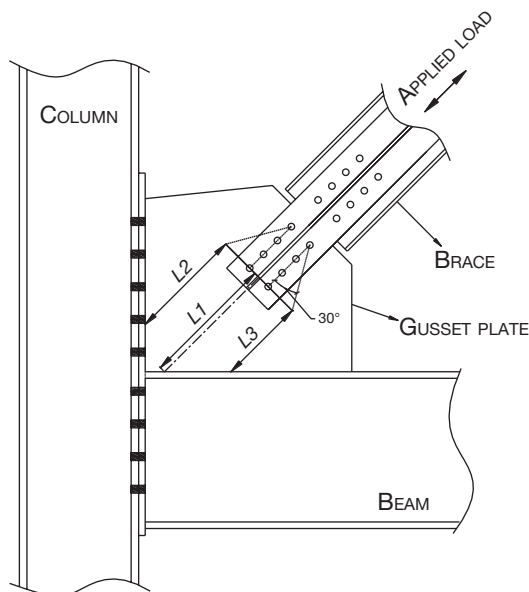


Fig. 1. Geometrical variables and effective width.

the specimens that did not fail by gusset plate buckling, as well as those with unrealistic boundary conditions. Also, specimens with loading eccentricity and stiffened gusset plates were not considered in this study. A summary of the experimental and numerical research used in this paper are described in the next sections, and the details of database are presented in the Appendix.

Experimental Data

Cheng and Hu (1987) conducted 14 experimental tests on six full-scale corner gusset plate connections to investigate their compressive behavior and buckling capacity. The main parameters studied included geometric configuration, plate thickness, eccentricity, boundary conditions, and plate reinforcement. The test specimen consisted of two plate sizes (33.5 in. by 21.7 in. and 33.5 in. by 27.6 in.) and two plate thicknesses (approximately $\frac{1}{8}$ in. and $\frac{1}{4}$ in.) To evaluate the effects of eccentricity, additional specimens were considered in which gusset plates were attached to the brace using a single $\frac{5}{16}$ -in.-thick splice. All specimens were tested in compression for two separate boundary conditions, namely (1) fixed-fixed, where both the test frame and the bracing member were fixed laterally and rotationally, and (2) fixed-roller, where the brace was fixed and the test frame was allowed to move out-of-plane by using roller support. By comparing the compressive capacity of the test specimens with those calculated with Whitmore method, the authors reported that this method significantly overestimated the gusset plate ultimate strengths. This was primarily due to the fact that the governing failure mode was elastic buckling of the gusset plates.

Gross and Cheok (1988) tested three vertical brace sub-assemblies where the braces, columns, and connecting beam were pinned at the ends. The gusset plates' dimensions were 23 in. by 11 in. with a thickness of $\frac{1}{4}$ in. The research objectives were to study the connection behavior, the effect of eccentricity of the forces in the connection, and the influence of column orientation. All specimens experienced yielding prior to ultimate loads and failed by buckling, except one specimen that failed by tearing of the gusset plate. The researchers reported that the Thornton method with K factor of 0.65 significantly underestimated the ultimate capacity of the gusset plates achieved in the tests.

Brown (1988) experimentally tested 24 half-scale corner gusset plate connections with the main variables of study being gusset plate thickness, geometry, type, and orientation angles of bracing member. Three different gusset plate thicknesses were used with two types of bracing members, which had five different inclination angles ranging from 26° to 55° . It was reported that the majority of specimens failed by buckling of the longer free edge of the gusset plates, followed by large deflections that occurred out-of-plane.

Yam and Cheng (1993) conducted experimental tests

on 19 gusset plates in compression. The primary objective was to investigate the compressive behavior and ultimate capacity of the gusset plates, where the effects of several parameters were studied, including gusset geometry, plate thickness, brace angle, and out-of-plane boundary conditions. The governing failure mode for most of the specimens was sway buckling of the gusset plate. Three of the specimens were intended to study the effects of out-of-plane loading eccentricity. The researchers also studied the effects of frame actions and reported that the presence of moments on the beam and columns had negligible effect on the buckling capacity of the gusset plates. The gusset plates generally experienced significant yielding prior to the ultimate capacity even at a load level considerably lower than that calculated using the Whitmore method. The compressive strength of the specimens was almost directly proportional to the thickness of their gusset plates.

Rabinovich and Cheng (1993) cyclically tested five full-scale corner gusset plate connections. The specimens were designed based on the concept of weak gusset plate–strong bracing members proposed by the authors, such that the input energy would be dissipated by the gusset plate rather than the bracing member itself. The study parameters included gusset plate thickness, geometry, bolt slip, and adding a free edge stiffener. The main objective was to investigate the effects of these parameters and to examine if the cyclic loading would affect the ultimate capacity of the connections. The results indicated that while the tensile capacities of the specimens were not considerably affected by the cyclic loading, the compressive capacities were significantly reduced due to load reversals. It was reported that the Thornton method conservatively estimated the compressive capacity of the unstiffened gusset plates.

Nast et al. (1999) conducted cyclic tests on four full-scale corner gusset plate specimens, two of which had free-edge stiffeners. Only one of the unstiffened gusset plates was designed to buckle under compression. The intention of the research was to study the effects of free-edge stiffeners as well as bracing member-gusset plate interaction on the cyclic behavior of gusset plates.

Chen and Chang (2012) cyclically tested six low-yield point (LYP) steel gusset plate connections that were designed following the weak gusset–strong brace concept. The researchers used free-edge stiffeners and slot-type restrainers (STR) to prevent early buckling of the gusset plates. It was shown that the gusset plates with STR exhibited similar strength in tension and compression and that adding STR resulted in improved energy dissipation capacity of the connection.

Naghypour et al. (2013) tested a single corner gusset plate with a W-shape bracing member. The thickness and dimensions of the gusset plate were $\frac{5}{16}$ in. by 19.7 in. by 19.7 in., respectively. The specimen failed due to buckling of the gusset plate.

Finite Element Data

Chakrabarti (1987) used linear and nonlinear finite element models to evaluate the compressive behavior and buckling strength of eight gusset plate connections previously tested by other researchers. Of the eight specimens, only three were corner brace connections and thus are considered in this research. It was shown that the inelastic finite element models accurately captured the behavior of the specimens and that the failure was due to the inelastic buckling of the gusset plates.

Cheng et al. (1994) developed finite element models of the gusset plate specimens tested by Cheng and Hu (1987) and showed that the models could reasonably predict the buckling load of the gusset plates observed during the tests. A parametric study was then conducted to investigate the effect of a number of parameters on the compressive capacity of the gusset plates such as length and thickness of the splicing member. It was found that extending the splicing member toward the beam and column would increase the buckling capacity of the gusset plates. Also, an increase in the thickness of the splice plate would result in increased buckling strength of the gusset plate.

Walbridge et al. (1998) used the finite element method to capture the compressive behavior of the gusset plates previously tested by Yam and Cheng (1993) and Rabinovitch and Cheng (1993), followed by a comprehensive parametric study investigating several parameters, including the effects of interaction between the gusset plate and bracing member and the effects of load sequence as well as the potential of the concept of weak gusset plate–strong brace proposed by Rabinovitch and Cheng (1993).

Sheng et al. (2002) conducted a comprehensive parametric study on the compressive strength of gusset plate connections using nonlinear finite element models. The study parameters included gusset plate geometry, thickness, splice length, and connection type between splice member and the gusset plate (i.e., welded versus bolted). It was recommended that the splice member should be welded to the gusset plate rather than bolted. Also, the authors suggested that the gusset plate can be shaped according to the 30° dispersion angle so that the length of the connection between the gusset plate and the supporting members can be reduced.

Naghipour et al. (2013) studied the compressive behavior of gusset plates with test-verified FE models. The researchers attempted to capture the compressive behavior of the corner gusset plate in the buckling restrained braced (BRB) frame by incorporating a large brace section into the models such that the buckling occurred in the gusset plates. A numerical investigation was carried out that studied several key design parameters such as plate thickness, plate geometry, and connection length.

Fang et al. (2015) conducted a comprehensive numerical investigation on the compressive behavior of gusset

plate connections with an emphasis on the post-buckling resistance. The primary objective of that research was to study the strength of relatively slender gusset plates commonly used in lightweight structures or in high-strength steel structures. Detailed finite element models were created and verified against eight experimental tests conducted by Yam and Cheng (1993) with good agreement. A comprehensive parametric study consisting of 108 FE models was conducted covering a wide range of parameters, including plate thickness, material properties, gusset plate thickness and dimensions, bolt spacing, and arrangements. Also, the effects of initial imperfection and material strain hardening were studied.

MODELING USING GENETIC PROGRAMMING

Genetic programming (GP), introduced by Koza (1992), is one of the most powerful machine learning techniques, which can be used to find relationships between variables in a dataset. In this technique, computer programs are encoded and evolved to solve or approximately solve problems using an evolutionary algorithm. Due to its superiority over traditional statistical models, GP has been gaining popularity among researchers in the past two decades. GP tools, which rely primarily on a valid database, have been used by a number of researchers to derive empirical predictive models for various structural engineering problems, including steel structures (e.g., Cevik, 2007a, 2007b). GP-based models can be very useful when the relationship between variables is quite complex or when mechanics-based equations become erroneous due to significant uncertainty. In this research, gene expression programming (GEP), which is an extended version of GP, is implemented to derive a relationship between compressive capacity and key properties of corner gusset plates.

Model Development

In order to develop an accurate predictive model, both geometrical variables and material properties of gusset plates were considered. A careful review of past experimental and numerical studies, as well as a sensitivity analysis of the database, revealed that the most important parameters affecting the compressive behavior of gusset plates are as follows: material yield strength, F_y ; plate thickness, t ; plate buckling length, L ; plate cantilever length, C ; connection length, L_c ; and fastener distance perpendicular to the brace axis, S . The geometric variables used in the models are shown in Figure 2. It should be recognized that the compressive capacity of gusset plates is also affected by other factors, such as initial imperfection and brace inclination angle. However, because the initial imperfections for the majority of specimens were not reported and because the out-of-plumbness

of the brace (and the gusset itself) is typically unknown before fabrication, the initial imperfection was accounted for implicitly. Also, Yam and Cheng (2002) reported that the brace angle had negligible effect on the ultimate capacity of the gussets. This was also confirmed with a sensitivity analysis of the database. Figure 3 shows histograms of different variables used in developing the GEP model.

Based on the preceding discussion, the ultimate compressive capacity of the corner gusset plates was considered to be a function of six parameters as follows:

$$P_u = f(F_y, t, L, C, L_c, S) \quad (1)$$

For model development purposes, the database was randomly divided into three categories: (1) learning data set, (2) validation data set, and (3) testing data set. The learning and validation data sets, referred to as training data, were used to develop the model, and the testing data set, referred to as unseen data, was used to evaluate the performance of the model with a set of data that was not used in the modeling process. Of the 205 data sets, 143, 31, and 31 data sets were used for learning, validation, and testing, respectively. To minimize the influence of random selection, three different combinations were generated for these categories. The genetic programming algorithms were implemented in GeneXproTools software (GEPSoft, 2013).

The most important parameters affecting the GEP predictive models are the number of programs (chromosomes), the number of terms or sub-ETs (genes), and the head size of the genes. These parameters, which determine the size, complexity, and precision of the models, were selected on the basis of trial and error and recommendation from previous researchers. It is recognized that due to the random nature of the GP algorithms, the optimum model is not typically achieved with a single run (Gandomi et al., 2011). As such, to achieve a model with minimal errors, numerous

runs were carried out by varying key parameters and criteria used in the algorithms. Table 1 presents a summary of the parameters used in the algorithms.

In order to select the best predictive model, the following objective function, which considers the performance of the models for both the learning and validation data sets, was defined (Gandomi et al., 2011) as:

$$OBJ = \left(\frac{n_L - n_V}{n_T} \right) \left(\frac{MAE_L}{R_L^2} \right) + \left(\frac{2n_V}{n_T} \right) \left(\frac{MAE_V}{R_V^2} \right) \quad (2)$$

where n_L , n_T , and n_V are the number of learning, training, and validation data sets, respectively. MAE_L and MAE_V are, respectively, the mean absolute error for learning and validation data sets, and R is the correlation coefficient, which can be calculated as follows:

$$MAE = \frac{\sum_{i=1}^n |u_i - t_i|}{n} \quad (3)$$

$$R = \frac{\sum_{i=1}^n (u_i - \bar{u}_i)(t_i - \bar{t}_i)}{\sqrt{\sum_{i=1}^n (u_i - \bar{u}_i)^2 \sum_{i=1}^n (t_i - \bar{t}_i)^2}} \quad (4)$$

where n is the number of samples, and u_i and t_i are the actual and computed values for the i th outputs, respectively. The average of the actual output values is \bar{u}_i , and the average of computed output values is \bar{t}_i . The best GEP model results in minimal value for the objective function, taking into account both the correlation coefficients and mean absolute errors. It should be noted that the R value alone is not a sufficient measure for evaluating the validity of the models. The outcome of the GEP algorithm is an expression tree (ET), which can be expressed as an empirical equation. In the model development and selection process, in addition to providing the best fitness values for the learning and validation data sets, attempts were made to avoid highly complex

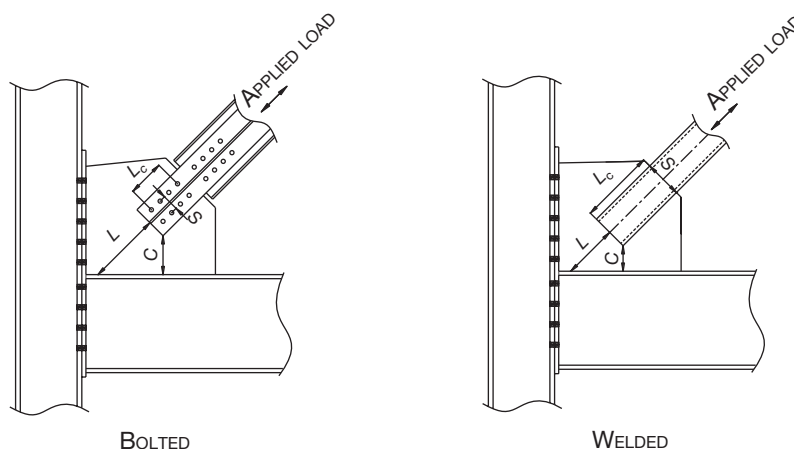


Fig. 2. Geometrical variables used in modeling process.

models. Figure 4 shows the expression tree (ET) for the best GEP model selected among all runs. The model consists of two sub-ETs, which are linked by the multiplication function. By substituting the terms into the model, the resulting empirical equation for estimating the compressive capacity of gusset plates takes the following formats in U.S. customary units and metric units, respectively:

$$P_u = \frac{(151.1t - 1.2)\sqrt{F_y L_c (2.94S^{1/3} + 5.04L^{1/2} + 2.63F_y^{1/2} - 14.43)}}{\left(8.98 + \frac{C}{t} + \frac{L_c}{L}\right)} \quad (5)$$

$$P_u = \frac{(2t - 0.4)\sqrt{F_y L_c (S^{1/3} + L^{1/2} + F_y^{1/2} - 14.43)}}{\left(8.98 + \frac{C}{t} + \frac{L_c}{L}\right)} \quad (5M)$$

where P_u is the nominal compressive strength of the gusset plate and all other terms were defined previously. The units of dimensions and yield strength are inches and ksi in Equation 5, and millimeters and MPa in Equation 5M. It is important to note that the preceding expressions are valid for the ranges of variables used in the training phase

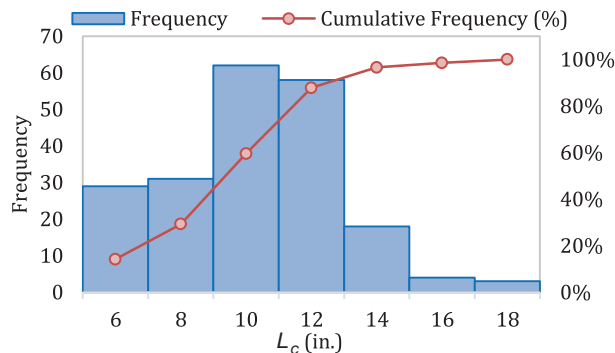
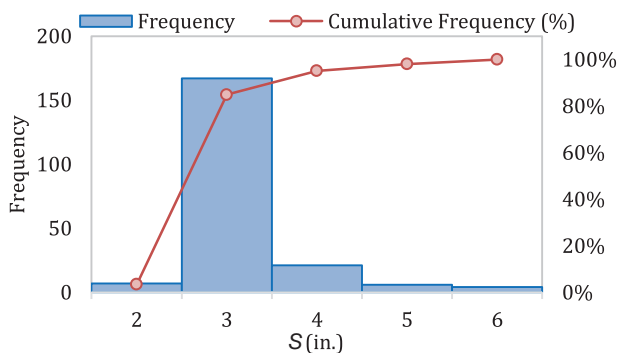
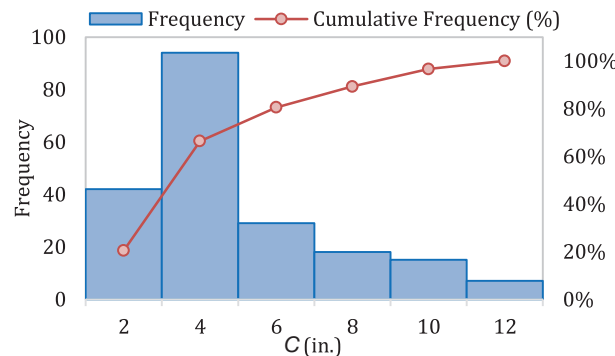
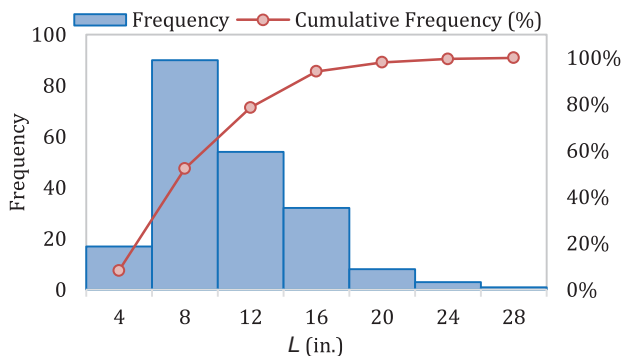
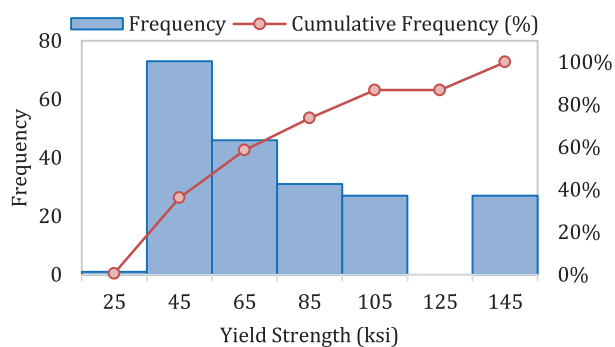
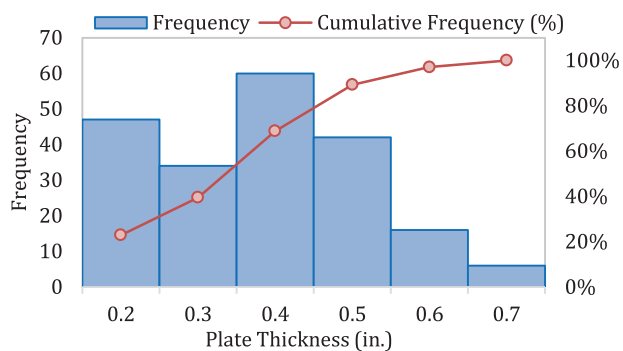


Fig. 3. Histograms of geometric and material properties of 205 gusset plate connections.

Parameter	Settings
Number of sub-ETs (genes)	1, 2, 3
Linking function	Addition, multiplication
Chromosomes	30, 50, 100
Head size	8, 9, 10, 12
Function set	+, -, ×, ÷, $\sqrt{\quad}$, $\sqrt[2]{\quad}$, $\sqrt[3]{\quad}$, $\sqrt[4]{\quad}$, ^2, ^3
Lower bound	-10
Upper bound	10
Number of variables	6
Gene size	26
Fitness function	RMSE

Model	R^2	MAE	MAPE (%)	RMSE	Mean $P_u/P_{calc.}$	STD $P_u/P_{calc.}$
GEP model	0.97	26.16	11.89	34.97	1.024	0.152
Thornton method ($K = 0.65$)	0.82	75.68	30.50	97.30	1.346	0.574
Thornton method ($K = 0.5$)	0.80	73.59	27.77	100.09	1.202	0.343
Dowswell (2006)	0.83	72.33	29.68	92.77	1.618	1.641

illustrated in Figure 3. These empirical equations allow for prediction of the compressive capacity of new gusset plate designs based on previously published test results via hand calculations. As such, they are recommended to be used in predesign and preliminary stages or in conjunction with the existing design methods.

Model Validation and Performance Evaluation

The accuracy of the predictive expression derived using the GEP technique was evaluated by several performance measures, including the coefficient of determination, R^2 ; mean absolute error, MAE; and root mean squared error, RMSE. Figure 5 shows the relationship between the estimated compressive strengths of gusset plates using Equation 5 and the actual experimental and FE values. As shown, R^2 and error values are quite close for the three categories of data sets, especially for the validation and testing data sets, indicating a good generalization capability of the empirical expression. The resulting high coefficients of determination, which are close to unity for all three sets of data, reveal a fairly good correlation between the estimated values and target compressive capacities.

Figure 6 shows the prediction performance of the GEP-based model together with the results of effective length factor method for 31 gusset plates considered as testing (or

unseen) data sets, which were not used in developing the model. The gusset plates used for testing purpose are a random selection of test specimens and finite element models. The vertical axis represents the target-to-predicted ratio of the compressive strengths, where the target values are the buckling capacity of gusset plates used for testing.

For comparison purpose, the compressive capacities of gusset plates were calculated using the column analogy method with effective length factors of 0.5 and 0.65 as well as those recommended by Dowswell (2006). As shown, the higher accuracy of the presented expression in predicting the target values is clearly illustrated in these graphs.

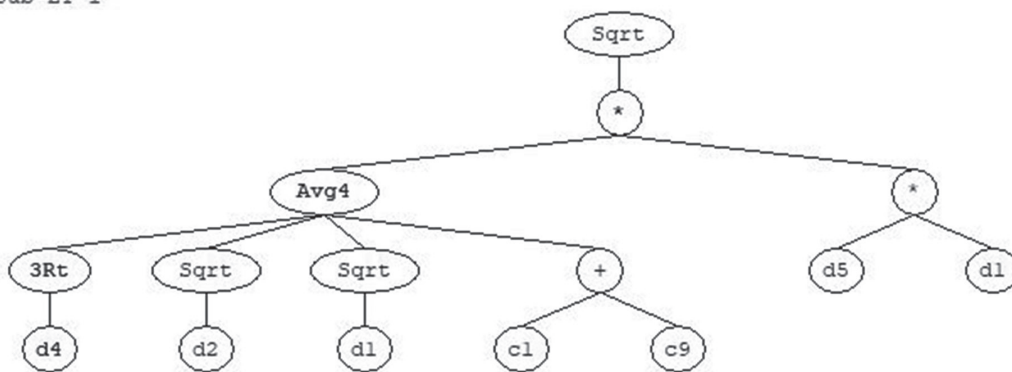
Figure 7 shows the correlation between the estimated and actual compressive strengths for all gusset plates considered in this study (whole sets of data) using the two approaches. The comparison indicates that the coefficient of determination for the proposed expression is significantly higher than those of the column analogy method with the different values of K factor considered in this research. Also, for the whole sets of data, both the mean absolute error and the root mean squared error for the GEP-based model are considerably less than those of the latter method.

Table 2 presents a summary of values for the performance measures used for model validation. As shown, the mean value of compressive strength to predicted strength ratios for the derived expression is very close to unity (1.024), with

a standard deviation of 0.152, while, as reported by previous researchers, the predicted values of the column analogy method are conservative for the majority of specimens. The best R^2 factor based on the column analogy method was 0.83 achieved using the recommended K factors from Dowswell (2006). The significantly lower error values and standard

deviations, as well as the higher correlation coefficient of the predicted buckling capacities using the presented empirical equation compared with the results of existing methods, indicate that this model is capable of predicting the ultimate strength of gusset plates with acceptable precision.

Sub-ET 1



Sub-ET 2

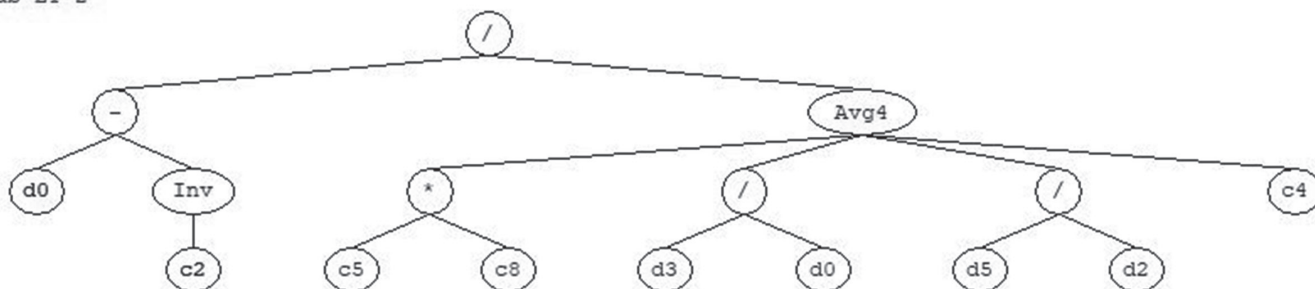


Fig. 4. Expression tree of the predictive model.

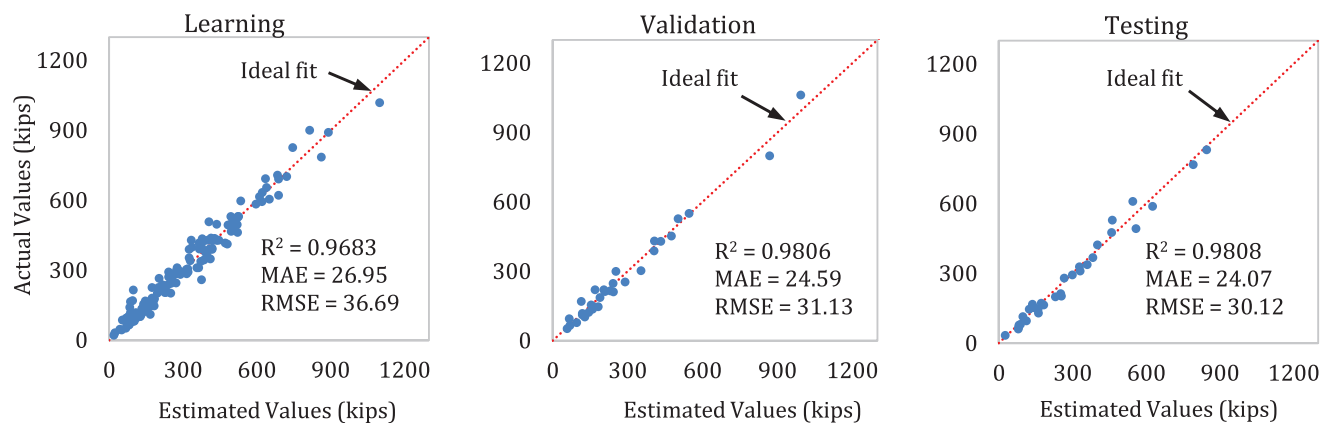


Fig. 5. Estimated compressive strength versus experimental/FE values for learning, validation, and testing data sets.

SUMMARY AND CONCLUSIONS

In this study, an evolutionary computing technique, called gene expression programming (GEP), was used to derive an empirical expression for predicting the compressive capacity of corner gusset plates. A simple yet accurate equation was derived based on a comprehensive database from past experimental and numerical research. For comparison purposes, the predicted values from this equation were compared with the results of the effective length factor method (Thornton method) commonly used in current design practice. The compressive strength of the gusset plates was separately calculated using effective length factors of 0.5, 0.65, and those recommended by Dowswell (2006). In comparison with the latter method, the proposed GEP-based model has a significantly better correlation with the experimental and FE data, and results in more consistent test-to-predicted ratios, with the mean value being 1.024 (STD = 0.152). For the 205 data sets used, the mean absolute percentage errors (MAPE) for the GEP-based formulation and Thornton method were, respectively, 11.9% and 27.8%, indicating a better prediction

performance of the presented equation. However, because the expression derived using the GEP algorithm is based purely on data, as in other empirical predictive models, it should be used only in the variable ranges studied in this paper. As such, it is not intended to replace the current design approach based on the column analogy method, but rather to serve as a cross check on the results of existing methods because it allows the designers to examine if their predicted values are consistent with the previously published test results and FE data. The proposed model can be a useful tool for assessing the compressive strength of gusset plates in preliminary and pre-design stages via hand calculation.

ACKNOWLEDGMENTS

This research program was funded by the C.W. Carry Chair in Steel Structures and the department of Civil and Environmental Engineering at the University of Alberta. The authors wish to thank Prof. Cheng Fang of Tongji University for providing their research database.

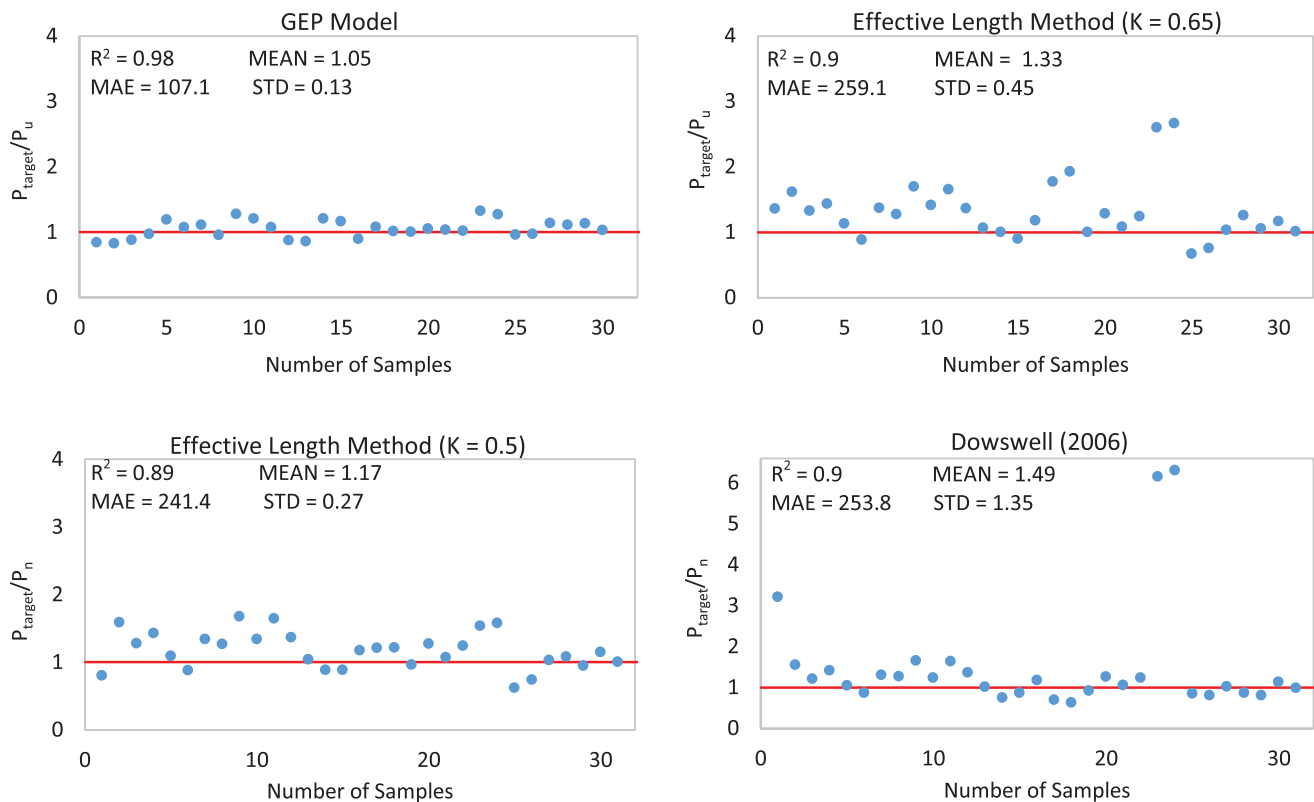


Fig. 6. Prediction performance of GEP-based expression for testing data sets and comparison with the effective length factor method.

REFERENCES

- Brown, V.L. (1988), "Stability of Gusseted Connections in Steel Structures," PhD Dissertation, University of Delaware, Newark, Del.
- Chakrabarti, S.K. (1987), "Inelastic Buckling of Gusset Plates," PhD Dissertation, University of Arizona, Tucson, Ariz.
- Cevik, A. (2007a), "A New Formulation for Longitudinally Stiffened Webs Subjected to Patch Loading," *Journal of Constructional Steel Research*, Vol. 63, pp. 1,328–1,340.
- Cevik, A. (2007b), "Genetic Programming Based Formulation of Rotation Capacity of Wide Flange Beams," *Journal of Constructional Steel Research*, Vol. 63, pp. 884–893.
- Chen, S.-J. and Chang, C.-C. (2012), "Experimental Study of Low Yield Point Steel Gusset Plate Connections," *Thin-Walled Structures*, Vol. 57, pp. 62–69.
- Cheng, J.J.R. and Hu, S.Z. (1987), "Comprehensive Tests of Gusset Plate Connections," *Proceedings of the 1987 Annual Technical Session*, Structural Stability Research Council, pp. 191–205.
- Cheng, J.J.R., Yam, M.C.H., and Hu, S. (1994), "Elastic Buckling Strength of Gusset Plate Connections," *Journal of Structural Engineering*, American Society of Civil Engineers, Vol. 120, No. 2, pp. 538–559.
- Dowswell, B. (2006), "Effective Length Factors for Gusset Plate Buckling," *Engineering Journal*, AISC, Vol. 43, No. 2, pp. 91–102.
- Fang, C., Yam, M.C.H., Zhou, X., and Zhang, Y. (2015), "Post-Buckling Resistance of Gusset Plate Connections: Behavior, Strength, and Design Considerations," *Engineering Structures*, Vol. 99, pp. 9–27.
- Ferreira, C. (2006), *Gene Expression Programming: Mathematical Modelling by an Artificial Intelligence*, 2nd Ed. Springer-Verlag, Germany.
- FHWA (2009), *Guidelines for Design and Rating of Gusset-Plate Connections for Steel Truss Bridges*, Federal Highway Administration, U.S. Department of Transportation, McLean, Va.

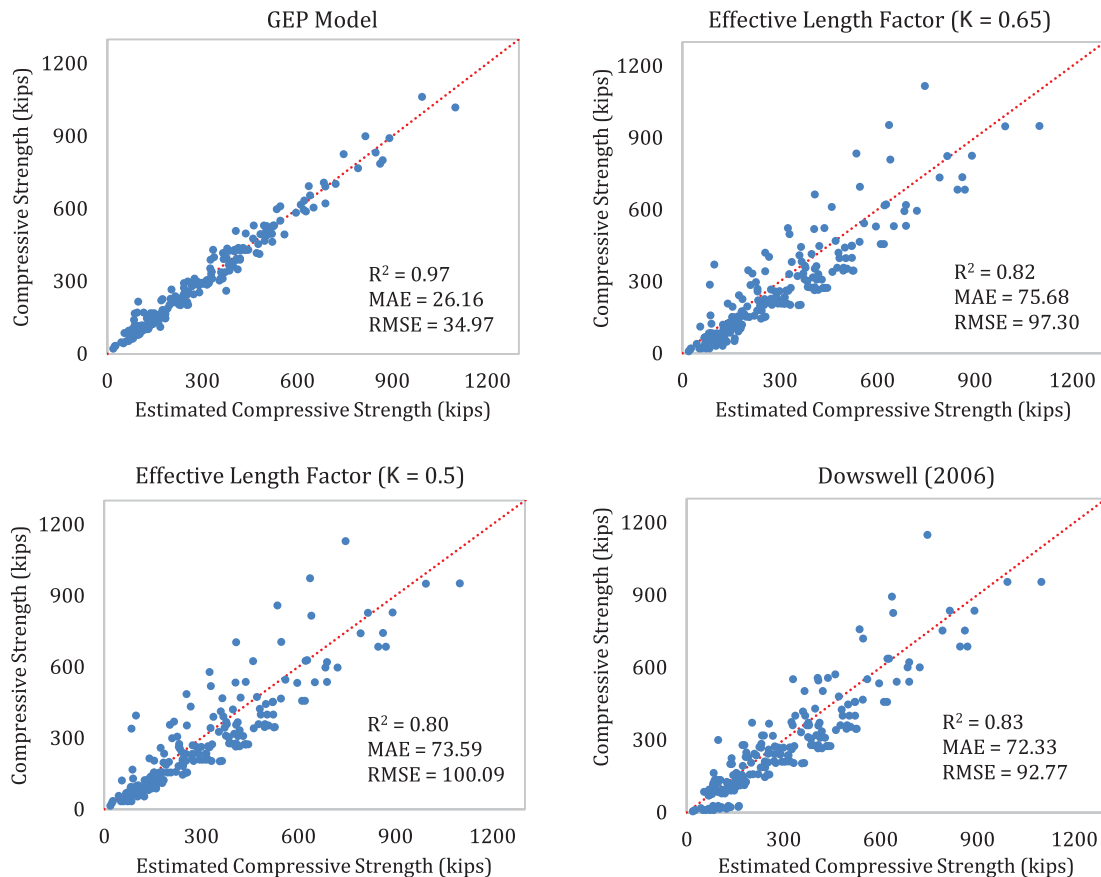


Fig. 7. Correlation of estimated and actual values of compressive capacity for the whole data.

- Gandomi, A.H., Tabatabaei, S.M., Moradian, M.H., Radfar, A., and Alavi, A.H. (2011), "A New Prediction Model for the Load Capacity of Castellated Steel Beams," *Journal of Constructional Steel Research*, Vol. 67, pp. 1,096–1,105.
- GEPSOFT (2013), GeneXproTools, Version 5.0.
- Gross, J.L. and Cheok, G. (1988), "Experimental Study of Gusseted Connections for Laterally Braced Steel Buildings," National Institute of Standards and Technology, Gaithersburg, Md., November.
- Koza, J.R. (1992), *Genetic Programming: On the Programming of Computers by Means of Natural Selection*. MIT Press, Cambridge, Mass.
- Naghipour, M., Abdollahzadeh, G., and Shokri, M. (2013), "Analysis and Design Procedure of Corner Gusset Plate Connections in BRBFs," *Iranica Journal of Energy and Environment*, Vol. 4, pp. 271–282.
- Nast, T.E., Grondin, G.Y., and Cheng, J.J.R. (1999), "Cyclic Behavior of Stiffened Gusset Plate Brace Member Assemblies," Structural Engineering Report No. 229, University of Alberta, Department of Civil and Environmental Engineering, Edmonton, Canada, December.
- Rabinovitch, J. and Cheng, J.J.R. (1993), "Cyclic Behavior of Steel Gusset Plate Connections," *Structural Engineering Report No. 191*, University of Alberta, Department of Civil and Environmental Engineering, Edmonton, Canada, August.
- Sheng, N., Yam, M.C.H., and Iu, V.P. (2002), "Analytical Investigation and the Design of the Compressive Strength of Steel Gusset Plate Connections," *Journal of Constructional Steel Research*, Vol. 58, pp. 1,473–1,493.
- Thornton, W.A. (1984), "Bracing Connections for Heavy Construction," *Engineering Journal*, AISC, Vol. 21, No. 3, pp. 139–148.
- Walbridge, S.S., Grondin, G.Y., and Cheng, J.J.R. (1998), "An Analysis of the Cyclic Behavior of Steel Gusset Plate Connections," Structural Engineering Report No. 225, University of Alberta, Department of Civil and Environmental Engineering, Edmonton, Canada, September.
- Whitmore, R.E. (1952), "Experimental Investigation of Stresses in Gusset Plates," Bulletin No. 16, University of Tennessee Engineering Experiment Station, Knoxville, Tenn., May.
- Yam, M.C.H., and Cheng, J.J.R. (1993), "Experimental Investigation of the Compressive Behavior of Gusset Plate Connections," *Structural Engineering Report No. 194*, University of Alberta, Department of Civil Engineering, Edmonton, Canada, September.
- Yam, M.C.H., and Cheng, J.J.R. (2002), "Behavior and Design of Gusset Plate Connections in Compression," *Journal of Constructional Steel Research*, Vol. 58, No. 5, pp. 1,143–1,159.

APPENDIX

Reference	ID	F_y (MPa)	t (mm)	L (mm)	C (mm)	L_c (mm)	S (mm)	P_u (kN)	P_T (kN)	P_{GEP} (kN)
Chakrabarti (1987)	1	248	6.35	203	72	102	76	305.59	281.81	418.23
	2	248	6.35	232	77	102	76	312.71	290.79	414.083
	3	248	6.35	203	74	102	76	317.6	295.08	412.00
Cheng and Hu (1987)	C1-Free	505	6.7	275	147	375	135	441.7	1642.99	956.17
	C2-Free	240	3.11	275	147	375	135	122.4	90.19	144.74
	C3-Free	505	6.7	487	297	375	135	380.1	1271.94	621.21
	C4-Free	240	3.11	487	297	375	135	89.6	34.26	88.26
Gross and Cheok (1988)	1A	321.99	6.35	171	25	102	76	515.99	359.83	752.98
	1B	321.99	6.35	171	25	102	76	427.03	359.83	752.98
	2A	321.99	6.35	178	27	102	76	613.85	379.85	741.76
	2B	321.99	6.35	178	27	102	76	658.34	379.85	741.76
	3B	321.99	6.35	199	30	102	76	391.44	375.32	733.21
Brown (1988)	1	330.95	6.38	146	32	114	102	800.68	476.12	736.14
	2	311.64	4.98	81	22	191	0	533.79	331.98	517.76
	3	311.64	5.03	146	32	114	102	444.82	335.15	504.98
	9	311.64	4.88	68	27	191	0	354.08	314.18	446.67
	10	311.64	5	84	23	191	0	487.08	333.65	520.19
	11	330.95	6.35	133	42	114	102	737.96	473.25	649.11
	13	330.95	6.3	105	47	114	102	620.08	469.25	584.58
	14	330.95	6.3	29	0	191	0	598.73	455.99	596.15
	15	330.95	6.35	121	34	114	102	685.92	474.80	689.64
	16	330.95	6.35	68	26	191	0	654.33	456.35	674.89
	17	311.64	4.93	147	32	114	102	533.79	326.02	491.27
	18	330.95	6.38	94	31	191	0	687.25	457.88	718.50
	20	310.26	9.55	72	37	191	0	783.33	649.55	1002.98
Rabinovitch and Cheng (1993)	A1	449	9.32	172	69	280	70	1682	1621.68	1759.24
	A2	443	6.18	172	69	280	70	1128	1001.62	945.17
	A5	449	9.32	336	185	280	70	907	1537.26	1178.62
Nast et al. (1999)	T2	424	9.61	166	53	280	70	1690	1584.85	1929.10
Yam and Cheng (1993; 2002)	GP1	295	13.3	167	66	210	68	1956	1212.64	1906.80
	GP2	305	9.8	167	66	210	68	1356	917.00	1281.83
	GP3	275	6.5	167	66	210	68	742	526.06	650.13
	SP1	295	13.3	452	267	350	68	1606	1815.16	1495.94
	SP2	305	9.8	452	267	350	68	1010	1316.22	903.35
	AP1	295	13.3	192	75	210	68	1720	1228.72	1887.65
	AP2	305	9.8	192	75	210	68	1210	929.96	1255.53
	AP3	275	6.5	192	75	210	68	728	536.09	628.18
	MP1	295	13.3	167	66	210	68	1933	1212.64	1906.80
	MP2	305	9.8	167	66	210	68	1316	917.00	1281.83

Reference	ID	F_y (MPa)	t (mm)	L (mm)	C (mm)	L_c (mm)	S (mm)	P_u (kN)	P_T (kN)	P_{GEP} (kN)
Yam and Cheng (1993; 2002)	MP3	275	6.5	167	66	210	68	721	526.06	650.13
	MP3A	275	6.5	167	66	210	68	819	526.06	650.13
	MP3B	275	6.5	167	66	210	68	821	526.06	650.13
Walbridge et al. (1998)	GP1B1	300	6	172	69	280	70	688	668.75	682.47
	GP1B3	300	6	172	69	280	70	692	668.75	682.47
	GP2B7	300	9	172	69	280	70	1292	1049.39	1252.49
	GP3B11	300	12	172	69	280	70	1793	1409.84	1876.12
Sheng et al. (2002)	1	295	13.3	237	115	140	68	1626	895.20	1377.94
	2	295	13.3	167	66	210	68	1987	1212.50	1906.80
	3	295	13.3	97	16	280	68	2349	1533.34	2352.94
	4	295	13.3	237	115	140	68	1595	889.59	1377.94
	5	295	13.3	167	66	210	68	1949	1209.39	1906.80
	6	295	13.3	97	16	280	68	2335	1530.07	2352.94
	7	305	9.87	237	115	140	68	1143	673.72	893.62
	8	305	9.87	167	66	210	68	1432	923.35	1294.82
	9	305	9.87	97	16	280	68	1867	1175.08	1726.17
	10	305	9.87	237	115	140	68	1122	666.39	893.62
	11	305	9.87	167	66	210	68	1402	915.30	1294.82
	12	305	9.87	97	16	280	68	1814	1166.58	1726.17
	13	275	6.5	237	115	140	68	509	360.65	421.88
	14	275	6.5	167	66	210	68	696	526.61	650.13
	15	275	6.5	97	16	280	68	989	693.35	978.90
	16	275	6.5	237	115	140	68	498	347.94	421.88
	17	275	6.5	167	66	210	68	666	504.96	650.13
	18	275	6.5	97	16	280	68	920	669.61	978.90
	19	295	13.3	237	115	140	68	1480	895.20	1377.94
	20	295	13.3	167	66	210	68	1793	1212.50	1377.94
	21	295	13.3	97	16	280	68	2208	1533.34	2352.94
	22	295	13.3	237	115	140	68	1232	895.22	1377.94
	23	295	13.3	167	66	210	68	1490	1212.50	1906.80
	24	295	13.3	97	16	280	68	2061	1509.76	2352.94
	25	305	9.87	237	115	140	68	878	673.76	893.62
	26	305	9.87	167	66	210	68	1082	923.35	1294.82
	27	305	9.87	97	16	280	68	1454	1156.93	1726.17
	28	275	6.5	237	115	140	68	404	360.77	421.88
	29	275	6.5	167	66	210	68	560	526.61	650.13
	30	275	6.5	97	16	280	68	765	682.36	978.90
Chen and Chang (2012)	E8t	100	17	300	141	240	100	1084	642.19	1205.972
Naghipour et al. (2013)	Test	300	8	377	196	140	90	403.3	546.12	488.942
	1	300	4	377	196	140	90	112.72	67.71	138.232

Reference	ID	F_y (MPa)	t (mm)	L (mm)	C (mm)	L_c (mm)	S (mm)	P_u (kN)	P_T (kN)	P_{GEP} (kN)
Naghipour et al. (2013)	2	300	4	307	146	210	90	201.07	173.29	206.282
	3	300	4	237	97	280	90	368.75	368.48	305.592
	4	300	4	167	47	350	90	750.64	574.12	486.302
	5	300	8	519	296	140	90	247.11	492.29	379.68
	6	300	8	449	246	210	90	391.43	699.10	520.71
	7	300	8	379	197	280	90	625.45	921.35	682.21
	8	300	8	309	147	350	90	1032.25	1148.49	886.56
	9	300	8	239	98	420	90	1677.35	1369.60	1151.31
	10	300	12	499	204	140	90	893.18	869.06	1004.03
	11	300	12	429	164	210	90	1428.89	1162.80	1357.01
	12	300	12	359	124	280	90	1867.46	1463.94	1746.60
	13	300	12	289	84	350	90	2156.27	1766.18	2196.34
	14	300	12	219	44	420	90	2433.37	2066.45	2708.55
	15	300	16	673	304	140	90	1219.83	1179.57	1326.19
	16	300	16	603	264	210	90	1819.91	1564.75	1735.36
	17	300	16	533	224	280	90	2228.95	1957.76	2150.58
	18	300	16	463	184	350	90	2657.41	2352.69	2591.89
	19	300	16	393	144	420	90	3069.46	2748.29	3071.10
	Fang et al. (2015)	G1T4P48S355	355	4	205	92	192	68	318.47	200.89
G1T4P48S460		460	4	205	92	192	68	372.58	210.52	346.12
G1T4P48S690		690	4	205	92	192	68	488.45	209.79	462.36
G1T4P48S960		960	4	205	92	192	68	612.44	209.79	586.36
G1T4P55S355		355	4	167	65	220	68	388.977	301.36	370.44
G1T4P55S460		460	4	167	65	220	68	456.721	345.19	446.60
G1T4P55S690		690	4	167	65	220	68	606.764	395.22	599.34
G1T4P55S960		960	4	167	65	220	68	772.8	401.02	762.56
G1T4P65S355		355	4	127	37	260	68	601.914	438.74	506.47
G1T4P65S460		460	4	127	37	260	68	686.954	539.86	613.36
G1T4P65S690		690	4	127	37	260	68	853.758	723.08	828.21
G1T4P65S960		960	4	127	37	260	68	1069.83	880.76	1058.23
G1T8P48S355		355	8	205	92	192	68	1027.31	787.47	908.47
G1T8P48S460		460	8	205	92	192	68	1216.44	1006.93	1091.61
G1T8P48S690		690	8	205	92	192	68	1465.9	1467.13	1458.21
G1T8P48S960		960	8	205	92	192	68	1629.49	1972.76	1849.28
G1T8P55S355		355	8	167	65	220	68	1083.01	890.96	1095.39
G1T8P55S460		460	8	167	65	220	68	1274.1	1145.62	1320.60
G1T8P55S690		690	8	167	65	220	68	1504	1689.66	1772.25
G1T8P55S960		960	8	167	65	220	68	1810.3	2304.70	2254.865
G1T8P65S355		355	8	127	37	260	68	1400.82	1033.76	1346.36
G1T8P65S460		460	8	127	37	260	68	1711.59	1335.20	1630.51
G1T8P65S690		690	8	127	37	260	68	2320.42	1988.67	2201.63
G1T8P65S960		960	8	127	37	260	68	2772	2743.95	2813.11

Reference	ID	F_y (MPa)	t (mm)	L (mm)	C (mm)	L_c (mm)	S (mm)	P_u (kN)	P_T (kN)	P_{GEP} (kN)
Fang et al. (2015)	G1T12P48S355	355	12	205	92	192	68	1747.31	1224.50	1673.79
	G1T12P48S460	460	12	205	92	192	68	2124.58	1582.52	2011.21
	G1T12P48S690	690	12	205	92	192	68	2900.86	2360.20	2686.65
	G1T12P48S960	960	12	205	92	192	68	3529.45	3261.70	3407.17
	G1T12P55S355	355	12	167	65	220	68	1846.1	1364.68	1942.53
	G1T12P55S460	460	12	167	65	220	68	2244.68	1765.62	2341.90
	G1T12P55S690	690	12	167	65	220	68	3047.47	2639.62	3142.84
	G1T12P55S960	960	12	167	65	220	68	3630.5	3658.17	3998.69
	G1T12P65S355	355	12	127	37	260	68	2236.09	1564.30	2259.10
	G1T12P65S460	460	12	127	37	260	68	2722.38	2025.69	2735.88
	G1T12P65S690	690	12	127	37	260	68	3772.88	3034.28	3694.175
	G1T12P65S960	960	12	127	37	260	68	4425.8	4214.69	4720.22
	G2T4P48S355	355	4	369	208	240	68	234.093	85.80	189.56
	G2T4P48S460	460	4	369	208	240	68	267.511	85.80	225.70
	G2T4P48S690	690	4	369	208	240	68	326.182	85.80	297.60
	G2T4P48S960	960	4	369	208	240	68	378.112	85.80	373.84
	G2T4P55S355	355	4	324	176	275	68	305.734	138.34	227.19
	G2T4P55S460	460	4	324	176	275	68	359.391	138.34	271.04
	G2T4P55S690	690	4	324	176	275	68	462.057	138.34	358.40
	G2T4P55S960	960	4	324	176	275	68	555.734	138.34	451.17
	G2T4P65S355	355	4	274	141	325	68	367.881	269.91	284.62
	G2T4P65S460	460	4	274	141	325	68	438.521	271.84	340.43
	G2T4P65S690	690	4	274	141	325	68	582.854	271.84	451.82
	G2T4P65S960	960	4	274	141	325	68	724.178	271.84	570.33
	G2T8P48S355	355	8	369	208	240	68	689.756	859.94	672.81
	G2T8P48S460	460	8	369	208	240	68	779.976	1072.10	801.09
	G2T8P48S690	690	8	369	208	240	68	963.185	1477.79	1056.27
	G2T8P48S960	960	8	369	208	240	68	1137.19	1861.80	1326.91
	G2T8P55S355	355	8	324	176	275	68	826.217	1001.34	788.43
	G2T8P55S460	460	8	324	176	275	68	936.766	1263.22	940.59
	G2T8P55S690	690	8	324	176	275	68	1193.58	1786.87	1243.74
	G2T8P55S960	960	8	324	176	275	68	1450.62	2320.64	1565.70
	G2T8P65S355	355	8	274	141	325	68	1034.62	1193.31	954.44
	G2T8P65S460	460	8	274	141	325	68	1140.27	1522.27	1141.59
	G2T8P65S690	690	8	274	141	325	68	1470.6	2206.49	1515.12
	G2T8P65S960	960	8	274	141	325	68	1819.72	2948.87	1912.51
	G2T12P48S355	355	12	369	208	240	68	1579.45	1432.30	1344.85
	G2T12P48S460	460	12	369	208	240	68	1774.92	1841.85	1601.26
	G2T12P48S690	690	12	369	208	240	68	2051.31	2717.02	2111.33
	G2T12P48S960	960	12	369	208	240	68	2385.87	3706.81	2652.29
G2T12P55S355	355	12	324	176	275	68	1838.42	1615.21	1549.66	
G2T12P55S460	460	12	324	176	275	68	2101.79	2081.91	1848.73	

Reference	ID	F_y (MPa)	t (mm)	L (mm)	C (mm)	L_c (mm)	S (mm)	P_u (kN)	P_T (kN)	P_{GEP} (kN)
Fang et al. (2015)	G2T12P55S690	690	12	324	176	275	68	2437.76	3086.881	2444.57
	G2T12P55S960	960	12	324	176	275	68	2833.76	4236.761	3077.39
	G2T12P65S355	355	12	274	141	325	68	2141.99	1867.57	1830.77
	G2T12P65S460	460	12	274	141	325	68	2494.34	2412.48	2189.74
	G2T12P65S690	690	12	274	141	325	68	2852.31	3594.31	2906.23
	G2T12P65S960	960	12	274	141	325	68	3324.18	4961.21	3668.48
	G3T4P48S355	355	4	233	91	192	68	371.034	212.18	297.24
	G3T4P48S460	460	4	233	91	192	68	437.266	225.97	356.43
	G3T4P48S690	690	4	233	91	192	68	575.427	227.08	474.77
	G3T4P48S960	960	4	233	91	192	68	719.009	227.08	600.87
	G3T4P55S355	355	4	195	72	220	68	397.926	316.73	358.28
	G3T4P55S3460	460	4	195	72	220	68	470.737	368.18	430.85
	G3T4P55S690	690	4	195	72	220	68	629.87	435.35	576.19
	G3T4P55S960	960	4	195	72	220	68	801.044	455.37	731.30
	G3T4P65S355	355	4	155	52	260	68	568.928	456.12	446.89
	G3T4P65S460	460	4	155	52	260	68	646.998	567.72	539.43
	G3T4P65S690	690	4	155	52	260	68	820.584	779.77	725.13
	G3T4P65S960	960	4	155	52	260	68	1044.14	978.29	923.67
	G3T8P48S355	355	8	233	91	192	68	1088.63	790.16	937.53
	G3T8P48S460	460	8	233	91	192	68	1300.07	1011.40	1124.22
	G3T8P48S690	690	8	233	91	192	68	1659.82	1476.91	1497.46
	G3T8P48S960	960	8	233	91	192	68	1879.22	1991.07	1895.17
	G3T8P55S355	355	8	195	72	220	68	1127.05	893.73	1081.45
	G3T8P55S3460	460	8	195	72	220	68	1338.31	1150.24	1300.51
	G3T8P55S690	690	8	195	72	220	68	1640	1699.91	1739.22
	G3T8P55S960	960	8	195	72	220	68	1950.7	2324.17	2207.41
	G3T8P65S355	355	8	155	52	260	68	1407.39	1036.27	1264.41
	G3T8P65S460	460	8	155	52	260	68	1718.7	1339.41	1526.23
	G3T8P65S690	690	8	155	52	260	68	2324.81	1998.08	2051.64
	G3T8P65S960	960	8	155	52	260	68	2793.99	2762.02	2613.39
	G3T12P48S355	355	12	233	91	192	68	1819.98	1225.33	1727.41
	G3T12P48S460	460	12	233	91	192	68	2214.06	1583.91	2071.39
	G3T12P48S690	690	12	233	91	192	68	3069.19	2363.30	2759.11
	G3T12P48S960	960	12	233	91	192	68	3838.68	3267.65	3491.89
	G3T12P55S355	355	12	195	72	220	68	1913.44	1365.52	1940.52
	G3T12P55S460	460	12	195	72	220	68	2326.19	1767.03	2333.59
	G3T12P55S690	690	12	195	72	220	68	3214.68	2642.77	3120.80
	G3T12P55S960	960	12	195	72	220	68	3969.37	3664.25	3960.91
	G3T12P65S355	355	12	155	52	260	68	2262.95	1565.05	2189.05
	G3T12P65S460	460	12	155	52	260	68	2765.05	2026.95	2642.34
G3T12P65S690	690	12	155	52	260	68	3875.47	3037.11	3551.98	
G3T12P65S960	960	12	155	52	260	68	4892.97	4220.16	4524.53	