A new formulation for rotation of bare-steel joints at elevated temperatures using genetic programming

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Abstract

This study presents an original application of Genetic Programming (GP) for the formulation of rotation capacity of bare-steel joints at elevated temperatures for the first time in the literature. The proposed GP model is based on an experimental database obtained as a result of a wide range of experimental study. The rotation is obtained as a function of joint’s temperature, the applied moment, material properties such as the yield strength of the joint’s components and the geometry of the beams, the column, the end-plates and the bolts. The proposed GP model fits actual experimental results with a very high accuracy. The proposed model is practical to be used by further researchers.

*Keywords*: bare-steel, semi-rigid joints, genetic programming, elevated temperature, rotation

1 Introduction

The mechanical properties of steel degrade rapidly with increasing temperatures causing lose of both stiffness and load carrying capacity of steel’s structural members and leading in severe cause to the collapse of the structure. In a steel framed structure, joints play a critical role in controlling fire induced progressive structural collapse due to the presence of axial restraints offered to the connecting beam by the surrounding structure. To improve understanding of the effects of joints on steel framed structural behaviour in fire and to help design better joints to minimise fire induced structural collapse, the use of numerical modelling in predicting the joint’s behaviour has become popular as a viable alternative to the high cost experimental testing. Recently soft computing techniques have arisen as an alternative approach in this field as a robust modelling tool. Among these soft computing techniques, Neural Network (NN) models have been developed to predict the connection behaviour at elevated temperatures (Al-Jabri et al. 2009; Al-Jabri and Al-Alawi 2007). On the other hand, there has also been attempt to use another soft computing technique, namely as genetic programming for the formulation of various parameters of steel structures (Guzeleby 2007; Cevik 2007a; Cevik 2007b). However there is an obvious lack of application regarding the use of soft computing techniques in modelling the fire performance of steel structures.

This paper presents a new GP-based formulation to compute the behaviour of semi-rigid bare-steel unstiffened joints under fire conditions. The developed GP model can be used for similar connections under fire by observing various factors influencing the connection's behaviour such as: (a) geometrical factors (i.e., member sizes), (b) material factors (i.e., strength and stiffness), and (c) loading conditions (i.e., static and fire). The proposed GP model is presented as a mathematical function that can be practically used by researchers. This model can be used to compute the rotational capacity of
the connection and the contribution of individual components of the connection as well as the contribution of the loading to the overall connection's behaviour without conducting costly fire tests.

2 Genetic programming (GP)

Genetic programming (GP) proposed by Koza (Koza, 1992) is an extension to Genetic Algorithms (GA). Koza defines GP as a domain-independent problem-solving approach in which computer programs are evolved to solve, or approximately solve, problems based on the Darwinian principle of reproduction and survival of the fittest and analogs of naturally occurring genetic operations such as crossover (sexual recombination) and mutation (Figure 1).

![Genetic Programming Flowchart (Koza, 1992).](image)

Gene expression programming (GEP) software which is used in this study is an extension to GP that evolves computer programs of different sizes and shapes encoded in linear chromosomes of fixed length. The chromosomes are composed of multiple genes, each gene encoding a smaller sub-program. Furthermore, the structural and functional organization of the linear chromosomes allows the unconstrained operation of important genetic operators such as mutation, transposition, and recombination (Ferreira, 2001). APS 3.0, a GEP software developed by Candida Ferreira, is used in this study.

The fundamental difference between GA, GP and GEP is due to the nature of the individuals: in GAs the individuals are linear strings of fixed length (chromosomes); in GP the individuals are nonlinear entities of different sizes and shapes (parse trees); and in GEP the individuals are encoded
as linear strings of fixed length (the genome or chromosomes) which are afterwards expressed as nonlinear entities of different sizes and shapes (i.e., simple diagram representations or expression trees). Thus the two main parameters GEP are the chromosomes and expression trees (ETs). Two languages are utilized in GEP: the language of the genes and the language of ETs. A significant advantage of GEP is that it enables to infer exactly the phenotype given the sequence of a gene, and vice versa which is termed as Karva language.

For each problem, the type of linking function, as well as the number of genes and the length of each gene, are a priori chosen for each problem. While attempting to solve a problem, one can always start by using a single-gene chromosome and then proceed by increasing the length of the head. If it becomes very large, one can increase the number of genes and obviously choose a function to link the sub-ETs. One can start with addition for algebraic expressions or for Boolean expressions, but in some cases another linking function might be more appropriate (like multiplication or IF, for instance). The idea, of course, is to find a good solution, and GEP provides the means of finding one very efficiently.

3 Experimental database-geometry of the joints

The cruciform bolted beam-to-column steel joints tested experimentally (Leston-Jones, 1997; Al-Jabri et al., 2005) were considered for the construction of the experimental database. Two of the joints (Fire1 and Fire2) have the same member sizes but different end-plate thicknesses whilst the third joint (Fire3) has larger member sizes. The first two joints consist of two 254x102UB22 beams connected to a 152x152UC23 column using six M16 bolts and 8 mm (Figure 2) and 12 mm thick flush end-plates for Fires1 and 2, respectively. The third joint (Fire3) comprised a pair of 356 x 171UB51 beams connected to a 254 x 254UC89 column by 10 mm thick flush end-plates with eight M20 Grade 8.8 bolts. The fourth joint is a flexible end-plate joint with beam and column sizes similar to Fire3 but the end-plates dimension is different. In total fifteen elevated temperature tests were modelled with 331 and 61 cases were used for training and testing the proposed model, respectively.

Figure 2. Flush end-plate joint detail for Fire1 tests (FR1).
4 Development of the GP model

The main focus of this study is the formulation of rotation capacity of bare-steel joints at elevated temperatures using Genetic Programming based on the experimental database given in section 4. The rotation will be obtained as a function of the following parameters:

- joint’s temperature,
- the applied moment,
- material properties such as the yield strength of the joint’s components and
- the geometry of the beams, the column, the end-plates and the bolts.

Sixteen different input parameters were used to model the joint’s moment-rotation-temperature response. In the development of GP model, a training set consisting of 331 cases was utilized that were obtained from the experimental data and a testing of 61 cases that were selected randomly from the experimental data. Typical training patterns used as part of the training data set and their ranges with basic statistics is shown in Tables 1.

<table>
<thead>
<tr>
<th>Testing Parameters</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Std.Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment (M), KNm</td>
<td>24.8413</td>
<td>4.40</td>
<td>110.00</td>
<td>28.3307</td>
</tr>
<tr>
<td>Temperature (T), ºC</td>
<td>359.2003</td>
<td>13.71</td>
<td>766.55</td>
<td>218.8217</td>
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<tr>
<td>Beam depth (Db), mm</td>
<td>289.5561</td>
<td>254.0</td>
<td>355.00</td>
<td>48.2999</td>
</tr>
<tr>
<td>Beam width (Bb), mm</td>
<td>126.2077</td>
<td>101.60</td>
<td>171.50</td>
<td>33.4274</td>
</tr>
<tr>
<td>Beam flange thickness (Tb),mm</td>
<td>8.4546</td>
<td>6.80</td>
<td>11.50</td>
<td>2.2476</td>
</tr>
<tr>
<td>Beam web thickness (tb), mm</td>
<td>6.2985</td>
<td>5.7</td>
<td>7.40</td>
<td>0.8130</td>
</tr>
<tr>
<td>Beam yield Strength (py), N/mm²</td>
<td>353.6837</td>
<td>322.0</td>
<td>412.0</td>
<td>43.0395</td>
</tr>
<tr>
<td>Column depth (Dc), mm</td>
<td>190.3852</td>
<td>152.40</td>
<td>260.30</td>
<td>51.5996</td>
</tr>
<tr>
<td>Column width(Bc), mm</td>
<td>188.8474</td>
<td>152.20</td>
<td>256.30</td>
<td>49.7824</td>
</tr>
<tr>
<td>Column flange thickness (Tc), mm</td>
<td>10.4964</td>
<td>6.80</td>
<td>17.30</td>
<td>5.0213</td>
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<td>Column web thickness (tc), mm</td>
<td>7.3842</td>
<td>5.80</td>
<td>10.30</td>
<td>2.1520</td>
</tr>
<tr>
<td>No of bolts in each row (Nb)</td>
<td>3.3520</td>
<td>3.0</td>
<td>4.0</td>
<td>0.4782</td>
</tr>
<tr>
<td>Bolt diameter (db), mm</td>
<td>17.4082</td>
<td>16.0</td>
<td>20.0</td>
<td>1.9129</td>
</tr>
<tr>
<td>End-plate thickness (tp), mm</td>
<td>10.0051</td>
<td>8.0</td>
<td>12.0</td>
<td>1.7837</td>
</tr>
<tr>
<td>End-plate width (Bp),mm</td>
<td>145.3061</td>
<td>130.0</td>
<td>190.0</td>
<td>23.8582</td>
</tr>
<tr>
<td>End-plate depth (Dp), mm</td>
<td>287.0026</td>
<td>260.0</td>
<td>375.0</td>
<td>44.9994</td>
</tr>
</tbody>
</table>

The GP formulation is obtained as follows:

\[
\Phi = K1* K2* K3* K4* K5* K6 \\
\Phi = \text{Rotation (milirad)} \\
K1 = \frac{M}{(\text{atan}(\sqrt{\text{atan}(4.72)})^\text{(T^((1.0/9.0)))}} \\
K2 = \text{Db*db*(db-((1.704-Dp-Tb)+(M-Tb)+T))};
\]
K3 = (T - (Bb + (tp * sqrt(py)) * (py / T/M) * db));
K4 = (Tc/db/(((py + tb)^(1.0/3.0)) + cos(M));
K5 = ((sin((6.24 * T)) * (T / (Db/Tb/6.24)))) + T);
K6 = ((-5.86 - T - M - tp) * tc)/tb/(Bb*Bp*Bp*Tb)/(Dp*(-5.86)*Bp));

Statistical parameters of testing and training sets and overall results of GP model are presented in Table 2. The GP results vs. actual test results are presented in Figure 6. GP results are observed to be very close to actual test results.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>COV</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing Set</td>
<td>1.37</td>
<td>0.98</td>
<td>0.79</td>
</tr>
<tr>
<td>Training Set</td>
<td>1.27</td>
<td>0.71</td>
<td>0.92</td>
</tr>
<tr>
<td>Overall</td>
<td>1.29</td>
<td>0.85</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Figure 3. Comparison between predicted and experimental results

5 Conclusion

This paper proposes a new empirical formulation for the computation of rotation of bare-steel joints at elevated temperatures using Genetic Programming in terms of temperature, moment, number of bolts, material characteristics such as yield strength and geometry of beams, columns and end plates. The database for used for GP modeling is obtained as a result of a wide range of experimental study. The predictions of proposed GP model is observed to be quite accurate compared to test results (R²=0.89). The GP model presented in this study is given in an explicit form as simple mathematical functions for further use. Researchers can practically use this GP model safely for the prediction of rotation of bare-steel joints at elevated temperatures.
References


