FINITE ELEMENT ANALYSIS OF DOUBLE ANGLE TRUSS CONNECTIONS

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ABSTRACT: Shear lag can be described as a phenomenon that creates a loss in resistance in a tension member connected through only part of its cross-section. It is a complex problem which has been under study for many years by researchers. Parameters that influence the shear lag phenomenon are many and difficult to assess: type and size of cross-section, type of connection, length of welds, length of member, joint eccentricities, etc.

Connections between double-angle web members and chords in trusses or open web steel joist are considered herein. Finite element analyses of such connections were done using ANSYS with solid elements and non linear material. Comparisons between calculated stresses and strain gauge readings from tests done previously by the authors show excellent agreement, both at the yield and ultimate load levels. A parametric study of the connections using finite element analyses is described, and the influence of the different parameters is established. Finally, tentative conclusions are drawn regarding the influence of shear lag in double angle truss connections.

1. INTRODUCTION

Steel trusses fabricated with double-angle web members are considered herein, in which joints are made economically by welding one leg of the web angles directly to the chord member. Figure 1 shows such a truss and Figure 2 shows the welded connection under study. Tension web members are designed using Clause 13.2 of Canadian Standard S16-01 Limit States Design of Steel Structures (CSA 2001) in which shear lag is taken into account. Shear lag is a phenomenon that affects tension members connected at their ends through only part of the cross-section. Tensile stresses are transferred from the member into the connected parts and the stress distribution along the connection is non linear, resulting in a loss of strength.

Laboratory tests on simplified specimens were carried out recently by the authors (Benaddi and Bauer 2002, Bauer and Benaddi 2002b). Six specimens were tested with double-angle members ranging in size from 2-L38x38x4.8 up to 2-L76x76x4.8. The test set-up is shown in Figure 3. The main test parameters are shown in Table 1. Specimens had an overall length of 2500 mm, the longest possible that would fit conveniently in the testing machine, which left a clear length for the double-angle member of over one meter between connections. All specimens were instrumented with eight strain gauges. Figure 4 shows a test specimen at failure and Figure 5 shows the strain gauge locations.

A literature review on the subject of shear lag in steel welded connections, a summary of the Canadian code requirements together with a numerical example, as well as a description of the six laboratory tests are given elsewhere (Bauer and Benaddi 2002a).
Table 1. Main test parameters for ÉTS specimens.

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</thead>
<tbody>
<tr>
<td>ÉTS-1</td>
<td>2L-38 x 38 x 4.8</td>
<td>Equal Legs</td>
<td>340</td>
<td>5</td>
<td>87</td>
</tr>
<tr>
<td>ÉTS-2</td>
<td>2L-51 x 51 x 4.8</td>
<td>Equal Legs</td>
<td>461</td>
<td>5</td>
<td>112</td>
</tr>
<tr>
<td>ÉTS-3</td>
<td>2L-64 x 51 x 4.8</td>
<td>Short Legs Back to Back</td>
<td>521</td>
<td>5</td>
<td>122</td>
</tr>
<tr>
<td>ÉTS-4</td>
<td>2L-64 x 64 x 4.8</td>
<td>Equal Legs</td>
<td>582</td>
<td>5</td>
<td>136</td>
</tr>
<tr>
<td>ÉTS-5</td>
<td>2L-76 x 51 x 4.8</td>
<td>Short Legs Back to Back</td>
<td>582</td>
<td>5</td>
<td>138</td>
</tr>
<tr>
<td>ÉTS-6</td>
<td>2L-76 x 76 x 4.8</td>
<td>Equal Legs</td>
<td>703</td>
<td>5</td>
<td>169</td>
</tr>
</tbody>
</table>

2. FINITE ELEMENT MODEL

Single web member angles corresponding to simplified specimens Nos. ÉTS-1 to ÉTS-6 were modeled using finite elements in order to study the stress distribution at the connection, evaluate the decrease in resistance due to shear lag effects and compare results with those of the laboratory tests. Analyses were conducted using the ANSYS program that included material and geometric non linearity due to plasticity and large displacements.

The element used to model the angles was SOLID45, suitable for plastic analysis, a three dimensional element defined by eight nodes having three degrees of freedom at each node. Input data for the SOLID45 element includes Young’s modulus, Poisson’s ratio and the non linear stress-strain curve of the material. A typical stress-strain curve, shown in Figure 6, obtained from coupon tests of the steel angles was used as material properties for the finite element models.

Output data for the SOLID45 element includes the average plastic strain and equivalent stress. With ANSYS, several options are available for describing plastic behaviour and, in the present study, a Multilinear Isotropic Hardening (MISO) was chosen, which uses the Von Mises yield criterion coupled with an isotropic work hardening assumption, as recommended for large strain analysis.

The Newton-Raphson approach was used in which the load is subdivided into a series of load increments applied over several load steps. Within each load step, ANSYS performed several solutions or sub steps, with several equilibrium iterations at each sub step in order to obtain a converged solution. The program checked for convergence at each load step and iterated until the final solution converged. The load was divided into several load steps and hence was applied gradually as in the laboratory tests.

3. ANALYTICAL RESULTS

The finite element model for specimen ÉTS-1 is shown in Figure 7. The model is twice the length of the longitudinal weld, that is, sufficiently long for obtaining a uniform stress distribution away from the connection according to St. Venant’s principle. The model is quite shorter than the laboratory specimen, and comparisons with longer models will be made in order to establish the effect of the length parameter.

Load was applied to the model as pressure on the surface of the element faces at one end of the angle. The welded connection was modelled at the other end as fixed supports along the toe and the heel of the angle. The width and length of the supports matched those of the welds in the test specimens.

Longitudinal strains and von Mises stresses at the last load step for specimen ÉTS-1 are shown in Figures 8 and 9, respectively. Longitudinal strains from the finite element analysis are compared with
strain gauge readings from the laboratory tests at location 1 and 8 (Figure 5) and are found to be in excellent agreement. See Figures 10 and 11.

In the finite element analyses, the ultimate strength, $F_{u,\text{FEA}}$, was defined as the pressure applied at the loaded end of the angle at the last load step, that is, at which the iteration still converged. Comparison between the strength of coupons taken from laboratory specimens Nos. ÉTS-1 to 6 and the strength obtained from finite element analyses are shown in Table 2. Values of $F_{u,\text{FEA}}/F_{y,c} - 1$, ranging from 1% to 11% for tests Nos. ÉTS-1, 5 and 6, confirm that the finite element analyses were all carried out past yield. Values of $1 - F_{u,\text{FEA}}/F_{u,c}$, ranging from 25% to 27%, represent the loss in strength due to shear lag as predicted by the finite element analyses. Table 2 also shows the loss in strength calculated according to S16-01 and that obtained from the laboratory tests, $F_{u,\text{TEST}}/F_{y,c} - 1$. Comparison with the later values indicates that the finite element analyses give a somewhat conservative estimate of the shear lag effect. Refinements of the finite element mesh as well as the use of smaller load steps may improve values of the predicted ultimate strengths.

Table 2. Loss in strength due to shear lag based on finite element analyses, S16-01 and laboratory tests.

<table>
<thead>
<tr>
<th>No.</th>
<th>Yield Strength from Coupons $F_{y,c}$ [MPa]</th>
<th>Ultimate Strength from Coupons $F_{u,c}$ [MPa]</th>
<th>Ultimate Strength from F.E.A. $F_{u,\text{FEA}}$ [MPa]</th>
<th>$F_{u,\text{FEA}}/F_{y,c} - 1$ [%]</th>
<th>$1 - F_{u,\text{FEA}}/F_{u,c}$ [%]</th>
<th>Reduction due to Shear Lag According to S16-01 [%]</th>
<th>$F_{u,\text{TEST}}/F_{y,c} - 1$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ÉTS-1</td>
<td>393</td>
<td>531</td>
<td>398</td>
<td>1</td>
<td>25</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>ÉTS-2</td>
<td>349</td>
<td>492</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>ÉTS-3</td>
<td>318</td>
<td>461</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>15</td>
<td>–2</td>
</tr>
<tr>
<td>ÉTS-4</td>
<td>345</td>
<td>499</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>ÉTS-5</td>
<td>339</td>
<td>487</td>
<td>356</td>
<td>5</td>
<td>27</td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td>ÉTS-6</td>
<td>348</td>
<td>527</td>
<td>385</td>
<td>11</td>
<td>27</td>
<td>12</td>
<td>4</td>
</tr>
</tbody>
</table>

Note: 1 Results for these specimens will be presented elsewhere.

4. CONCLUSIONS

This section summarizes the conclusions of this paper. These are briefly given below:

1. Non linear material and large displacement finite element analyses were performed for three of six specimens tested recently by the authors. The analyses were carried out past the yield point, well into the plastic region.
2. Comparisons made at two locations near the connection of specimen ÉTS-1 showed excellent agreement between strains obtained from the finite element analysis and values from strain gauge readings taken during the laboratory tests.
3. The loss in strength due to shear lag calculated using the finite element analyses, based on the last load for which the iteration converged, was compared with similar values calculated according to S16-01 and those obtained from the laboratory tests. Values from the finite element analyses were found to be conservative, ranging from 25% to 27%.

It can be concluded that, with the limited analytical data presented here, finite element analyses provide a somewhat conservative estimate of the shear lag effect in welded angle connections. In order to get a better understanding of the joint behaviour, further refinements of the finite element models are required including improved mesh, smaller load steps and better modeling of the welds, as well as increased overall length of the angles.
5. ACKNOWLEDGEMENTS

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6. REFERENCES


Figure 1. Typical truss with double-angle web members (Canam Steel).
Figure 2. Connection with equal length longitudinal welds.
Figure 3. Test set-up.

Figure 4. Specimen No. ÉTS-4 at failure.

Figure 5. Strain gauge locations for test specimens Nos. ÉTS-1 to 6.
Figure 6. Input stress-strain curve for the finite element model of specimen ÉTS-1.

Figure 7. Finite element model for specimen ÉTS-1.
Figure 8. Strains along the longitudinal axis of the angle at ultimate load for specimen ÉTS-1. (Units are mm/mm).

Figure 9. von Mises stresses at the ultimate load for specimen ÉTS-1. (Units are Pascals).
Figure 10. Strain readings from laboratory test versus strain values from finite element analysis at strain gauge location 1. Test specimen ÉTS-1.

Figure 11. Strain readings from laboratory test versus strain values from finite element analysis at strain gauge location 8. Test specimen ÉTS-1.