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Preface

These proceedings contain the papers presented at the TENTH INTERNATIONAL CONFERENCE ON ADVANCES IN STEEL STRUCTURES (ICASS 2020) held in Chengdu, China, from 21 to 23 August 2022. The international conference series on Advances in Steel Structures was initiated in 1996 under the support of The Hong Kong Polytechnic University, which remains very active in fostering its continuation-joined a few years later by the Hong Kong Institute of Steel Construction.

These proceedings bring together most recent findings in numerical, theoretical and experimental research, as well as its practical implementation in design practice in the areas of Assembled Structure, Bridge, Cold-formed Steel, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue, Fire, High-Strength Steel, Impact and Protection, Intelligent Construction, New Material, Seismic Resistance, Stability, Stainless Steel, Structure Systems, Testing & Monitoring. The papers presented in these proceedings come from a wide range of countries/regions and will be a great reference source.

Specially, the subject matter has been categorized under the broad heading of:

**Volume I:** Keynotes Lectures, Assembled Structure, Bridge, Cold-Formed, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue


Each of the papers was subjected to stringent review by a panel of experts in the respective area. This peer review began with an assessment of the submitted abstracts and following this, authors were invited to submit their full manuscripts. Each manuscript was then carefully reviewed by relevant experts, and their recommendations on accepting, rejecting or modifying the submissions were strictly adhered to, before inclusion in the conference proceedings.
COMPARATIVE STUDY ON STABILITY OF WELDED AND HOT-ROLLED Q420 L300×30 COLUMNS

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Abstract: More heavy latticed steel transmission towers are being proposed and constructed in response to the increasing power demand of the rapid developments in China; new steel sections, Q420 L300×30 equal-leg angles, both welded and hot-rolled, are now available in the market. However, previous studies focused less on these large angles and their stability; corresponding design methods were also insufficient. Thus, this research aims to reveal the residual stress distributions and the axial-loaded behaviors of the L300×30 columns, in which sectioning method and FEM analysis were used. The stress distribution models of the welded L300×30 (WL30) and the hot-rolled L300×30 (RL30) sections were compared. Several φ-λ curves in the strong and weak axes were calculated with ABAQUS and compared with the Chinese and European design codes. While axially loaded, it is found that the WL30 columns, which have tensile residual stress at the heel and the toes, are stronger in both axes than the RL30 columns; selections of the design column curves were recommended.

Keywords: Residual Stress; Stability; Steel Angle; Heavy Cross Section

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1 INTRODUCTION

More heavy latticed steel transmission towers are being proposed and constructed in response to the increasing power demand of the rapid developments in China. Energy-consuming eastern cities in the Chinese coastal area rely on the electricity generated from the west, where hydropower is abundant; there have been ongoing constructions of transmission lines in the west-east direction. The high-voltage direct current technology was recently adopted to increase transmission efficiency, requiring a higher cable-to-ground clearance and stronger load-bearing towers. New steel sections, Q420 L300×30 equal-leg angles, both welded and hot-rolled, are now available in the market to meet the demand.

Previously, few studies had focused on large angle sections, especially the welded ones. Researchers from Lehigh University were among the first to study the residual stress of the structural steel columns and their stability; stress on welded plates of 152.4×12.7 to 508×25.4 mm [1] and a welded A7 steel L254×12.7 equal-leg angle was measured [2]. The stress of eight angle sections ranging from L180×16 to L300×35 was obtained by Može P. et al., using the water jet cutting technique [3]. In addition, some empirical equations derived from welded box sections [4] were proposed by Young B.W. to predict the stress distribution and the magnitude [5]; an easy mechanical model was used by Moshaiov A. et al. to simplify the complex thermal-
elastoplastic strain/stress development during welding [6]. Also, with the advance of the Chinese construction industry, various grades of welded steel sections were studied by Ban [7].

However, the residual stress data of large welded angles of a size such as L300×30 is still insufficient; thus, this research aims to reveal the residual stress distributions of welded Q420 L300×30 angles and compare their axial-loaded stability with the hot-rolled ones; selections of the corresponding design column curves would also be recommended.

2 RESIDUAL STRESS MEASUREMENTS

2.1 Preparation of test specimens

All specimens were made of Q420 steel, and seven standard tensile tests were conducted according to GB/T 228.1-2010 [8] to obtain the material properties listed in Table 1; WL30 and RL30 represent the welded and the hot-rolled Q420 L300×30 sections. The tensile coupons were sampled according to GB/T 2975-2018 [9]; their mechanical properties satisfy the requirements of GB/T 1591-2018 [10].

The residual stress specimens were cut from the longer L300×30 angles and sliced into small strips according to the sectioning method described by Tall L. et al. [1, 2]. There were three specimens of the welded angles by the authors and the other three of the hot-rolled ones by Gao [11]. The wire electrical discharge machining technique, WEDM, was adopted to section the angles into 270×30×10 mm strips as shown in Figure 1; then, the Whittemore strain gauge [12] was used to measure the stress relief after sectioning. Two exposed surfaces of each strip were measured, distinguished as inside and the outside surfaces in this paper.

Table 1: Material properties of Q420 steel

<table>
<thead>
<tr>
<th>Mark</th>
<th>Section Type</th>
<th>Average of</th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>E (GPa)</td>
<td>f&lt;sub&gt;y&lt;/sub&gt; (MPa)</td>
</tr>
<tr>
<td>WL30</td>
<td>Welded angle</td>
<td>212.0</td>
<td>440.1</td>
</tr>
<tr>
<td>RL30</td>
<td>Hot-rolled angle</td>
<td>207.8</td>
<td>445.1</td>
</tr>
</tbody>
</table>

Figure 1: Angle specimen after sectioning

2.2 Results of experiments and distribution models

The residual stress measurements of the welded L300×30 angles are shown in Figure 2, with the average values of the data inside and outside drawn in the solid red lines. Notice that the
tight space of the internal heel constrains any measurement taken inside; therefore, only the data outside was obtained at the heel.

![Figure 2: Residual stress measurements of the welded L300×30 angles (WL30)](image)

Figure 2: Residual stress measurements of the welded L300×30 angles (WL30)

To further characterize the stress distribution, all the welded L300×30 (WL30) measurements were plotted together, and a unique distribution model was assigned. A clear trend could be easily recognized by observing the average data, and a 4-segment linear model was used to regress the average values. A tensile stress plateau was assigned at the heel to consider the distribution trend and the theoretically higher tension around the weld seam despite the more scattered measurements. On the other hand, Gao [11] did a similar analysis to identify the distribution model for the hot-rolled L300×30 (RL30) sections; a 2-segment linear model was suggested.

Figure 3 summarizes the residual stress distribution models used in this study; the magnitudes are expressed in the ratios dividing stress values by the yield strength, $f_y$ in Table 1; the width of the angles is 300 mm and denoted as $w$. A section adopting either distribution model is in the force and the moment equilibrium.

The residual stress models of the welded (WL30) and the hot-rolled (RL30) sections are different in patterns and stress magnitudes. A welded section has tension at the heel and the toes, while a hot-rolled one has compression at those regions; stress at the mid-leg portion is also in the reverse directions from each other. The WL30 model has the maximum tension of 0.66 $f_y$ at the toes and the maximum compression of 0.16 $f_y$ at the mid-leg portion; the RL30 model has the maximum compression of 0.26 $f_y$ at the heel and the toes.

![Figure 3: Residual stress distribution models](image)
3 NUMERICAL ANALYSIS

3.1 Description of ABAQUS models

The FEM models were carefully constructed to ensure reliability. The C3D20R solid elements with length to thickness ratios smaller than three were used; the mesh was evenly spaced on the cross-sections where the short edge of a single element was about 10 mm. The static arch length algorithm was used to capture the maximum strength. The calculated results of the elastoplastic FEM models were compared with 23 experiments done by Ban [7] in 2012; the range of the experimental axial loads was from 500 kN to 2200 kN. A good agreement between the FEM and the test results has been achieved, verifying the reliability of the numerical models.

3.2 Results of numerical calculations

Figure 4 shows the FEM calculated strength of the 72 axial-loaded columns about different axes, with F, F-N, and FT referring to the positive, the negative flexural buckling about the x-x (weak) axis, and the flexural-torsional buckling about the y-y (strong) axis. The bending direction about x-x causing compression at the heel is defined as the positive side. The strength values were normalized by Equation 1.

\[ \varphi = \frac{P_{u,FEM}}{A \times f_y} \]  

where \( P_{u,FEM} \) is the maximum bearing loads obtained from the FEM simulations; \( A \) is the cross-sectional area; \( f_y \) is the material yield strength.

It is clear that the flexural buckling mode about x-x controls the column strength of both the welded and the hot-rolled sections; the strength differences between the flexural and the flexural-torsional modes increase along with the increase of the column height. The reason is that the strength contribution from torsional resistance is less affected by the change of the member length. Thus, while the flexural strength about x-x drastically decreases, the flexural-torsional strength about y-y only decreases slightly with the increasing column height.

Figure 4: Axial strength of L300×30 columns

Figure 4 also shows the RL30 strength differences between the positive and the negative flexural buckling; in contrast, the WL30 flexural strength about x-x is almost identical in both directions. The distinct differences between the positive and the negative flexural strength could
be explained by the combined effects of the hot-rolled residual stress and the section geometry. Figures 5 (b) and 6 (b) show the equivalent plastic strain, $\varepsilon_p$, contours on the L30-80 mid-height sections when the ultimate axial loads were reached; L30-80 refers to the L300×30 columns with 4.72 m height and $\lambda_x$ of 80. A similar yield area, $A_y$, was developed on the compressive side of the positive and the negative x-x flexure; however, there was a plastic strain concentration at the heel tip when buckling in the positive, decreasing the column stiffness, increasing the $p$-$\Delta$ effect, and eventually resulting in a lower ultimate axial strength.

![Figure 5: Equivalent plastic strain, $\varepsilon_p$, on the L30-80 mid-height sections when the ultimate axial loads about the positive x-x flexural buckling were reached](image)

On the other hand, the area further from the rotational axis, x-x, of the welded sections did not develop plastic strain due to the tensile residual stress; the plastic strain area was closer to the x-x axis as shown in Figures 5 (a) and 6 (a). The strength differences are negligible since the bending stiffness is mainly controlled by the area further from the rotational axis, which is primarily elastic for the welded sections in both buckling directions. The average difference of the flexural strength about x-x is around 10% for the hot-rolled sections, but it is 1% for the welded ones. The plastic strain distribution aforementioned could also explain the higher strength of the welded columns.

![Figure 6: Equivalent plastic strain, $\varepsilon_p$, on the L30-80 mid-height sections when the ultimate axial loads about the negative x-x flexural buckling were reached](image)

### 3.3 Comparison of stability

In order to compare the FEM results with the existing design codes, the slenderness ratios were normalized; then, the column strength about x-x and y-y was plotted in $\varphi\cdot\lambda_{x,n}$ and $\varphi\cdot\lambda_{y,z,n}$ coordinates as shown in Figure 7 and 8. Finally, the smaller flexural strength values between the positive and the negative x-x directions were selected as the representative strength.
Figures 7 (a) and (b) demonstrate the strength of the welded (WL30) and the hot-rolled (RL30) columns buckling about the x-x axis, compared with the design curves of the Chinese GB 50017-2017 [13] and the European EN 1993-1-1:2005 [14] standards. It is clear that the welded columns are stronger than the hot-rolled ones; the strength differences are more distinct at range from $\lambda_{x,n}=0.5$ to $\lambda_{x,n}=1.5$, and the WL30 strength is around 12% higher than the RL30 one. Table 2 shows that the WL30 curve is 4.2% higher than the GB 50017-a curve and almost overlays with the EN 1993-1-1-a0 curve with less than 1% strength difference; in contrast, the RL30 curve is nearly identical to the GB 50017-b and EN 1993-1-1-b curves.

Similarly, Figures 8 (a) and (b) demonstrate the strength of the welded (WL30) and the hot-rolled (RL30) columns buckling about the y-y axis. Although the welded columns are stronger than the hot-rolled ones, the average difference is about 3%; the higher strength of WL30 could be contributed from the elastic leg toes as shown in Figure 9 (a) and the more evenly distributed yield area, $A_y$, compared to RL30 as shown in Figure 9 (b). Table 2 shows that the WL30 curve is 8.7% higher than the GB 50017-a curve and 4.2% higher than the EN 1993-1-1-a0 curve; in contrast, the RL30 curve is 5.7% higher than the GB 50017-a curve and 1.4% higher than the EN 1993-1-1-a0 curve.
Figure 9: Equivalent plastic strain on the L30-80 mid-height sections when the ultimate axial loads about the y-y flexure-torsional buckling were reached

### Table 2: Strength comparison with the design codes

<table>
<thead>
<tr>
<th>Section Type</th>
<th>About Axis</th>
<th>Buckling Mode</th>
<th>Code to Compare</th>
<th>Average of ($φ_{FEM}/φ_{Code})-1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Curve a0</td>
</tr>
<tr>
<td>WL30</td>
<td>x-x</td>
<td>Flexural</td>
<td>GB 50017</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>x-x</td>
<td>Flexural</td>
<td>EN 1993-1-1</td>
<td>0.9%</td>
</tr>
<tr>
<td></td>
<td>y-y</td>
<td>Torsional Flex.</td>
<td>GB 50017</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>y-y</td>
<td>Torsional Flex.</td>
<td>EN 1993-1-1</td>
<td>4.2%</td>
</tr>
<tr>
<td>RL30</td>
<td>x-x</td>
<td>Flexural</td>
<td>GB 50017</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>x-x</td>
<td>Flexural</td>
<td>EN 1993-1-1</td>
<td>-10.9%</td>
</tr>
<tr>
<td></td>
<td>y-y</td>
<td>Torsional Flex.</td>
<td>GB 50017</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>y-y</td>
<td>Torsional Flex.</td>
<td>EN 1993-1-1</td>
<td>1.4%</td>
</tr>
</tbody>
</table>

### 4 CONCLUSIONS

- The welded angles have tensile residual stress at the heel and the toes, while the hot-rolled angles have compressive residual stress at those regions. Therefore, two different stress distribution models for each type of section were used.
- With the different stress distributions, it is found that the welded L300×30 columns are stronger about both the strong and the weak axes than the hot-rolled columns.
- The differences in the stability were elaborated with respect to the residual stress and the plastic strain distributions on the sections. The area further from the rotational axis being elastic is beneficial to the overall stability.
- It is recommended to use GB 50017 curve a and EN 1993-1-1 curve a0 for the welded L300×30 column designs; on the other hand, to use curve b of both GB50017 and EN 1993-1-1 for the hot-rolled L300×30 column designs.

### REFERENCES


[9] GB/T 2975-2018 Steel and steel products: Location and preparation of samples and test pieces for mechanical testing, State Administration for Market Regulation, China, 2018

[10] GB/T 1591-2018 High strength low alloy structural steels, State Administration for Market Regulation, China, 2018


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