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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.
EXPERIMENTAL INVESTIGATION OF RESIDUAL STRESS IN WELDED T-SECTION BY DOMESTIC Q460 HIGH STRENGTH STEEL

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Abstract: Residual stress is one of the most important initial imperfections for the buckling behavior of steel compression members. An experimental investigation was carried out to quantify the longitudinal residual stress in welded T-section of domestic Q460 high strength steel. The residual stress of 8 specimens with various dimensions was measured by using the splitting method. Based on the experimental data, the magnitude and distribution of both compressive and tensile residual stresses in the entire section were obtained. It was found that the magnitude of tensile residual stresses near the weld was hardly correlated with the sectional dimension, but the magnitude of compressive residual stress in the flange was inversely proportional to the plate thickness and the width-thickness ratio. Moreover, there was no interaction between the flange and web since the total residual stress was close to zero within each plate. According to those conclusions, the distribution model was proposed and compared well with the experimental results. The new model can be used to describe the residual stress in Q460 HSS welded T-section accurately and reliably.

Keywords: Domestic Q460; High strength steel; Welded T-section; Residual stress; Experiment; Finite element analysis

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1 INTRODUCTION

For decades, high strength steel (HSS) has been well applied in many high-rise buildings and large-scale structures in the world[1-3]. Welding is generally regarded as a highly effective means of connecting steel plates to form a structure. It has the benefit of saving the materials, easy construction, and reliable sealing. However, during the process of welding and cooling, residual stresses are always produced in sections due to non-uniform temperature distribution. Residual stresses have a negative effect on the mechanical performance of steel structural members, such as the stiffness, fatigue, and stability. Therefore, it is important to obtain the magnitude and distribution of residual stresses in sections of HSS members.

The residual stress models for HSS sections may be different from those for normal strength steel (NSS) sections due to the following three major reasons: (1) the material properties and manufacturing processes for HSS sections are different from those of NSS ones; (2) the maximum tensile residual stress near the welded region may be lower than the yield strength ($f_y$) of HSS while that is normally taken as $f_y$ for NSS; (3) the residual stress patterns of HSS welded section may be related to the section dimensions. Consequently, it is necessary to investigate the residual stresses in HSS sections.
In the past years, many researchers conducted experimental investigations into the residual stresses in HSS sections. For steel grade Q460, Wang et al.\cite{4,5} investigated the residual stresses in three welded H-sections and three box sections made of Q460 using conventional sectioning method and hole-drilling method, and proposed the corresponding simplified residual stress pattern. Ban et al.\cite{6,7} conducted the residual stress measurements of six box sections and eight welded H-sections made of Q460 steel using the sectioning method, and established the distribution models of residual stresses. Yang et al.\cite{8,9} fabricated sixteen welded H-sections, measured the cross-sectional residual stress distribution through the use of the sectioning method, and presented the simplified model for predicting residual stresses. Nie et al.\cite{10} examined the residual stress of weld box sections made of Q460GJ using the sectioning method and proposed the simplified residual stress distribution model based on the experimental results. Somodi et al.\cite{11} carried out a series of residual stress measurements on welded box sections made of several kinds of steel with the yield strength ranging from 235 MPa to 960 MPa using the sectioning method, and proposed an improved residual stress model based on test results. The residual stress patterns of these HSS welded H-sections and box sections were found to be similar in shape, but significantly smaller, when compared with those corresponding residual stresses of NSS welded section. For HSS welded T-section, it is necessary to investigate whether those conclusions for H-sections and box sections are still reliable for T-sections or not.

Recently, Cao et al.\cite{12} presented an experimental study to examine the residual stress in 800 MPa HSS welded T-sections using the sectioning method, and proposed a simplified model based on the magnitude and distribution of residual stresses. From the investigation, the residual stress patterns of HSS welded T-sections were found to be similar in shape compared with those of normal strength steel (NSS) welded T-section, while the residual stress ratio for HSS was lower than that for NSS. However, the study was only concentrated on the residual stress distribution for HSS welded T-sections with yield stress of 800 MPa. The simplified model proposed by Cao may be not accurate for Q460 weld T-sections, which is more widely applied in practice.

In general, many studies on the residual stress on welded H-sections and box sections made of HSS were carried out while only limited information on residual stresses in welded T-sections is available so far. Furthermore, in steel structure design specifications, such as GB50017-2017\cite{13}, Eurocode 3\cite{14}, and ANSI/AISC360-16\cite{15}, the reliable and accurate distribution model of the longitudinal residual stress for HSS welded T-section is not given for the lack of research in this area. Hence, it is necessary to conduct a series of residual stress measurements on Q460 welded T-sections and to obtain the magnitude and distribution of both tensile and compressive residual stresses.

2 EXPERIMENTAL INVESTIGATION

2.1 Material tests

The tension coupons are cut from the domestic Q460 HSS plate. According to GB/T 2975-2018\cite{16} and GB/T228.1-2010\cite{17}, six tension coupons are fabricated using flame cutting method and conducted the static tensile test to obtain the basic mechanical properties of the steel. The tension coupons are shown in Figure 1. The tensile test results are given in Table 1, where $t$ is the thickness of the plate, $E$ is the Young’s modulus, $\nu$ is the Poisson ratio, $f_y$ is the yield strength, $f_u$ is the tensile strength and $\delta$ is the percentage of elongation after fracture. To use those material properties in the subsequent investigation, the average value is selected for each thickness of steel plates (see Table 1).
From the data in Table 1, it is shown that the material properties of Q460 HSS are different from those of NSS, so that characteristic will affect the magnitude and distribution of residual stress of HSS welded T-sections.

![Tension coupons](image1)

(a) Tension coupons  
(b) Coupon dimension

**Figure 1:** Specimens of the static tensile test.

**Table 1:** Tensile test results.

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<th>Specimen</th>
<th>$t$ /mm</th>
<th>$E$ /GPa</th>
<th>$f_y$ /MPa</th>
<th>$f_u$ /MPa</th>
<th>$f_y/f_u$</th>
<th>$\delta$</th>
<th>$\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>189</td>
<td>488</td>
<td>663</td>
<td>0.676</td>
<td>25.3%</td>
<td>0.274</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>187</td>
<td>502</td>
<td>665</td>
<td>0.755</td>
<td>24.9%</td>
<td>0.279</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>192</td>
<td>510</td>
<td>665</td>
<td>0.767</td>
<td>25.6%</td>
<td>0.272</td>
</tr>
<tr>
<td>Average</td>
<td>8</td>
<td>189</td>
<td>500</td>
<td>664</td>
<td>0.733</td>
<td>25.2%</td>
<td>0.275</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>199</td>
<td>572</td>
<td>705</td>
<td>0.811</td>
<td>24.1%</td>
<td>0.289</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>194</td>
<td>593</td>
<td>683</td>
<td>0.868</td>
<td>25.2%</td>
<td>0.279</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>198</td>
<td>503</td>
<td>669</td>
<td>0.752</td>
<td>24.9%</td>
<td>0.286</td>
</tr>
<tr>
<td>Average</td>
<td>12</td>
<td>197</td>
<td>556</td>
<td>686</td>
<td>0.810</td>
<td>24.8%</td>
<td>0.285</td>
</tr>
</tbody>
</table>

2.2 Section specimen preparation

To test the magnitude and distribution of residual stresses in Q460 HSS welded T-sections, eight specimens are fabricated from the same virgin plates used in tension coupons. The specimen sectional shape is illustrated in Figure 2 and the measured geometric dimensions of test specimens are given in Table 2.

![Specimen sectional shape](image2)

**Figure 2:** Specimen sectional shape.
Table 2: Sectional dimensions.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$B$ /mm</th>
<th>$H$ /mm</th>
<th>$t_f$ /mm</th>
<th>$t_w$ /mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-1</td>
<td>99.7</td>
<td>108.9</td>
<td>7.40</td>
<td>7.36</td>
</tr>
<tr>
<td>R-2</td>
<td>120.3</td>
<td>126.0</td>
<td>7.40</td>
<td>7.40</td>
</tr>
<tr>
<td>R-3</td>
<td>149.7</td>
<td>156.4</td>
<td>7.40</td>
<td>7.46</td>
</tr>
<tr>
<td>R-4</td>
<td>201.0</td>
<td>206.3</td>
<td>7.38</td>
<td>7.42</td>
</tr>
<tr>
<td>R-5</td>
<td>98.8</td>
<td>112.2</td>
<td>11.80</td>
<td>11.78</td>
</tr>
<tr>
<td>R-6</td>
<td>119.8</td>
<td>129.4</td>
<td>11.82</td>
<td>11.78</td>
</tr>
<tr>
<td>R-7</td>
<td>148.2</td>
<td>160.8</td>
<td>11.78</td>
<td>11.88</td>
</tr>
<tr>
<td>R-8</td>
<td>199.5</td>
<td>210.2</td>
<td>11.74</td>
<td>11.76</td>
</tr>
</tbody>
</table>

The plates of test specimens are cut with flame cutting method and welded together by fillet welds. In each T-section, two fillet runs are carried out, and a pre-heating temperature between 120 and 150 °C is adopted to prevent the cold hydrogen cracking. During the welding process, the GMAW is conducted and the shielding gas is Ar80%+CO₂20%. The voltage of welding is 25 V, the current of welding is 220 A, the welding speed is about 250 mm/min and the flow rate of shielding gas is 30 L/min. The fillet weld size is 8 mm being filled with the filler wire type ER55-D2 (1.2 mm).

2.3 Sectioning method

The sectioning method is implemented in the experimental process. The electric drill is used to make the standard holes before cutting, and the flame wire cutting machine is used to slice the entire section into strips. The Whittemore strain gauge with a gauge length of 250 mm and a sensitivity of 0.05 mm is applied to obtain the strains of each strip during measuring.

Figure 3 is a sample of specimens for welded T-sections taking the typical section R-7 for example. To ensure the representative initial residual stress distribution over the entire profile, the experimental segments must be long enough, so the length of the adopted central portion was recommended no less than 3.0 times of the lateral dimension. Moreover, the segments must be far enough away from the ends, so the distance from both ends is recommended no less than 1.5-2.0 times of the lateral size. According to the above guidance, the length of the adopted central portion is 500 mm, and the distance from both ends is 250 mm. The number of measured points of section R-7 is fifteen both in the flange plate and in the web plate. For other section sizes, the width of the strip specimens is also taken as 10 mm. Two holes are prepared on each strip with a distance of 250 mm in the two ends for the installation of the Whittemore strain gauge.

According to Figure 3, the experimental procedure is described in following three steps. In the first step, the cutting lines are drawn, the holes for the Whittemore gauge are drilled, and the initial readings are taken for each couple of holes on both surfaces. In the second step, the adopted central portion is separated, the formal sample of a specimen with the length of 270 mm is separated, and then the reading for each couple of gauge holes on both surfaces is measured again. In the third step, the flange and web are separated, and then the flange plate and the web plate are completely sliced into strips and the final readings on both surfaces are taken. Figure 4 shows all the strips being sliced from specimen R-7 during the test.

The released strain of each strip of the specimen is obtained by comparing the initial reading taken in the first step and the final reading taken in the third step. The residual stress is obtained by the use of Hooke’s Law, i.e. the released strain multiplied by the elastic modulus of the steel. Combining the residual stress of each strip, the distribution of residual stresses in the entire cross-section can be obtained.
3 TEST RESULTS AND ANALYSIS

3.1 Test results

Based on test data, the magnitude and distribution of residual stress in eight HSS welded T-sections are described in Figure 5. There are three measured results for each strip including those at both surface of the plate and their average values.

Figure 5 shows that the distribution of the residual stress in welded T-sections has the following characters:

(1) Similar to previous studies, the residual stress distribution of HSS sections is similar in shape compared with that of NSS sections. The residual stresses near the welds and the flame cutting edges of plates are tensile stresses, while the residual stresses in other regions of plates are compressive stresses.

(2) The maximum tensile residual stress near the weld in HSS sections is lower than the measured yield strength ($f_y$) of steel, and also less than the nominal yield strength (460 MPa) of steel. Whereas, for NSS sections, it is normally taken the maximum tensile stress as $f_y$.

(3) The tensile residual stress has no correlation with the sectional dimension, while the compressive residual stress is found to be significantly related to the plate thickness and the width-to-thickness ratio of the plate. In the subsequent section, that characteristic will be discussed in detail.

To facilitate the study of the residual stresses in Figure 5, the residual stress distribution model of the welded T-section is initially set to the shape shown in Figure 6 where $\sigma_{t1}$ represents the maximum tensile residual stress near the weld region of the flange, $\sigma_{t2}$ and $\sigma_{t3}$ represent the maximum tensile residual stress at the two flame cutting edges of flanges, $\sigma_{c1}$ and $\sigma_{c2}$ denote the maximum compressive residual stress at the portions of two outstand flanges, $\sigma_{w1}$ and $\sigma_{w2}$ represent the maximum tensile residual stress at both ends of the web, $\sigma_{wc}$ denotes the maximum compressive residual stress at the portion of the web. Table 3 summarizes all those characterized values of the residual stresses in the sections of eight test specimens. The exact parameters in Figure 6 and the corresponding calculation formula will be described in the following sections.
Figure 5: Residual stress distribution of HSS welded T-sections (tensile residual stress in positive and compressive residual stress in negative).
Figure 6: Illustration of the residual stress on welded T-sections.

Table 3: Characterized values of the residual stresses in the sections of eight test specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$\sigma_{f1}$ /MPa</th>
<th>$\sigma_{f2}$ /MPa</th>
<th>$\sigma_{w1}$ /MPa</th>
<th>$\sigma_{w2}$ /MPa</th>
<th>$\sigma_{wc}$ /MPa</th>
<th>$\sigma_{wt1}$ /MPa</th>
<th>$\sigma_{wt2}$ /MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-1</td>
<td>-235.5</td>
<td>-247.2</td>
<td>278.6</td>
<td>-150.6</td>
<td>-150.6</td>
<td>278.6</td>
<td>259.8</td>
</tr>
<tr>
<td>R-2</td>
<td>-218.4</td>
<td>-237.2</td>
<td>297.4</td>
<td>-75.3</td>
<td>18.8</td>
<td>-200.1</td>
<td>297.4</td>
</tr>
<tr>
<td>R-3</td>
<td>-278.6</td>
<td>-233.4</td>
<td>372.7</td>
<td>18.8</td>
<td>-7.5</td>
<td>-112.9</td>
<td>372.7</td>
</tr>
<tr>
<td>R-4</td>
<td>-188.2</td>
<td>-184.5</td>
<td>338.8</td>
<td>41.4</td>
<td>90.4</td>
<td>-124.2</td>
<td>338.8</td>
</tr>
<tr>
<td>R-5</td>
<td>-145.2</td>
<td>-282.6</td>
<td>361.0</td>
<td>-54.9</td>
<td>23.5</td>
<td>-141.3</td>
<td>361.0</td>
</tr>
<tr>
<td>R-6</td>
<td>-184.4</td>
<td>-231.5</td>
<td>243.3</td>
<td>-39.2</td>
<td>90.3</td>
<td>-149.1</td>
<td>243.3</td>
</tr>
<tr>
<td>R-7</td>
<td>-145.2</td>
<td>-125.6</td>
<td>329.6</td>
<td>121.7</td>
<td>137.4</td>
<td>-113.8</td>
<td>329.6</td>
</tr>
<tr>
<td>R-8</td>
<td>-153.0</td>
<td>-160.9</td>
<td>274.7</td>
<td>98.1</td>
<td>78.5</td>
<td>-113.8</td>
<td>274.7</td>
</tr>
</tbody>
</table>

3.2 Effects of width-to-thickness ratio of plate

To study the effects of the width-to-thickness ratio of the plate, the relationship between the magnitude of the residual stress and the width-to-thickness ratio is demonstrated in Figure 7.

According to Figure 7(a), it is identified that the tensile residual stresses are hardly correlated with the width-to-thickness ratio of the plate. That is because the tensile residual stress near the weld region is induced by the heat input in the process of welding due to the deformation of melted steel constrained by the surrounding cold steel. Hence, if the amount of the heat input is determined, the tensile residual stress is only related to the elastic modulus of the material, which is a constant for all kinds of steels, and hardly correlated with the width-to-thickness ratio of the plate.

Moreover, as shown in Figure 7(b), when the width-to-thickness ratio of the plate is less than 16, the compressive residual stresses decrease by the increase of the width-to-thickness ratio of the plate. However, the compressive residual stresses maintain constant if the width-to-thickness ratio of the plate increases over 16. That is also because of the same energy input during welding. Hence, as the same energy input during welding, the magnitude of the tensile residual stress near the weld region remains constant, but the magnitude of the compressive residual stress at the portion of the plate is decreased due to the increase of the width-to-thickness ratio of the plate.
3.3 Effects of plate thickness

To study the effects of the plate thickness on the residual stress, the test results of two groups of different sections are drawn in Figure 8. One comparative group is the specimen R-1 ($t=8$ mm) and R-7 ($t=12$ mm), the other is the specimen R-2 ($t=8$ mm) and R-8 ($t=12$ mm). In each group, the plate thickness is different, while the width-to-thickness ratio of the flange and web is similar, i.e. for the first group, $b_f/t_f$ is about 6 and $h_0/t_w$ is about 13, for the second group, $b_f/t_f$ is about 8 and $h_0/t_w$ is about 16.

From Figure 8 and Table 3, it is found that the distribution shape of the residual stress is similar, but the magnitude of the residual stresses is different between those two sections. Taking R-2 and R-8 for example, the compressive residual stresses $\sigma_{fc1}$ and $\sigma_{fc2}$ in flanges of R-2 are 43% and 47% larger for R-8, respectively, and the compressive residual stress $\sigma_{wc}$ in the web of R-2 is 76% larger for R-8. However, the tensile residual stress $\sigma_{ft1}$ in the flange of R-2 is 8% more than that of R-8, the tensile residual stresses $\sigma_{ft3}$ in the flange of R-2 are 76% less than that of R-8, and the tensile residual stress $\sigma_{wt2}$ in the web is 22% larger for R-8. Therefore, it can be concluded that the plate thickness has a significant effect on the compressive residual stress, i.e. the compressive residual stress is inversely proportional to the thickness of the plate. However, the tensile residual stress is hardly correlated with the plate thickness.
3.4 Effect of plate correlation

To identify the correlation between the flange and web, $\sigma_{crr}$, the unbalanced stress in the whole cross-section is calculated by the following formula (1).

$$\sigma_{crr} = \frac{\sum_{i=1}^{n} \sigma_{ri} A_i}{A}$$

Where $n$ is the number of splitting strips, $\sigma_{ri}$ is the measured value of residual stress for each strip (tensile stress in positive and compressive stress in negative), $A_i$ is the cross-sectional area of each strip, and $A$ is the cross-sectional area of each test specimen.

According to the self-balancing characteristics of residual stress, the value of the unbalanced stress is closed to zero. However, the calculated result according to the measured value is generally not zero due to the effect of the measurement error. From Figure 9, it is found that the magnitude of unbalanced stress in the whole cross-section is smaller than the steel yield strength. For the majority of specimens, the value of $\sigma_{crr}$ is less than 5% of the measured yield strength of the steel, and only for a few of specimens, the value of $\sigma_{crr}$ is more than 5% but less than 10% the measured yield strength of the steel. Those characteristics are also found in the unbalanced stress of the individual flange and the web.

Consequently, it is indicated that the residual stress in the HSS welded T-section is a kind of self-balancing stress, not only in the whole cross-section but also in the individual flange and the web. That characteristic is similar to the distribution model of the residual stress in NSS welded T-section, which was proposed in Chinese standards for steel structures design.

4 DISTRIBUTION MODEL OF RESIDUAL STRESS

4.1 Existing distribution model of residual stress in welded T-section

As shown in Figure 10, the distribution model of residual stress in NSS welded T-section with flame cutting plate is suggested in Chinese standards for steel structures design. The maximum tensile residual stress is directly set to the nominal yield strength of the steel, and the compressive residual stress is no correlation of the sectional dimension. According to the above investigation, it is identified that the maximum tensile residual stress is less than the nominal yield strength of HSS steel, and the magnitude of the compressive residual stress is affected by the sectional dimension, such as the width-to-thickness ratio of the plate and the plate thickness. Hence, it is necessary to present an accurate distribution model for Q460 HSS welded T-section.

![Figure 9: Unbalanced stress of the specimen.](image1)

![Figure 10: Existing distribution model of residual stress in welded T-section.](image2)
4.2 Shape of residual stress distribution

According to the measured value of residual stress in Figure 5 and the above discussion, a segmented linear distribution model is proposed for the residual stress pattern of Q460 HSS welded T-section with flame cutting plate, as shown in Figure 6. The tensile residual stress in the sectional region near the weld and in the edges of the plate are constant. The compressive residual stress in the middle region of the outstand flange and web is also constant, and the value of stress is determined by the sectional dimension. In the other regions of the section, the residual stress changes linearly between the constant ones.

Besides, according to the self-balancing characteristics of residual stress in cross-section, the distribution model is completely symmetrical about the symmetry axis (i.e. in Figure 6, \( \sigma_{c_0} = \sigma_{c_1} = \sigma_{c_2}, \sigma_{ft_2} = \sigma_{ft_3} \)). Moreover, the residual stress in the individual flange and web is self-balancing, i.e. the value of total stress in each plate is equal to zero.

4.3 Define of tensile residual stress

According to the above discussion, the tensile residual stress is hardly related to the plate width-to-thickness ratio \((b_f/t_f, h_0/t_w)\) and the plate thickness \((t_f, t_w)\). Therefore, the magnitude of the tensile residual stress in HSS welded T-section can be considered as constant.

To identify the distribution of the tensile residual stress in flanges, the test results are collected in Figure 11. Considering the symmetric characteristic of the residual stress in the entire section, all of the test results are summarized together corresponding to the position in the half of the flange. Moreover, for the convenience of statistics, each half flange is divided evenly into 10 portions. It is noted that the maximum tensile residual stress in the flange is occurred in the position near the weld, and is suggested as 345 MPa (i.e. 75% of the nominal yield strength of Q460 HSS) to cover almost all of the test results. Nevertheless, the tensile residual stress in the flame cutting edge of the flange is beneficial to the overall stability of the compression member of T-section, so it is suggested as the average of test results, 46 MPa (i.e. 10% of the nominal yield strength of Q460 HSS).

To identify the distribution of the tensile residual stress in webs, the test results are summarized in Figure 12. For the convenience of statistics, each web is divided evenly into 10 portions. It is concluded that the maximum tensile residual stress in the web is occurred in the position near the weld, and is suggested as 345 MPa (i.e. 75% of the nominal yield strength of Q460 HSS) to cover almost all of the test results. The tensile residual stress in the flame cutting edge of the web is similar to that of the flange, so it is suggested as the average of test results, 300 MPa (i.e. 65% of the nominal yield strength of Q460 HSS).

![Figure 11: Test results of residual stress in the flange.](image1)

![Figure 12: Test results of residual stress in the web.](image2)
4.4 Define of compressive residual stress

As concluded in section 3.2 and 3.3, the compressive residual stress is significantly correlated with the plate width-to-thickness ratio ($b_f/t_f$, $h_0/t_w$) and the plate thickness ($t_f$, $t_w$). Therefore, the magnitude of compressive residual stress is identified through the data fitting method using the software MATLAB based on the test results. In the process of fitting, the self-balancing characteristic of stress in the flange and web needs to be considered, and it is important to ensure that the calculated value is agree with the test results. Consequently, the simplified formula to describe the compressive residual stress in the flange and web is presented, as shown in formula (2), where $\sigma_{fc}$ is the compressive residual stress in the portion of two outstand flange, and $\sigma_{wc}$ is that in the portion of the web.

$$
\begin{aligned}
\sigma_{fc} &= 80 - \frac{2100}{t_f} - \frac{500}{b_f/t_f} \geq -460 \| \leq -46 \\
\sigma_{wc} &= 200 - \frac{2400}{t_w} - \frac{1700}{h_0/t_w} \geq -460 \| \leq -46
\end{aligned}
$$

However, according to formula (2), it should be notice that the calculated value of $\sigma_{fc}$ or $\sigma_{wc}$ may be unreasonable large than the yield strength of steel, if the magnitude of the plate thickness ($t_f$, $t_w$) and the plate width-to-thickness ($b_f/t_f$, $h_0/t_w$) is small. Therefore, the nominal yield strength of Q460 HSS (460 MPa) and 10% of the nominal yield strength of Q460 HSS (46 MPa) are taken as the lower and upper limit of the calculated result of formula (2), respectively.

The distribution model of residual stress in Q460 HSS welded T-section is described in Figure 13. According to the self-balancing characteristics of stress in the flange and web, the distribution range of the residual stress is deduced by fitting and also shown in Figure 13.

So far, all the parameters in the distribution model are determined. Based on that model in Figure 13, the calculated results of residual stress are plotted in Figure 5 for comparison those with the test ones, and it is concluded that those are in good agreement. So, it can be reported that the distribution model in Figure 13 can be used to describe the residual stress in Q460 HSS welded T-section accurately and reliably.

5 CONCLUSIONS

In this paper, eight specimens for investigating the magnitude and distribution of residual stress in domestic Q460 HSS welded T-section are testing through the use of the sectioning
method. Based on the test results, the effects of the plate thickness, the width-to-thickness ratio of the plate, and the interactions between the flange and web are clarified. Finally, the distribution model and the corresponding calculation formula of residual stress are proposed. The specific conclusions are as follows:

1) The distribution of the residual stress in the HSS section is similar in shape compared with that of the NSS section. However, the ratio of maximum tensile residual stress to the nominal yield strength of steel is significantly reduced. For example, the maximum tensile residual stress near the weld region is 75% of the nominal yield strength of Q460 HSS, while that is equal to the nominal yield strength of NSS steel. Thus, the reduction of the ratio is beneficial to the stability of HSS compression members.

2) The magnitude of compressive residual stress is directly related to the sectional dimensions, i.e. it is inversely proportional to the plate thickness and the width-to-thickness ratio of the plate. This characteristic is not considered in Chinese standards for steel structures design.

3) Based on the test results, the distribution model and the corresponding calculation formula of the residual stress in the whole T-section are presented and compared well with the experimental results. The new model can be further applied to describe the residual stress in Q460 HSS welded T-section with other section geometric properties.

The proposed distribution model can be used in the stability study of HSS compression member, and either the measured residual stress or the calculated ones can be directly taken as the initial deflection into the subsequent numerical analysis of the component stability. Furthermore, these conclusions are good references for both compiling the design specification of HSS and revising the existing design standards.

REFERENCES

These proceedings contain the papers 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.

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