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Distributions of residual stresses in stiffened plates with one and two stiffeners

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This study was undertaken for a better understanding of the residual stress distributions associated with welds typically found in ship hulls. Specimens that represent small sections of an actual ship hull were built and tested using the neutron diffraction method at the Canadian Neutron Beam Centre in the Chalk River Laboratories. The specimens comprised 9.5 mm thick steel plates stiffened by $L127 \times 76 \times 9.5$ steel angles. This paper presents one- and three-dimensional distributions of all three components of residual stress created from the production of the steel plate and from the welding of one and two stiffeners onto the parent steel plate. Subsequently, the longitudinal stress in the transverse direction of the stiffened plate specimens was compared with the Faulkner model. It was found that the Faulkner model is able to predict the general distributions of this stress; however, it was unable to predict the stress values correctly.

Keywords: residual stress; weld; stiffener; ship hull; neutron diffraction

1. Introduction

Ship hulls are made of stiffened steel plates. Steel stiffeners such as angle sections, T-sections and I-sections are connected to the steel plates by welding. The welding process creates residual stresses in the ship hull. The primary reason for these residual stresses is the differences in the amount the weld metal shrinks as it hardens and cools to the surrounding temperature. Failure of ship hulls can occur due to various factors and their combinations. One of the contributing factors is the initiation and growth of cracks in the hull structure. The cracks often initiate at the weld of the stiffener-plate connections because of the presence of high residual stresses at that location. Then the cracks progress away from the weld and into the plate. As a result, the ship hull may lose its structural integrity and the ship may eventually capsize unless a timely and appropriate preventative action, such as repairing the crack, is undertaken. Therefore, a detailed and correct understanding of distributions for all three components of the residual stress in a ship hull is very important.

Previous studies have shown how the residual stresses in welded steel members can vary depending on the level of heat input used in the welding process (Gao et al. 1997; Wimpory et al. 2003; James et al. 2006); the type of weld, such as fillet and butt welds (Wimpory et al. 2003; Röhrup 2005), and weld bead on plate (Paradowska et al. 2005; Price et al. 2006); and variations in weld filler material (James et al. 2006). However, these studies were undertaken on specimens not representative of ship hulls. A few

studies were also undertaken primarily to determine the longitudinal component of the residual stresses, i.e. the stress component in the direction of the weld and stiffener, in ship hull-stiffened plate specimens (Somerville et al. 1977; Dexter and Pilarski 2002; Cho et al. 2004). These studies were undertaken using conventional methods such as the hole-drilling method the sectioning method and the X-ray diffraction method. These methods are relatively simple. However, they usually assume a plane strain condition or a simple uni-axial strain condition in the welded stiffened plate of a ship hull structure, since these methods are not able to collect all three-strain components. Furthermore, these methods are able to measure the surface strains only since the measurements of strains using these methods are usually limited to a small depth of the plate. For example, sectioning methods can only measure the strain components at the surface of the plate and hole-drilling methods are limited to near-surface strains (Paik 2009). The X-ray diffraction method is able to measure strain components several microns deep by removing material using electro-polishing, but it is believed that the electro-polishing alters the true residual stresses and their distributions (Gao et al. 1997; Röhrup 2005).

Currently, information on the longitudinal component of residual stresses in the transverse direction (y) on the surface of the ship hull is available. The typical distribution for the longitudinal stress component is assumed to be a tensile block at the weld balanced by a compressive stress block between the stiffeners as shown in Figure 1b (Dwight

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Figure 1. (a) Typical ship hull, (b) idealised stress distribution and (c) Faulkner stress.

and Moxham 1969). This distribution was later improved by Faulkner (Faulkner 1975) to a triangular tensile zone with a peak tensile stress at the weld as shown in Figure 1c. The Faulkner model has been used by many other researchers for estimating longitudinal residual stress in ship hulls (Akhras et al. 1998; Dexter and Pilarski 2002).

The primary objective of this study is to determine the accurate distributions of all three components of residual stress associated with plate-stiffener-welded connections typically found in ship hulls. To obtain the desired stress distributions through the entire depth of the plate, the state-of-the-art neutron diffraction (ND) method was used. The ND method was chosen because it is able to produce a detailed and accurate residual stress-mapping image for all three residual stress components (normal, transverse and longitudinal) through the entire depth of the plate, up to approximately 20 mm in steel, and in both longitudinal (z) and transverse (y) directions. In addition, the ND method allows residual stress measurements without the destruction of the sample (International Standardization Organization and the Versailles Project on Advanced Material and Standards (ISO/TTA) 2001; Hutchings et al. 2005). Three specimens were built and tested to obtain the following information: (1) the locked-in stresses induced from the manufacturing and rolling process used in producing the plate; (2) the distributions of residual stresses in a stiffened steel plate that are created from welding a stiffener onto the parent plate and (3) the effect of welding a second stiffener on the residual stress distribution.

2. Neutron diffraction

The ND method uses the crystal lattice of the sample material as an atomic strain gauge. The elastic strain in the material is calculated by comparing the difference between the crystal lattice spacing of the stressed material and a reference value of the stress-free material. The ND method uses Bragg's Law to calculate the average elastic lattice strain in the gauge volume. A beam of neutrons, with wavelength λ , from a continuous source diffractometer is passed through the sample and diffracts in accordance with Bragg's law, as shown in Equation (1). (ISO/TTA 2001; Krawitz 2001; Hutchings et al. 2005)

$$\lambda = 2d_{hkl} \sin \theta_{hkl}^B, \quad (1)$$

where, d_{hkl} is the lattice spacing of the planes hkl in the crystalline solid, as shown in Figure 2, and $2\theta_{hkl}^B$ is the angle at which the neutrons are scattered coherently and elastically by the properly oriented lattice planes hkl and is called (Bragg's angle).

The ND method output data includes the φ and φ_0 values, which are used to calculate the lattice d-spacing and the error in d-spacing (μ d-spacing) values by using Equations (2) and (3). The φ angle represents the angle between the incident and refracted beam and the φ_0 angle is the same angle related to the reference sample. Equation (4) is used to calculate the strain components by comparing the d-spacing to the stress-free reference sample d-spacing. Equation (5) shows the calculation for the errors in the strain values, which are found by comparing the d-spacing with the d-spacing error. Then using Equation (6), the stress values for each component are calculated using the three strain components.

$$d\text{-spacing} = \left| \frac{\lambda}{2 \sin \left(\frac{\varphi - \varphi_0}{2} \right)} \right|, \quad (2)$$

$$\mu d\text{-spacing} = \left| \frac{\lambda}{2 \sin \left(\frac{\varphi - \varphi_0 + \mu\varphi}{2} \right)} \right| - (d\text{-spacing}), \quad (3)$$

$$\varepsilon = \left(\frac{d\text{-spacing}}{d_0} - 1 \right) \times 1,000,000, \quad (4)$$

Figure 2. Lattice spacing with incident and refracted beam.

Table 1. Mechanical properties of material.

Material	Grade	Tensile strength (MPa)	Yield strength (MPa)	Modulus of elasticity (GPa)	Strain at rupture (%)
Plate	350WT	507.3	405	205	41
Stiffener	300W	527.5	350	204	39
Weld	E70C-6M H4	512.7	390	209	35

$$\mu\varepsilon = \left(\frac{\mu d\text{-spacing}}{d\text{-spacing}} \right) \times 1,000,000, \quad (5)$$

$$\sigma_x = \frac{E}{1+\nu} \left(\varepsilon_x + \frac{\nu}{1-2\nu} (\varepsilon_x + \varepsilon_y + \varepsilon_z) \right). \quad (6)$$

The current study was completed at the Canadian Neutron Beam Centre located in the Chalk River Laboratories (CRL), Chalk River, Canada. The National Research Universal Reactor at the CRL produces 120 MW average of operating power, with a 3×10^{18} neutron/m² thermal neutron flux. The current study used the L3 spectrometer, an ANDI diffractometer that is equipped with a 32-element multi-wire 3 He detector with locating accuracy better than 0.1 mm, strain precision of 0.5E-4 and a selection of computer-controlled positioning systems, handling loads up to 500 kg (NRC Canadian Neutron Beam Centre 2009).

3. Experimental procedure

3.1. Material properties

The steel used for the plate and stiffeners in this study were of 350WT and 300W grades, respectively (Canadian Standards Association (CSA) 2004). The material required for all of the specimens was ordered at the same time to ensure that the same material is used to build all three specimens. All the specimens were cut from one large plate using the cold-cut water jet method in order to minimise the additional residual stresses induced by the cutting process. The stiffeners were L-shaped angle members of dimensions 127 mm $\times$ 76.2 mm $\times$ 9.5 mm. They were cut from one large angle member using a band saw, which is also a cold-cut method.

3.2. Mechanical properties of material

Typical mechanical properties of the parent plate metal, the stiffener metal, and the weld wire metal are shown in Table 1. Quasi-static tension (pull) tests were conducted according to the American Society for Testing and Materials (ASTM) standard (ASTM 2008) in the Structural Engineering Laboratory at the University of Windsor. Two coupon specimens were cut from each of the plate, angle and weld material. Test data obtained from the plate coupon spec-

imens generated higher yield strength than recommended for 350WT steel (CSA 2004). The weld samples were made from only the weld material by depositing a large multi-pass weld bead on a plate, of which a coupon was cut to ASTM standard size. The moduli of elasticity and stress at the upper yield point (first yield stress) for all three materials (plate, angle and weld material) are shown in Table 1. The nominal stress-strain curves for plate, angle and weld material are shown in Figure 3.

3.3. Welding specifications

The metal core arc welding (MCAW) process was used for welding the stiffeners. A licensed welder completed all of the welding. The properties of the wire metal that was used are shown in Table 1. The specimens were fully restrained during the welding and the cooling processes. The heat input used was moderate and controlled using a constant current and welding speed and is shown in Table 2. Specimen 1 was a plane plate and therefore no stiffeners were welded on to this specimen.

4. Test method

4.1. Test matrix

Three specimens, as shown in Table 3, were built and tested using the ND method. The first specimen was a square plate with no stiffeners. This specimen was used to determine the residual stress distribution in the parent plate that develops from the manufacturing and rolling process of the plate. The second specimen was a rectangular plate with one stiffener welded off-centre of the plate. This specimen was used to determine the three-dimensional distributions of residual stresses that occur in the ship hull when a stiffener is welded. The third specimen was a rectangular plate with two stiffeners welded at 250 mm centres. The objective of this specimen was to determine the effect of welding an adjacent stiffener on the residual stresses in the ship hull.

4.2. Test set-up

The ND method was used to measure all the three stress components and the measurements were carried out on the L3 spectrometer at the CRL, Canada. The test set-up was required to be changed and adjusted for each specimen and for measurements of each stress component because the specimen dimensions were large. As a result, the time required for stress measurements for the three specimens was very long and it varied from six days to 20 days for each specimen. The test set-up required specialised skills and careful attention.

Two different set-ups and several scattering slit sizes were used. The first set-up used a wavelength of 1.6650 Å, using the (1 1 5) reflection with the detection

Figure 3. Nominal stress-strain behaviour.

angle $2\theta_M$ at approximately 98.93° . The second set-up used a wavelength of $1.5398 \text{ \AA}$, using the $(1\ 1\ \bar{5})$ reflection with the detector angle at about 90° . The second set-up was necessary when the plate specimen was positioned for the 45° longitudinal strain measurement because in this orientation the neutron counts were very low, due to travelling through part of the stiffener and/or weld. By changing the wavelength (λ) and subsequently the reflection of the monochromating crystal ($2\theta_M$) and ψ angle it was possible to continue the scans at a relatively faster rate. The scattering slit size also varied throughout the specimens from as small as $1 \text{ mm} \times 1 \text{ mm} \times 2 \text{ mm}$ to as large as $1.5 \text{ mm} \times 1.5 \text{ mm} \times 20 \text{ mm}$. The count times for each measurement were optimised to collect the required amount of data in a shorter amount of time, given that there were so many measurement points across all the specimens where the stresses were required to be collected.

Table 2. Welding specifications.

Specimen	(V)	Current (A)	Travel speed (mm/min)	Heat input (kJ/mm)	Cooling time (min)
1	N/A	N/A	N/A	N/A	N/A
2	25.6	185	114	2.49	55
3	25.8	186	118	2.45	65

4.3. Stress-free reference samples and nickel calibration

The stress-free reference samples for the plate were produced on-site at the CRL. Three small ‘matchstick’ prisms were cut from the parent plate material, with the longest dimension in the z direction for two samples and in the y direction for the third sample.

The nickel calibration is a small cadmium container filled with nickel powder producing values that were used in all of the final stress value calculations. The nickel calibration was completed at the beginning and at the end of each set-up to ensure consistency in the numbers throughout the entire set of measurements. The values for λ and φ_0 were specific to one test set-up and for a specific value of $2\theta_M$.

Table 3. Test matrix.

Specimen	Base plate (L $\times$ W $\times$ D)	Stiffener details	Welding method
1	$400 \times 400 \times 9.5 \text{ mm}$	No stiffener	No welding
2	$600 \times 400 \times 9.5 \text{ mm}$	One 600 mm long stiffener	MCAW
3	$600 \times 400 \times 9.5 \text{ mm}$	Two 600 mm long stiffeners spaced at 250 mm	MCAW

Figure 4. Detail for measurement points for Specimen 1.

5. Test results

5.1. Specimen 1

Specimen 1 was a plane plate with dimensions of 400 mm long (L) $\times$ 400 mm wide (T) $\times$ 9.5 mm thick (N) as shown in Figure 4. It is worth mentioning that the dimensions L , T and N in all the three specimens are measured in the z , y and normal (x) directions, respectively. No stiffener was welded on Specimen 1. The objective was to determine the distributions of locked-in stresses in the parent plate created from the rolling and/or manufacturing process. The specimen was measured for residual strains along the z and y directions at seven locations through the depth (x direction) of the plate. The origin was at the centre of the plate (point 1 in Figure 4) and measurements were taken in the y and z directions along lines 1–2 and 1–3, respectively. Strain components were measured to determine all three stress components.

The stress measurements were taken at 10 mm intervals along the y direction for 50 mm length from the centre of the plate (that is, along line 1–2) and at 0, 20, 40, 80, 120 and 180 mm from the centre of the plate (that is, along line 1–3) along the z direction. The measurements were taken at seven depths through the thickness of the plate (x). Therefore, a total of 77 ($=7 \times 11$) measurements were acquired for 11 locations (five in y , five in z and one at the origin). The first measurement for any particular location was taken at a depth of 0.6 mm below the top surface of the plate and the last measurement was taken at a depth of 8.4 mm below the top surface, which means at 1.1 mm above the bottom surface of the plate since the plate was 9.5 mm thick.

The normal stress (not shown in this paper) was found to be almost uniform across the plate in both y and z directions. The stress value ranged from -43 MPa (compression) to $+76$ MPa (tension), though in most cases it was between 20 MPa in compression and 30 MPa in tension.

The average transverse and longitudinal stresses are shown in Figure 5. In order to best show the clear pattern of stress for both components through the depth of

the plate, the average stress values were calculated at each depth across the plate. Hence, each point in this figure represents the average stress at a particular depth obtained either on the transverse line 1–2 or on the longitudinal line 1–3 (Figure 4). It can be seen that the transverse and longitudinal stresses change signs from positive (tension value) to negative (compression value), then from negative (compression value) to positive (tension value) and finally to negative (compression value) again as the depth of the plate increases. The maximum negative value (compressive stress) of both stresses occurs at about 3 mm above the bottom surface and the maximum positive value (tensile stress) occurs at about 5 mm above the bottom surface. The changes in transverse and longitudinal stress values through the thickness of the plate indicate that the parent plate had a locked-in bending stress in both y and z directions and it is most likely due to the rolling process of the plate's production. The stress pattern is not perfectly symmetric about the centre depth of the plate with the maximum (peak) compressive stress, which occurs at 3 mm, larger than the maximum tensile stress which occurs at 5 mm depth. However, there is a proper stress balance and this uneven pattern may signify an inconsistency in the rolling process.

The transverse stress shows a wider variation than the normal and longitudinal stress components. The actual value of the transverse stress component ranged from about 113 MPa in compression to 128 MPa in tension. The range of actual longitudinal stress values was between 37 MPa in compression to 90 MPa in tension. Therefore, it can be concluded that the rolling process, which was used to produce the steel plate, created a bending locked-in stress in both y and z directions.

5.2. Specimen 2

Specimen 2 was a stiffened plate with the dimensions of 600 mm (L) $\times$ 400 mm (T) $\times$ 9.5 mm (N). One 600 mm long angle stiffener was welded on this specimen (Figure 6). The objective was to determine one- and three-dimensional distributions of all three components of residual stress which were created from the welding process of the stiffener onto the parent plate and to compare the stress values with those obtained from the parent plate (Specimen 1). The origin (point 1) of measurements was located on the bottom surface (non-welded surface) of the stiffened plate specimen and the lines (3–1–4 and 1–2) on which the normal, transverse, and longitudinal strains were obtained are shown in Figure 6.

The strains were measured along the y direction (that is, along line 3–1–4) until 150 mm on one side (side with the weld bead) and 130 mm on the other side of the weld. Strains were also measured for 110 mm length along the weld centre line (along line 1–2) in the z direction (Figure 6).

Figure 5. Average transverse and longitudinal stresses in Specimen 1.

The location of the origin (point 1 in Figure 6) was chosen away from the edge of the plate to avoid the edge effects and also for convenience in the test set-up. The spacing of the measurements was as small as 1 mm near the centre of the weld and gradually increased up to 40 mm farther away from the weld in the y direction (on line

3–1–4), as shown in Figure 7. The strain measurements were taken at seven depths of the plate at 29 locations, for a total of 203 ($=29 \times 7$) measurement points. The measurements along the weld centre line (along line 1–2) were taken at one depth (at $x = 8.9$ mm, that is, near the welded surface of the plate) where the stress is expected to be maximum tensile. The objective was to study how the stress components vary

Figure 6. Detail for measurement points for Specimen 2.

Figure 7. Measurement spacing in the transverse direction for Specimen 2.

Figure 8. Normal stress at various depths measured on line 3–1–4.

along the length of the weld. These measurements were taken at six points plus at the origin (point 1) up to 110 mm (on line 1–2). Therefore, the total number of measurements for each strain component taken on this specimen is 209 points ($=203 + 6$).

Distributions of normal and transverse stress components obtained on line 3–1–4 are shown in Figures 8 and 9, respectively. It should be noted that a different graphical representation is used for plotting the stress distributions obtained from this specimen as compared to those shown for Specimen 1. Likewise, only four of the seven measurement depths are shown in these two figures to simplify the presented data while still maintaining the integrity of the residual stress distributions found in the specimen. The data for Specimen 2 is organised with the x -axis as the transverse distance from the origin against the stress value on the y -axis. From Figure 8, it can be seen that the distribution of the normal stress component on line 3–1–4 is erratic and follows no pattern, though the stress values were always much lower than the yield stress level. The value of normal stress ranges from about 75 MPa in compression to 147 MPa in tension. The maximum tensile stress occurs at

the weld centre. These values are nearly double the values found in the parent plate, that is, Specimen 1.

Figure 9 shows the distribution of the transverse stress component along line 3–1–4. The distribution of this stress component does not show a clear pattern either. However, unlike the distribution of the normal stress component, this distribution shows a general trend. Similar to the normal stress component, the maximum tensile value of the transverse stress occurs at the centre of the weld and its value on line 3–1–4 ranges from about 120 MPa in compression to 150 MPa in tension. These values compared with those obtained from the parent plate specimen (Specimen 1) are very similar in range.

Figure 10 shows the one-dimensional distribution for the longitudinal stress for line 3–1–4. Each line in Figure 10 represents the stress distribution for a specific depth of the plate. Unlike distributions for other two stress components, an obvious and clear pattern is found in the distribution of the longitudinal stress component. This figure also shows that the value of the longitudinal stress changes slightly through the depth of the plate and the maximum tensile stress is found at the depth of 8.9 mm, that is, near

Figure 9. Transverse stress at various depths measured on line 3–1–4.

the plate surface with the weld. For a specific depth of the plate, the longitudinal stress value is maximum tensile at the centre of weld and the stress reduces as the y distance from the weld centre increases and finally becomes compressive (negative) at a distance of about 40 mm on both sides from the centre of the weld. The longitudinal stress on line 3–1–4 ranges from about 218 MPa in compression to 457 MPa in tension. The maximum tensile stress value obtained from this specimen is 13% higher than the yield stress. It should be noted that the upper yield stress obtained from material tests on the plate is 405 MPa. The range of longitudinal stress values obtained from Specimen 2 compared with the parent plate specimen (Specimen 1) is more than five times. The stress value in the compressive plateau varied from about 0 to 200 MPa in compression. Figure 11 shows a three-dimensional representation of the longitudinal stress component obtained from line 3–1–4. This figure is not drawn to scale because the intention is to focus on the stress levels and distributions directly under the weld bead where the stress gradient was high and spacing of measurements was the smallest. In this plot the measurements are displayed at equal intervals, whereas in reality the measurement intervals ranged from 1 mm to 40

mm in the y direction. The figure shows that the stress level in this specimen changes through the depth in a similar pattern as was found in Specimen 1. The figure also shows that the variation in longitudinal stress is less than 50 MPa transversely across the weld bead.

As has been mentioned earlier, three stress components were also obtained along the weld centre line (line 1–2 in Figure 6) to study how the stress components vary in the z direction of this specimen. It was found that all the three stresses remain almost unchanged along the weld line and the maximum variation was about ± 30 MPa. The data collected for Specimen 2 provided a detailed image of the stress distributions when a stiffener is welded on the parent plate. The maximum tensile stress value (457 MPa) was found for the longitudinal stress component at the centre of the weld and the value was about 13% higher than the yield stress (405 MPa) of the plate specimen. This observation agrees well with previous studies (Dexter and Pilarski 2002; Price et al. 2006); however, the current study found slightly higher stress values. This may be due to a variety of factors such as different types of specimens, or heat input used in the study as compared to previous studies. The tensile stress block was almost balanced by the compressive stress

Figure 10. Longitudinal stress at various depths measured on line 3–1–4.

block. The tensile stress block is slightly larger and the small difference between the two was not adjusted to make them equal. The values were not altered because the residual stresses were measured at one transverse line only and the compressive balance of stresses may be located elsewhere on the plate.

5.3. Specimen 3

Specimen 3 was a stiffened plate which was 600 mm (L) $\times$ 400 mm (T) $\times$ 9.5 mm (N). The plate was stiffened with two 600 mm long angle stiffeners spaced at 250 mm centres (Figure 12). The primary objective was to study the effect of welding the second stiffener on the residual stress distributions. The specimen was measured for all three residual strain components in the transverse (y) direction. The strains were measured at three depths for 54 locations to optimise the test time (neutron beam time) since the test data from Specimen 2 showed small and negligible variations in strain values through the depth of the plate. Furthermore, strains at an additional four depths were also acquired at 11 measurement locations to verify whether or

not the variations of strain values through the depth of the plate of Specimen 3 were negligible.

Figure 12 shows the origin (point 1, which lies on the bottom surface of the plate) and the line (2–1–3) on which measurements were taken. The location of line 2–1–3 was chosen to avoid edge effects. Test data obtained from Specimen 2 shows that strains in the z direction do not vary much. Hence, no strain measurements along the length of the stiffener were taken in this specimen and thus it saved expensive neutron beam time. Figure 13 shows the spacing of the measurements in the y direction of the plate. Similar to Specimen 2, near the centre of the weld where stress gradient is expected to be high, the spacing of measurements was as small as 1 mm and it gradually increased up to 35 mm farther away from the weld.

Figure 14 shows one-dimensional distributions for the normal and transverse stress components obtained from Specimens 2 and 3 along line 3–1–4 and line 2–1–3, respectively. Each line in Figure 14 represents the distribution of average of all the stress values obtained at various depths for a particular stress component. This figure shows the comparison between the two different stress components of the same specimen, and also the comparison between the

Figure 11. 3-D distribution of longitudinal stress in transverse direction for Specimen 2.

distributions of the same stress component obtained from two different specimens, i.e. Specimens 2 and 3.

For Specimen 3, the actual normal stress component ranged from 152 MPa in compression to 32 MPa in tension and hence the range of normal stresses for Specimen 3 was

found to be 184 MPa. The range of 184 MPa for Specimen 3 was similar to the range of 222 MPa, which was found for Specimen 2. The range of the transverse stress component obtained from Specimens 2 and 3 were 270 MPa and 284 MPa, respectively, which are also very similar. However, the distributions for these two stresses in Specimen 3 are more compressive as compared to those found in Specimen 2 (Figure 14). Similar to both Specimens 1 and 2, the

Figure 12. Detail for measurement points in Specimen 3.

Figure 13. Measurement spacing in the transverse direction for Specimen 3.

Figure 14. Normal and transverse stresses in Specimens 2 and 3.

distribution for the normal stress component of Specimen 3 does not show any clear pattern. Since the normal and transverse components do not show a clear pattern when all of the collected data are presented, the average stress values were presented to show a better illustration of the stress trends in the specimens. The distribution for the transverse stress component is similar to that for the normal stress component (Figure 14). The transverse stress for Specimen 3 also has a maximum tensile value at the weld centre.

The actual value of the transverse stress component for Specimen 3 ranged from about 238 MPa in compression to 46 MPa in tension. The transverse stress value at the depth of 3.7 mm was more compressive by approximately 100 MPa than the stress values at other depths. This difference is best explained by the inherent locked-in stresses found in the parent plate, where at a depth of 3.7 mm the values were at the minimum. For example, at the distance 115 mm from the origin (point 1) the change in stress levels between the depth of 2.4 mm and 3.7 mm is about 90 MPa. In Specimen 1, the change in transverse stress levels between the same depths is similar (100 MPa). As was shown in Specimen 1, the maximum tensile (positive) stresses were found between

the depths of 5 mm and 6.3 mm, which are also apparent in Specimen 3.

The longitudinal stress was measured at the same locations and at the same depths where the normal and transverse stress components were measured (Figure 13). Figure 15 shows the one-dimensional distributions for the longitudinal stress for line 2–1–3. The distribution of the stress is similar to the one that was found in Specimen 2, though the maximum stress values are lower in Specimen 3. This figure shows that the maximum tensile (positive) stress develops at the weld centre and as the transverse distance from the weld increases the stress value reduces to a compressive (negative) value. A compressive stress plateau exists between the two stiffeners and the average compressive stress value in that plateau is about 150 MPa. The maximum tensile or positive stress occurs at the centre line of the first weld and at the depth of 8.9 mm, that is, close to the welded surface of the plate. The maximum tensile stress value obtained from this specimen was about 430 MPa, which is about 6% higher than the yield stress of the parent plate. Comparing the two tensile stress values at the centre of the welds of two stiffeners, it is found that the maximum tensile stress

Figure 15. Longitudinal stress at various depths on line 2–1–3.

was 430 MPa, which occurred at the first welded stiffener. The maximum tensile stress value at the first welded stiffener is about 10% higher than the maximum tensile stress at the second welded stiffener, which was 390 MPa. It can also be seen that the longitudinal stress value on line 2–1–3 ranged from 360 MPa in compression to 430 MPa in tension. These values compared with Specimen 2 are more compressive since these values for Specimen 2 were 218 MPa in compression to 457 MPa in tension. The same values if compared with Specimen 1 are about six times larger in Specimen 3. Similar to Specimen 2, the residual stress balance is slightly tensile but is most likely the result of a stress balance located elsewhere in the plate.

The compressive plateau between the two stiffeners shows that at a certain transverse distance from the centre line of the weld, the longitudinal stress value stabilises and hence shows very little variation beyond that distance. This plateau, which presents between the transverse distances of 20 mm and 208 mm, shows that the range of the longitudinal stress value was from roughly 220 MPa in compression to 100 MPa in compression.

Figure 16 shows the three-dimensional distribution plot (not-to-scale) for the longitudinal stress component. It is

obvious from this figure that the stress level does not change much through the depth of the plate and transversely in the weld bead. The stress value did not vary more than 50 MPa from one end of the weld bead to the other end.

6. Faulkner model

As has been mentioned earlier, Faulkner (1975) proposed a model for predicting one-dimensional distribution of the longitudinal stress component in the y direction of a welded stiffened plate used in ship hull construction (Figure 1c). Since this model was proposed based on strain measurements at the plate surface, it is not capable of providing any information on how the residual stress changes through the depth of the plate. The other drawback of the Faulkner model is that this model predicts only the longitudinal stress distribution in the y direction. Therefore in the current study the longitudinal stress component that was obtained nearest to the top plate surface (at a depth of 8.9 mm) and in the y direction is compared with the Faulkner model. The Faulkner model predicts a triangular stress distribution near the weld with a maximum tensile stress, which occurs at the centre of the weld and is equal to yield stress of the parent steel plate

Figure 16. 3-D view of longitudinal stress distribution on line 2-1-3 for Specimen 3.

Figure 17. Longitudinal stress on line 3-1-4 for Specimen 2 vs. Faulkner model.

Figure 18. Longitudinal stress on line 2–1–3 for Specimen 3 vs. Faulkner model.

as shown in Figures 17 and 18. This model predicts that the width of the base of the triangle is seven to eight times the thickness (t) of the parent plate. A Faulkner model also predicts a constant stress level for the entire compression plateau between the two adjacent stiffeners (Figure 1c) to balance the tensile stress block located in the heat-affected zone.

Figure 17 compares the longitudinal stress distribution obtained from the transverse line 3–1–4 for Specimen 2 at a depth of 8.9 mm with the one predicted by the Faulkner model. A good agreement between general patterns of these two distributions is found. The stress distribution obtained from the test data of Specimen 2 follows a triangular distribution with a base width, which is seven times the plate thickness. Figure 18 shows the longitudinal stress distribution along transverse line 2–1–3 at a depth of 8.9 mm for Specimen 3, superimposed with the Faulkner model. From this figure it can be seen that the longitudinal stress distribution in the y direction of Specimen 3 also agrees with the Faulkner model in a general sense. The width of the triangular base found from the test data of Specimen 3 is about 7.4 times the plate thickness. However, the maximum tensile stress values at the centre of weld found from Spec-

imens 2 and 3 are 13% and 6% higher, respectively, than the yield stress which is the maximum value predicted by the Faulkner model.

This study determined all the three stress components through the full depth of the plate and in both y and z directions of the plate specimens. However, the Faulkner model is limited to one-dimensional distribution of the longitudinal stress component in the y direction and at the top surface of the stiffened plate only. Therefore, only the distribution of longitudinal stress in the y direction obtained from Specimens 2 and 3 could be compared with the Faulkner model.

7. Conclusions

This study provided an accurate and complete understanding of three-dimensional distributions of all three residual stress components in all three directions of plane parent plate and stiffened steel plates typically found in ship hulls. This was possible because the ND method was used to map the residual strains. The conclusions in this paper are made based on the test data obtained from this study and therefore these conclusions are limited to specimens similar to those used in this study.

Specimen 1 shows that the manufacturing and rolling process in plate production produced locked-in bending stresses of considerable magnitude through the thickness of the plate.

The residual stress distributions obtained from two stiffened plate specimens, Specimens 2 and 3, provided a good knowledge of the effect of welding one and two stiffeners on the residual stresses in stiffened plates. The distributions for all the three stress components were found to be similar. The longitudinal stress in the y direction shows a clear pattern similar to the one predicted by the Faulkner model. However, the Faulkner model was not able to predict the maximum tensile stress values accurately. The distributions for the other two stress components obtained from stiffened plate specimens do not show any clear pattern. Interestingly, all the three stresses remain almost unchanged in the z direction and through the depth of the plate.

The maximum tensile value of the longitudinal stress occurs at the weld centre. When two stiffeners are welded, the value of the maximum tensile stress at the first welded stiffener was roughly 10% higher than that of the second welded stiffener. The maximum tensile stress that occurred in Specimen 3 was found to be less as compared to the one that occurred in Specimen 2. Hence, it can be concluded that welding of the second stiffener was beneficial.

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