SSC PROJECT SR-1456
Exact Mapping of Residual Stress in Ship Hull Structures
(First Quarterly Report on Literature Review)

Submitted
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1.0 Introduction

Residual stresses are caused by thermomechanical processing of steel. These processes either alter the shape of the metal or induce a temperature gradient which generates residual stress. Processes that alter the physical shape include machining, forging, rolling, drawing, etc. The welding, casting, and quenching processes introduce a temperature gradient to the metal.

Residual stresses developed in welded structures primarily as the result of differences in the amount the weld metal shrinks as it hardens and cools to the surrounding temperature. Residual stresses are highly unpredictable and often non-uniform. In order to produce acceptable results, several locations on the specimen must be measured for strain, since a steep gradient in strain may be produced by residual stresses.

Residual stresses are usually calculated from the elastic strain values. The elastic strain measured is either the existing strain or the change in strain when residual stresses are released. The elastic strain values are converted to stress values using the elastic strain constants. Residual stresses developed during the welding process are macrostresses (Type I) that are continuous from grain to grain and from phase to phase.

The method for measuring residual stress and the locations and number of measurements depend on the expected stress field. Preliminary tests may be required for a better estimate of the residual stress field. The chosen method also may depend on the nature of the specimen, for example, if the sample is too large to move and measure in a laboratory, the measurements need to be carried out using portable measurement devices in the field.

A scaled version of the actual specimen may be used for determining the residual stress distribution. However, it must be large enough to avoid improper readings, when a laboratory test method is chosen. Generally, the rule that is followed is that the length and width of the plate should be at least three times the plate thickness.

There are various methods available for measuring the residual stresses. These methods are divided into three major categories: (i) destructive, (ii) semi-destructive, and (iii) non-destructive. Discrepancies exist among these different types of test methods. This is because a
steep gradient of stress exists in the steel and because the test volume required for the different types of test methods vary as well.

The required test area or volume must be less than 1 mm$^2$ or 1 mm$^3$, respectively, to produce an accurate image of the stress field. The peak stress values may be missed if the test areas are too large for the very sharp stress gradients. Thus, the test area or volume size must be optimized for the best data collection with the minimal number of measurements taken, to detect the peak stresses and their values.

The type of test chosen may produce different types of errors. These errors are due to material characteristics of the steel such as, crystallographic texture, phase composition, grain size, and plastic strain.

2.0 Computer Modelling

The residual stress distribution is also determined using numerical methods such as finite element (FE) method. ABAQUS (Simulia 2008), which is a commercially available general purpose FE code, often used (Prime, et al. 2004) to determine the residual stress distribution in solids and structures. ABAQUS can be used to model the behaviour of solids under externally applied loads and body forces. ABAQUS is capable of three-dimensional models subject to static and dynamic loading patterns. Other FE codes such as ADINA (Hu and Jiang 1998) and ANSYS (Cho, et al. 2004) are also available and used for determining residual stresses.

Ayala-Uraga and Moan (2007) studied floating production storage and offloading vessels and formulated a time-variant reliability assessment for through-thickness crack in the hull girder. The propagation rate of long crack in the stiffened hull is greatly affected by still-water loading conditions and the residual stresses, the most notable are the stresses introduced by welding. They found that the presence of compressive residual stress between the stiffeners results in a much slower rate of crack propagation. However, as cracks propagate, the residual stress redistributes and decreases which produces an increase in the growth of the crack. The study used FE code to compare the time-variant reliability analysis formulation with a time-invariant reliability method for a long crack in a stiffened panel. The time-invariant method resulted in a
good approximation for the time-variant problem. The analysis results provided an outline for inspection, maintenance, and repair activities required for in-service floating production storage and offloading vessels. The study proved that the crack propagation rate is greatly affected by the still-water stresses and the residual stress can be ignored for conservative estimate.

3.0 Destructive Test Methods

Destructive test method is the most commonly used technique for determining residual stress distribution. This is because the method is convenient and simple (very small distance). Destructive methods are basically stress relaxation techniques, where the residual stress within a finite element is released and the change in strain is measured. As a result of destructive testing, the sample becomes inoperative and therefore, there must be enough material to test and destroy.

Destructive tests produce optimal results when the nature of the stress field and the magnitude of stress gradient are known. The stress field determined can be triaxial, biaxial, or uniaxial producing a stress gradient that is three, two, or one-dimensional, respectively. The magnitude of the stress gradient is inversely proportional to the size of the finite element measured along that gradient.

The most widely used form of destructive testing is the sectioning method. The sectioning method uses strain gauges to read the initial strain values. The material is then removed around the gauges and the final strain readings are taken. The strain due to residual stress in the metal is the difference between the initial and final strain values. The methods of removal include milling, sawing, grinding, drilling, and lathe turning. The method of metal removal can introduce high stress levels at the surface of the material and must be accounted for. The surface stresses introduced in this method can be minimized or even be removed by using electrochemical methods. Some metal removal methods reduce the residual stress by introducing heat and the process of annealing to the specimen. Chemical or electrolytic polishing is one type of material removal sectioning processes that does not change the actual residual stress pattern in the metal.
Recent interest has been in another form of destructive testing called the contour method. In this method, the specimen is cut by an electro-discharge machine with a flat cut. The specimen deforms as the residual stresses relax. The deviations of the contours are measured using laser scanning. The laser scanning determines the out-of-plane stresses. This method provides a two-dimensional stress field normal to the cut and is best used for measuring the longitudinal stress in a weld. The method is generally used when the stress levels are low and the specimens are smaller in size.

Hu and Jiang (1998) conducted laboratory tests to determine the ultimate strength of stiffened panels with varying amounts and types of damage. Then they compared the test results with the results obtained from nonlinear finite element analysis. The metal used in the specimens was hot-rolled 350 WT steel (CSA 2004). The length of all the specimens was 2000 mm (Figure 1). The stiffeners were tee sections with flange dimensions of 103.9 mm x 8.1 mm and web dimensions of 136.8 mm x 6.2 mm.

![Figure 1: FE representation of the specimens (Hu and Jiang 1998)](image)

![Figure 2: (a) Distance from edge of plate (mm) vs Stress at plate (MPa); (b) Distance from edge of flange (mm) vs Stress at flange (MPa); (c) Distance from junction of plate and web (mm) vs Stress at web (MPa). (Hu and Jiang 1998)](image)
The plate was 500 mm wide and 9.7 mm thick. Coupon test data indicated a yield strength of 425 MPa for the plate, 411 MPa for the web, and 395 MPa for the flange. The residual stresses were found in the longitudinal direction (Figure 1) using the sectioning method. Figure 2 shows the residual stress distributions obtained in the longitudinal direction. The nonlinear finite element models were developed using ADINA (ADINA 2008). A four-node quadrilateral shell element was used to simulate the plate and stiffeners. The residual stress due to welding was simulated using a thermal stress application. The FE models and the laboratory tests provided similar stress patterns. However, the magnitude varied since the actual welding processes were not as closely monitored. The longitudinal stress values were tensile near the weld with a steep conversion to compressive stress away from the weld (Figure 2 (a)). The maximum value of stress was almost equal to the tensile yield stress of the metal. The results from the FE method and the physical tests are compared in Figure 2. The FE analyses indicated that the behaviour of a stiffened panel is greatly affected by the degree and location of the residual stresses from welding.

Prime et al. (2004) used the contour method with laser scanning to measure residual stresses normal to the cross-section. The specimens were ferritic steel BS 4360 grade 50D (ASTM 2008a) with minimum yield strength of 355 MPa. The plate was flame-cut to a size of 1000 mm x 150 mm x 12.5 mm with an 8 mm U-groove at the centre. A 12-pass weld was made in the groove using Tungsten Inert Gas (TIG) and metal active gas (MAG) wire for the welding process. The plate was clamped for all passes except the last two, resulting in a 7° bend in the plate from the weld line. The plate was then cut into 200 mm wide strips from the centre of the plate for testing. The 200 mm samples were measured using the contour method and neutron diffraction. A comparison between two contour methods using the higher resolution non-contact laser surface contouring method and using the conventional touch probe machine, (typically using a Coordinate Measuring Machine (CMM)) were undertaken. The stress distribution from the contour methods were finally determined using FE code, ABAQUS. The results between the two contours methods showed a good agreement. However, higher resolution was possible with the laser scanning, which is the best choice for more moderate variations in stress profiles. The comparison between the neutron diffraction results and the contour methods showed a good agreement as well. The also used the neutron diffraction method and the results obtained from the neutron diffraction method and the laser surface contouring method are shown in Figure 3.
Semi-destructive test methods are commonly used when the integrity of the sample need to be kept intact. Majority of the semi-destructive methods are stress relaxation techniques, similar to the destructive methods. These methods do not completely destroy the component but still inflict minimal damage to the surface of the sample. Examples of semi-destructive test methods are: hole-drilling, ring coring, trepanning, indentation, and spot annealing methods.

The most commonly used semi-destructive method is the hole-drilling method which uses either shallow holes or deep holes. The method uses strain gauges to measure the change in the surface strain caused by residual stresses which are released when a hole is drilled in the surface. The remaining material then readjusts to reach equilibrium. Another method called the ring coring
method is similar to the hole-drilling method, except a ring is drilled around the strain gauge and a cylinder of metal is isolated around the gauge of strain-free material. The depth of the measurement in both methods is roughly equal to the diameter of the hole. The most accurate results are obtained at a depth of half the diameter.

Since the stress is assumed constant over the entire area, these methods should not be used where the stress gradient is high. Local plastic yielding occurs during the drilling process; therefore areas where the stresses are greater than one-third the yield strength must be avoided. The drilling also causes strain hardening in the area around the hole and can cause an error of up to 70 MPa (10 ksi). The thickness of the measured sample must be at least four times the hole diameter and the holes must be spaced at least eight times their diameter to obtain accurate results.

Wilken (1976) examined the use of the hole-drilling method in comparison with the splitting-up (sectioning) method. The hole-drilling method is a semi-destructive method and thus, useful for in-service structures. In comparison with the splitting-up method, the hole-drilling method was found to be much easier to apply and yielded similar results. However, the hole-drilling method requires the use of complicated mathematical computations and makes several assumptions which may be incorrect. The assumptions are:

1. The stress is uniform across the whole thickness of the sheet.
2. The plate is unlimited in all directions.
3. The validity of Hooke’s law.
4. The constant nature of residual stresses in the region of the measuring point.
5. The avoidance of plastic deformation at the edge of the drilled hole, affected by placing the measuring sensor at a certain distance from it.

The accuracy of the hole-drilling method was first compared to the splitting up (sectioning) method on plated I-girders welded in various sequences. The results obtained from the two methods were considered accurate within reasonable error limits and proved the validity of the hole-drilling method. Then hole-drilling experiments were carried out on the welds of the longitudinal frame of a ship. Compressive residual stresses were found in the webs and high tensile residual stresses were found in the flange near the weld. The ship was in service for 18
months and no cracks had developed at the time when the hole-drilling procedure was conducted. Since this research was conducted in the 70s, the use of finite element method was not common practice and thus, it was not used.

Several ships experienced catastrophic failures in the 1940s. Therefore, Meriam et al. (1946) conducted several tests on actual ship subassemblies to determine a method of measurement of residual stresses from welding. Strain gauges were used and holes were drilled around the gauge to remove the plug of metal containing the gauge. Two measurements were taken: (i) after the welding process and (ii) after the drilling. All strains measured were assumed to be elastic and elastic equations were used to convert the measured strain values to stress. Due to the nature of the equipment available at the time, the shortest length gauge was 6 mm (¼ in); consequently the steep nature of the stress near the weld was averaged over the area and precise values were not available. This method only allowed measurement of surface stresses and no measurements through the thickness of the plate were undertaken. All stresses were assumed as to average over the plate thickness, and therefore remain constant through the thickness. The final results found using this method were satisfactory with an error of ±13.8 MPa (±2000 psi).

Cho et al. (2004) compared the residual stresses due to welding process and due to post-weld heat treatment using FE code, ANSYS (ANSYS 2008), and the hole-drilling method. The type of metal used was SM400B (A131 Gr. 50) with a yield stress of 294.2 MPa, a Young’s Modulus of 210.8 GPa, and a Poisson’s ratio of 0.3, all at 20°C. A ten pass regular butt weld, a twelve pass K-type butt weld, and a nine pass V-type weld were analyzed using the FE method. The ten pass butt weld produced a minimum residual stress of -267 MPa (compression) and a maximum value of 333 MPa (tension). Following the post-weld heat treatment the maximum residual stress found was 38 MPa. The K-type weld produced a range of residual stresses from -300 MPa to 316 MPa which were reduced to a 39 MPa maximum following the heat treatment. The V-type weld produced a minimum residual stress of -239 MPa and a maximum value of 265 MPa, which were reduced to -34.2 and 30.7 MPa, respectively following the heat treatment. The welding process was simulated in ANSYS with the time for the heat transfer analysis for each weld pass as the total weld length (varies) divided by the welding velocity (20 cm/min). The hole-drilling method of measuring surface residual stresses was used on the butt weld and the results were consistent. A post-weld heat treatment was programmed for the K- and V-type
welds and produced a significant drop (85%) in residual stress values. The results for the ten pass regular butt weld are compared in Figure 4.

Somerville et al. (1977) measured distortions and residual stresses in stiffened panels. The panels were constructed of various sizes and welded with varying sizes and spacing of stiffeners. Two types of steel were used: mild steel (yield stress = 262 MN/m² or 262 MPa) and ‘B’ quality steel (yield stress = 355 MN/m²). They studied the contraction of the stiffener weld as it cools and the compressive stresses that develop in the plate. They measured surface strains using dial gauges. The stiffeners caused limited or no access to some areas. Thus, modifications in measurement techniques were made using indents instead of drilled holes. The results of these tests provided a very rough estimate of the residual stress field and the distortion effects. The lack of equipment available at the time of testing provides little correlation with the results achieved from more recent experiments.

Weng and Lo (1992) used the blind hole-drilling method of ASTM E837 (ASTM 2008b) to measure the residual stresses in welded structures and compared the results to those found using the sectioning method. Since hole-drilling creates local plasticity due to stress concentration in the metal, calibration tests were performed to determine calibration coefficients. The ASTM E837 method provides calibration coefficients but only when stress values are less than 50% of
the yield stress. Twelve samples were produced using A36 and A572 grade 50 structural steel plates of thicknesses 15 mm and 32 mm. Residual stresses were measured in three different types of joints: butt, tee, and corner. The welding was done using the submerged arc welding (SAW) method. The diameter of the drill used was 1.57 mm, and the maximum depth of the hole is 1.2 times the diameter, as specified in ASTM E837 (ASTM 2008b), roughly equal to 1.88 mm. The hole-drilling method, therefore, could only measure surface stresses and not the internal stresses. Also, due to the nature of the strain gauges and hole-drilling technique, the residual stresses were measured only to the edge of the weld and the stresses within in the weld and welded part could not be measured. The residual stress near the weld was found to be from 84% to 100% of the yield stress (312 MPa to 377 MPa) and therefore required the recalculated calibration coefficients for the local plasticity from drilling the holes. For surface stress measurements, the hole-drilling method was found to have similar results to those found using the sectioning method. The results are shown in Figure 5. The results are plotted by distance from welded edge (mm) versus the residual stress (MN/m$^2$). Figure 5(a) shows the residual stress values found in both the x- and y-directions of the butt welded joint. Figure 5(b) shows the residual stress values (MN/m$^2$) for the tee joint plotted against the distance from the welded edge (mm). Figure 5(c) shows the residual stress in the x- and y-directions on the corner welded plate.
Figure 5: Residual stresses in welded specimens (Weng and Lo 1992)
5.0 Non-Destructive Test Methods

Non-destructive test methods produce no permanent physical damage to the specimen and structure. The most common methods are X-ray diffraction, the magnetic Barkhausen noise technique, and neutron diffraction, which will be discussed in a later section.

X-ray radiation was discovered in 1896, and used for residual strain determination 20 years later when Bragg’s equations were formulated. X-ray diffraction has minimal capability of penetrating the crystalline structures of typical engineering materials. The penetration path length is adjustable by appropriate selection of specific x-ray energies and wavelengths, but is still limited to a few tens of microns. X-rays are diffracted by the cloud of electrons surrounding the nucleus of the sample material. Recently, with the introduction of third-generation synchrotron sources, which provide higher x-ray energies, there are no absorption edges and the attenuation length increases noticeably with increasing energy. This combined with the relatively high x-ray intensities that they produce leads to path length of centimetres in steel (Krawitz 2001).

The magnetic Barkhausen noise technique is used in ferromagnetic metals to measure the number and magnitude of sudden magnetic reorientations made by expansion and contraction of the magnetic fields. The stresses are measured by the inductive measurement of a noise-like signal, generated when a magnetic field is applied to the metal. However, the depth of measurement only varies between 0.01 and 1.5 mm. The depth possible depends on frequency range of Barkhausen noise signal analyzed and the conductivity and permeability of the sample material.

Gao et al. (1998) tested three welded HSLA-100 (ASTM 2007) steel plate specimens with WIC joint configuration using standard X-ray diffraction to determine the residual stress fields. The plates were 19 mm thick and were heat treated, quenched, hardened to produce yield strengths between 690 MPa and 830 MPa. All specimens were preheated to 50°C then gas metal arc welding was used with MIL-120S-1 welding consumables. The first specimen was welded with no restraints on its edges and with a heat input of 14 kJ/cm. The second specimen was restrained and was subjected to the same heat input as the first specimen (14 kJ/cm). The third specimen was not restrained and welded with a higher heat input of 17 kJ/cm. The X-ray diffraction
measurements were acquired using a portable apparatus. Subsurface measurements were achieved using electropolishing, removing 50 μm layers between each reading. X-ray diffraction can only measure approximately several microns deep into most engineering materials. The residual stress measurements were taken in the longitudinal, transverse, and 45° directions from the weld bead. The longitudinal stress component is in the direction of the weld, the transverse stress component is perpendicular to the weld direction, and the 45° direction bisects these two stress components. The results from these experiments show that welding heat input has a significant effect on the residual stress values. A higher heat input produces less residual stress. The decrease is a result of a slowed cooling rate which causes a restriction in shrinkage and phase transformations. They also found that the restraining of the sample also has a considerable effect on the residual stress field. It was found that additional tensile residual stresses may be introduced due to the restraint. However, phase transformations may occur during restraint and produce compressive stresses. The measurements obtained using the X-ray diffraction technique show similar stress fields as previously established (Weng and Lo 1992; and Hu and Jiang 1998). The longitudinal surface stresses were tensile near the weld and compressive away from the weld. At the surface of the plate, the transverse stresses were compressive near the weld and increased to tensile stresses as the distance from the weld increases. The stresses measured at 45° from the weld were found to be values within the envelope of the longitudinal and transverse stresses. The results are shown in Figure 6 for all three samples for the three different directions of surface residual stresses. Figure 6(a) shows the first sample that was welded with the low heat input (14 kJ/cm) and no end restraints. Figure 6(b) shows the residual stress in the second sample, with the low heat input (14 kJ/cm) and end restraints, plotted against the distance from the weld. Figure 6(c) shows the residual stress values of the third sample, with high heat input (17 kJ/cm) with end restraints, plotted against the distance from the weld.
Gauthier et al. (1998) studied the use and validity of the magnetic Barkhausen noise (MBN) method. The MBN method uses the theory that a ferromagnetic material, such as structural steel, when undergoing a change in magnetization will produce noise in the form of voltage pulses which are induced in a coil set near the sample. The MBN signal increases with the presence of tensile stresses and decrease in the presence of compressive stresses therefore, provides an accurate picture of the residual stress field. The sample used was an L-shaped cold-formed steel beam with a yield stress of 466 MPa and an elastic modulus of 203 GPa. The results were compared with the cutting and sectioning method, the hole drilling method, and X-ray diffraction method. All these methods provided comparable results. The MBN method requires very close (~0.1μm) proximity to the sample and the stress measurements in the corner of the sample are not accurate. Therefore, the use of this method in measuring welds of stiffeners does not produce acceptable results of the sharp gradients present in the welding stress field.

Figure 6: Surface residual stress distributions of (a) RS1 - 14kJ/cm, no restraint, (b) RS2 - 14kJ/cm, with restraint, (c) RS3 - 17kJ/cm, no restraint (Gao, et al. 1997)
Rörup (2005) tested a 550 mm x 120 mm x 12.5 mm 355 MPa steel plate with 150 mm x 30 mm x 12.5 mm longitudinal stiffeners were welded on both surfaces of the plate using a two pass fillet weld, as shown in Figure 7. The plates were all saw cut from one larger plate. The specimen was loaded with two constant compressive cyclic load ranges; 140 N/mm² or 180 N/mm². The test showed that after an initial fatigue crack, perpendicular to the stiffener, the growth rate increases under the compressive loading cycle until a sudden deceleration or stop in expansion. The initial residual stresses were measured using both the X-ray diffraction method and the hole drilling method. The stresses were found to be lesser on the surface of the plate where the stiffener was welded later. The redistributed stress field at the crack tip due to the cyclic loading were measured using the neutron diffraction and X-ray diffraction methods for comparison. These results were then compared with the FE model and analysis as shown in Figure 8. The residual stress was modeled in the FE analysis using heat flux input. The FE analysis predicted similar stress values as was found in the physical experiments. The residual stresses due to the welds controlled the fatigue life of the plate under a compressive cyclic load. The fatigue life of the stiffened panel increased due to the crack propagation phase of the loading. At the weld toe and the crack tip, the residual stresses are in tension. With the

Figure 7: Test specimen with a typical crack and residual stress distribution (Rörup 2005)
introduction of the cyclic compressive loading, the crack propagates in the compressive residual stress region. The crack as it expands, moves the tensile stress region forward as it loses strength, which in turn causes the crack growth to slow or stop completely.

6.0 Neutron Diffraction

Neutron diffraction method is a non-destructive test method. This method uses either a steady state reactor or a pulsed neutron source. A steady state reactor is designed for research and produces a high neutron flux with a minimal amount of heat, in contrast to a reactor used for nuclear power. The reactor generates a Maxwellian distribution of neutron energies that are dependent on temperature. A monochromator is used to remove a single usable wavelength from the neutron beam, which is used to provide the scattering data from the material. A steady state reactor produces a constant wavelength for testing procedures. A pulsed neutron source generates neutrons using a process called spallation. A burst of high-energy particles (protons or electrons) strike a metal sheet which produces a broad range of neutron energies with a broad range of velocities. Therefore, these neutrons will take varying amounts of time to reach the detector or time-of-flight instrument, producing the scattering information of the material.

Neutron diffraction utilizes the crystal lattice of the sample material as an atomic strain gauge. The average elastic lattice strain in the gauge volume is calculated as the difference in the lattice plane spacing compared to the lattice plane spacing of the stress-free sample. A beam of neutrons, with wavelength $\lambda$, from a continuous source diffractometer is passed through the sample and diffracts in accordance with Bragg’s law, as in Equation 1.
\[ \lambda = 2d_{hkl} \sin \theta^P_{hkl} \] \hspace{1cm} (1)

Where, \( d_{hkl} \) is the lattice spacing of the planes \( hkl \) in the crystalline solid, as shown in Figure 9.

\( 2\theta^P_{hkl} \) 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. In this figure, the incident beam is labelled as \( k_i \) and the refracted beam as \( k_f \). \( G_{hkl} \) is the reciprocal lattice vector, perpendicular to the lattice planes.

Crystal space lattices are categorized according to their symmetry, translation, reflection, and rotational characteristics. There are 14 crystal space lattices called Bravais lattices, the most common for engineering materials are the fcc, bcc, and hexagonal.

All lattice points are on a plane in the crystal, known as Miller indices, and denoted \( hkl \). The \( hkl \) plane intersects the axes of the unit cell at \( a/h, b/k \) and \( c/l \), where \( hkl \) are the lowest integers with the proper ratio of intercepts, as shown in Figure 10. As stated before, the perpendicular distance between planes is \( d_{hkl} \).

The de Broglie wavelength of the neutron, \( \lambda \), is related to the momentum, \( p \), of the particle as shown in Equation 2.

\[ p = m_n v = \frac{h}{2\pi} = h k \] \hspace{1cm} (2)

Where, \( m_n \) is the mass of the neutron, \( v \) is the velocity, \( h \) is Planck’s constant, \( k \) is the wave vector of the neutron with a magnitude of \( 2\pi/\lambda \). The energy of the neutron is shown in Equation 3.

\[ E = \frac{1}{2} m_n v^2 = hv \] \hspace{1cm} (3)

where \( v \) is the frequency of radiation. For wavelengths useful for diffraction, thermalized neutron energies are significantly less than the equivalent energies of X-rays or electrons.

The lattice spacing (\( d_{hkl} \)) expands with tensile stresses and contract with compressive stresses. The difference in lattice spacing is measured by the shift in Bragg diffraction angle, \( 2\theta^P_{hkl} \). Strain in the direction of the scattering vector is given by Equation 4.
As a neutron approaches the nucleus of an atom, four outcomes are possible: (i) coherent scattering, (ii) incoherent scattering, (iii) absorption by the nucleus, and (iv) the most likely event is no scattering. Coherent scattering relates the space and time between atoms, whereas incoherent scattering is the individual atom relations with space and time. When the neutron is absorbed, the compound formed with the nucleus creates an emission of $\gamma$-rays, which may radioactively decay. The coherently scattered neutrons diffract at well-defined angles allowing for ease of measurement, whereas, incoherent scattering is isotropic and creates a background beneath the diffraction peaks, much smaller than the diffraction peaks from the coherently scattered neutrons.

Neutron diffraction can penetrate tens of centimetres into common engineering materials and is a non-destructive testing method that can monitor the stress changes due to an environmental factor, external loading, and body forces. Neutron diffraction measures the strain averaged over a sample volume defined by apertures, called Nominal Gauge Volume (NGV). The Instrumental Gauge Volume (IGV) is the volume over which the average strain is measured in a sample and is therefore, larger than the NGV. The Sampled Gauge Volume (SGV) is the volume over which the strain measurement is averaged, taken from the diffraction peak in the IGV. If the sampled gauge volume is greater than the characteristic volume, then the corresponding strain is not measured since it averages to zero.

$$d_{hkl} = \frac{\Delta d}{d} = -\Delta \theta_{hkl} \cot \theta_{hkl} \quad \text{(4)}$$
James et al. (2006) used neutron diffraction technique for measurement of residual stress in high strength steel (tensile strength > 600 MPa) butt welds and for determination of how residual stress depends on various factors such as, weld heat input, plate thickness, and filler material. The welding method used was metal inert gas (MIG) with a shielding gas composed of 80% argon and 20% carbon dioxide. The transverse stress measurements were made using neutron diffraction at mid-depth and 1 mm below the surface. The normal and longitudinal stress values were also collected. However, the study primarily focused on fatigue cracking, which initiates at the toe of the weld and develops parallel to the weld as a result of transverse stresses. The normal stresses were in compression in the upper portion of the plate and in tension in the lower portion of the plate. However, these values were small and all nearing zero therefore, producing a plane stress problem. The study also evaluated the use of undermatched, matched, and overmatched filler material. The specimen with undermatched filler material exhibited lower tensile maximum stresses than the matched and overmatched specimens. The compressive maximum stresses in the undermatched specimen are associated with the heat affected zone, while in the overmatched specimen; the compressive maximum stresses were outside of the heat affected zone. Specimens with two plate thicknesses were tested: 8 and 12 mm, and the thinner plate showed higher residual stress values than the thicker plate due to the fast rate of cooling, which were worsened by the lesser weld heat input. The details of the specimens are shown in Figure 11. The stress values obtained from the 12 mm thick specimen with overmatched weld

Figure 11: Cross-sectional (Y-Z) details of the multipass weld runs used to make the butt joints in the 8mm and 12mm thick plates of RQT701 steel - (a) 8 mm plate thickness with low heat input (1 kJ/mm), (b) 8 mm plate thickness with high heat input (3 kJ/mm), (c) 12 mm plate thickness with low heat input, and (d) 12 mm plate thickness with high heat input (James, et al. 2006)
metal with a low heat input (see Figure 11(c)) are shown in Figure 12.

Figure 12: Specimen - 12 mm thick, overmatched weld metal at low heat input 1 kJ/mm (a) Longitudinal (x) stress profile at four depths (b) Transverse (y) stress profile at four depths (c) Through-thickness (z) stress profile at four depths (James, et al. 2006)
Paradowska et al. (2006) examined the reference samples used in the neutron and synchrotron X-ray diffraction testing. The pseudo-strain values were the object of the testing and relate to the difference between the lattice spacing at a point and the average spacing across the sample. The specimens were low carbon steel welded using the flux-cored arc welding (FCAW) process. The samples were then created using electro-discharge machining (EDM) to generate a cube and a comb for testing. The measurements were taken in the transverse and normal directions of the weld using both methods as shown in Figure 13 and Figure 14, respectively. The final values showed that both neutron and synchrotron X-ray diffraction methods, the reference sample may be taken from the parent material. The microstructure and texture in the weld and the heat affected zone do not warrant the expensive procedure of manufacturing a comb for the specific reference values of each area.

Wimpory et al. (2003) measured residual stress in T-plate ferritic steel weldments of 25 mm, 50 mm, and 100 mm thick base plates for residual stress using neutron diffraction and deep hole drilling methods. The 25 mm thick base plate was welded using a T-fillet weld and the 50 mm
and 100 mm thick base plates were welded using partial penetration welds. The 25 mm and 50 mm plates were restrained to prevent distortion, however the 100 mm thick plate (Figure 15) was rigid enough and thus, no clamps were used. The finished welded specimens were sliced into 12.5 mm thick samples for measuring residual stresses using neutron diffraction method. A 100 mm thick section of the 100 mm thick T-plate weld was used for the deep-hole drilling method. The neutron diffraction tests were conducted at three different nuclear reactors; two monochromatic sources and one polychromatic source. The reference samples were taken from the base plate material in an area of no stress. A reference sample should also have been taken in the weld material for comparison. The steps in the deep-hole drilling method were as follows: a smooth reference hole was drilled and measured at various depths and angles then a cylinder surrounding the reference hole was extracted and the reference hole was again measured at the same locations. This method provided the longitudinal and transverse residual stresses. The normal stresses could be obtained if the axial distortions were also measured, but were not recorded in this study. The deep-hole measurements were taken at the point of intersection between the plate and the weld and continued towards the edge of the plate, as shown in Figure 15. Measurements were not taken into the weld and the stiffener. The deep-hole measurements and the neutron diffraction results were compared and

![Figure 15: Location of deep-hole drilling measurements on the 100 mm thick plate specimen (Wimpory, et al. 2003)](image)

![Figure 16: Transverse stresses in the 100 mm T-plate - ND measurement on a 12.5 mm slice and DHD measurement (Wimpory, et al. 2003)](image)
showed a good agreement as shown in Figure 16 and Figure 17. Neutron diffraction measurements were also taken on a post-weld heat treated sample of a 25 mm T-plate weld. The results showed that overall the residual stress in the sample were close to zero, however a post-weld heat treatment is not feasible in the construction of a ship. The results of all of these experiments were also compared with previous experiments that were conducted and again showed a good agreement. The results were also compared with the British Energy R6 and BS 7910 which show representations of residual stress fields for varying weld configurations. This comparison showed that these standards are very conservative and do not provide a very accurate picture of the stress distribution.

Pearce and Linton (2006) used neutron diffraction method to determine the residual stresses within a curved plate and a butt weld specimen. Both samples were constructed from BIS 812 Ema Steel. The measurements were conducted using the 211 peak and neutrons with a wavelength of 1.4 Å. The stresses were measured in the longitudinal, transverse, and normal directions. The results shown in Figure 18 have similar profiles as previously measured samples using different methods of measurement.

Lorentzen and Ibsø (1995) evaluated the residual stresses in offshore welds using neutron diffraction method for better understanding of the fatigue life of the structure when imposed to cyclic and stochastic loading. The specimens were constructed of St.52-3 (Fe510C) steel of 8
mm and 16 mm thicknesses, and were butt welded on either side of the plate with 5 and 10 mm plates, respectively. No post-weld heat treatments were used. The strain measurements were taken in the longitudinal direction only and the normal and transverse directions were ignored. The two directions were disregarded because of tests that were previously completed indicates that the principal directions change as a function of depth into the material. Therefore, to properly measure internal strains, the principal axes must be re-evaluated at all measurement depths. Only the surface stresses were found for this study since fatigue cracks generally occur due to the high tensile stresses at the surface of the material. The values obtained showed a maximum residual stress value of 50% the material yield stress.

Webster and Wimpory (2001) suggested procedures for obtaining consistent results using the neutron diffraction method of measurement. Their study shows that by placing the beam apertures as near the sample as possible minimizes the irregularities in identifying the centroid of the sample. Planes that do not exhibit bulk behaviour and are affected by plastic strain must be ignored. Single crystals within these planes are anisotropic and when subjected to different reflections will result in different strains, forming an erroneous field of stress. A proper value for the stress-free lattice spacing must also be obtained. The stress-free values should be taken from the parent material, as well as from the welding material.

Price et al. (2006) examined the residual stresses caused using MIG (metal inert gas) welding of a single bead-on-plate of low-carbon steel and the influence of restraint. The study was conducted using a 200 x 100 x 12 mm plate, where the first specimen was unrestrained and the second specimen was fully restrained by tack welding to a very thick steel plate. A 14 mm weld was made through the centre of the plate as shown in Figure 19.

![Figure 19: The direction of the measurements (transverse x, normal y, longitudinal would be z) using neutron diffraction on the single bead-on-plate (Price, et al. 2006)](image)
The neutron diffraction measurements were undertaken using a wavelength of 1.4 Å and detector angle of $2\theta_B = 73.5^\circ$. The transverse and normal stresses were found to be low, especially compared to the fully restrained sample, due to the deformation during welding of the unrestrained sample. In the centre of the weld the normal and transverse stresses were compressive for the unrestrained sample and tensile for the fully restrained sample. The peak stress was in the longitudinal direction occurred near the centre of the weld, and was observed to be higher than the specified yield stress of 285 MPa in the parent metal and 445 MPa in the weld metal; this is due to the increased hardness of the steel in the weld region. These peak values were also found to be higher in the fully restrained sample compared to the unrestrained sample, as shown in Figure 20. The experimental results of the unrestrained sample were compared with three-dimensional finite element modelling; using a commercial program called Sysweld+. Qualitatively, all of the data for transverse, normal, and longitudinal values were in agreement with the observed values during the experiments. However, the longitudinal stress values were in disagreement which was a result of the unrefined mesh and the true calibration of the welding heat source in the model.

Paradowska et al. (2005) studies the residual stress distribution in single and multi bead-on low carbon steel welds and correlated the data to construction methods and integrity specifications. The effect of restraint, the start and end of the weld and multi-pass welds were closely examined using the neutron diffraction technique. The hardness and microstructure was determined across the plate, weld, and heat affected zone. The hardness of the weld and the heat affected zone were a result of a critical cooling environment and the lack of a post-weld heat treatment. The results showed that for the unrestrained sample the normal and transverse stresses in the centre of the weld were compressive, whereas in the restrained sample these stresses were in tension. Overall, the transverse and normal stresses were low in the unrestrained sample as it was
permitted to deform during the welding process. The longitudinal peak stress in the weld was
higher than the yield stress of the plate metal, which corresponds to the increased hardness
values in the weld and heat affected zone. The residual stresses in the transverse and normal
directions peaked at half the maximum longitudinal stress values, which occurred in the heat
affected zone below the middle of the weld bead. The start and end of the weld had high
increases in stress levels and surpassed the yield strength of the plate material. For the plates
with two, three, and four weld passes, the welds overlapped 50%. When the second weld pass
was made, the weld underneath the overlap the residual stress values increased threefold but the
uncovered weld portion increased by only 70%. For the third weld pass, the stress remained the
same beneath the weld and decreased under the second pass to almost zero. The final weld pass
caused the residual stress transfer from all other weld passes into the final weld with a general
widening of the peak stress field. The tensile residual stresses in the toe of the weld were
reduced, with the fourth weld pass, to more favourable compressive values and lower tensile
values. The collected data can be utilized in the design of welds. The longitudinal stresses cause
transverse hydrogen cracking, in the toe of the weld the transverse stresses cause the introduction
of fatigue cracks, and the sequence of multi-weld passes greatly affects the distribution of the
residual stress field.

Holden et al. (2006) investigated several factors relating to measurement of residual stress in
welds. These factors include the varying microstructure through the weld and the change in
plastic deformation in the weld zone. They emphasized the importance of obtaining the
reference samples from a companion weld, in order to understand and determine more accurate
stress distributions. Three different samples using neutron diffraction were studied: a butt weld
between 8.6 mm thick, highly textured Zr-4 plates, a double-v butt-weld between 10 mm
weakly textured high-strength steel plates as shown in Figure 21 and a double-v butt-weld

![Figure 21: Longitudinal stress derived from measurements of (110), (002) and (112) reflections in the high strength steel SNC631 as a function of position through the weld (Holden, Suzuki, et al.)](image)
between 10 mm hot-rolled 304-type stainless steel plates. The results of their study confirmed that texture near the weld does not affect the stress field. Also, Type II strains from annealing and cooling can affect the macroscopic strains, therefore, intergranular strains can affect the measurement values.

Ganguly et al. (2006) examined the residual stresses in a 12-mm-thick variable-polarity plasma-arc welded aluminum 2024-T352 alloy plate using neutron diffraction. The residual stresses were measured using a combination of neutron and synchrotron X-ray diffraction after the plate was machined down to 7 mm thickness on either side of the weld (typical machining for the aerospace industry). The comparison of the two methods is shown in Figure 22. Synchrotron X-ray diffraction measurements were quick, made high penetration depths and allowed for very small gauge-volumes. However, synchrotron X-rays have very low diffraction angles, so it was impractical to measure strain in the normal direction. Therefore, a combination of synchrotron X-ray measurement for the longitudinal and transverse directions and the use of neutron diffraction for the normal direction provided excellent results. The transverse direction was measured using both methods to compare results obtained from the different machines. A stress-free reference comb, measured using both methods, showed a deviation of $d_0$ across the weld. The 12 mm thick specimens were also compared with the contour method and the results were agreeable. It was found that the machining stresses caused by skimming the sample from 12 mm to 7 mm caused little change in the stress distribution. The residual stress results showed high tensile stress in the longitudinal direction near the weld and the stresses in the normal and transverse directions were considerably lesser.

![Figure 22: Centerline longitudinal strain measured in the two as-welded 12-mm-thick plates using neutrons and synchrotron X-rays (Ganguly, Fitzpatrick and Edwards 2006)](image)
7.0 Chalk River Laboratories, Atomic Energy of Canada Limited Facility

Chalk River Laboratories (CRL) is equipped with a CANDU (CANada Deuterium Uranium) reactor, which uses pressurized heavy water (deuterium oxide) and uranium as fuel in the reactor. The source originates in an area of the moderator/reflector specially designed to optimize the thermal neutron flux. The beam tubes transport neutrons from the source to the region beyond the outer shielding of the reactor where neutron scattering instruments are situated. The beam tube usually contains an absorbing shutter to switch off most of the beam, or can be flooded with water to reduce the beam intensity to very low levels. The latter allows work to be carried out safely in the instrument’s beam exit region, where monochromating crystals or choppers may be located. The energy of the neutrons in the core of a reactor (2 to 3 MeV) is much too high to be useful for diffraction experiments and therefore, thermalized by a moderator.

Guide tubes are usually of rectangular cross-sections and, as the walls must be optically flat, made of float glass usually coated with a metal such as nickel. The use of a slightly bent guide, of several kilometres radius, allows for the removal of unwanted γ and fast neutron background, being transmitted through the walls into a biological shielding absorber surrounding the guide. The use of guides enables neutron beams to be transported to “guide halls,” which are located outside the main reactor shell. The various instruments on the same guide may take different vertical sections of the guided beam of the part of the beam transmitted through the monochromator of an upstream instrument. The design of the reactor is shown in Figure 23 and it is being used for the current study at the University of Windsor.
The current study will use the L3 Spectrometer, an ANDI Diffractometer, that is equipped with a 32-wire position sensitive detector. This equipment is shown in Figure 24.

The National Research Universal Reactor at the CRL produces 120MW, with a $3 \times 10^{18}$ neutron/m$^2$ thermal neutron flux. Key features of the centre include:

**Stress-scanner:** It has a typical minimum spatial resolution of 1 mm$^3$, locating accuracy better than 0.1 mm, strain precision 0.5E-4, 32-element multiwire 3He detector for high throughput, and a selection of computer-controlled positioning systems, handling loads up to 500 kg.

**Powder Diffractometer:** A 800-channel detector spanning 80 degrees of scattering angle simultaneously for high throughput with continuously variable wavelength and adjustable collimation before monochromator 0.2, 0.4 or 0.6 degrees.

**Weld Station:** This is used for in-situ studies of GTAW (gas tungsten arc welding) with a stationary welding torch and moving sample.

Typically, the danger of contamination at a neutron laboratory is nominal, with radiation being the chief concern; monitors are usually found on the equipment throughout the laboratory. Access to the measurement equipment is restricted by the use of interlocks when the neutron beam is engaged. All possible radiation is viewed as potentially hazardous, and exposure should be limited. The ALARA (as low as reasonably achievable) principle of exposure to radiation should always be respected.

The radiation profile of a sample after testing is assessed by a health physicist; who decides immediate access or request the sample to be placed in a radioactive material storeroom until the radioactive decay can occur. Usually the radiation level of the material to be

![Figure 24: L3 Spectrometer at Chalk River Laboratories (Canada 2008)](image-url)
permitted to leave the facility is 0.1 µSv at its surface. When a subject requires immediate removal from the facility, there are shielding, packaging, and certification requirements that are met to comply with national and international standards.

8.0 Reference


