ANALYSIS OF WELD SHRINKAGE TO OBTAIN COMPENSATION FACTORS FOR SHIP HULL CONSTRUCTION

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DECLARATION

This report contains no material, which has been accepted for the award of any other degree or diploma in any University or equivalent institution in Sri Lanka or abroad, and that to the best of my knowledge and belief, contains no material previously published or written by any other person, except where due reference is made in the text of this report.

I carried out the work described in this report under the supervision of Dr. H. K. G. Punchihewa.

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Abstract

Modern manufacturing faces two main challenges: more quality at lower prices and the need for the productivity improvement. In ship building industry, companies need to respond to market requirements efficiently, keeping their products competitive while reducing the cost. When considering complicated ship production processes up to final hull block erection, the productivity of each work station for hull assembly mainly depends on the dimensional quality of hull blocks. Poor dimensional accuracy leads to reworks such as re cutting, mechanical or thermal correction against misalignment, excessive welding for wide gap and thermal straightening and this will subsequently increases the total production cost.

One of the major dimensional accuracy control activities is the shrinkage margin design, which means that the optimal excess of plate is calculated and assigned into ship production drawings in order to compensate for the accumulated welding shrinkage through block assembly phases. In Sri Lankan context the most common practise to compensate for shrinkage has been to add excess material, usually 50-100 mm on one or two sides of a block that would be trimmed at the erection stage. Normally, this added material would be adequate to compensate for any weld shrinkage incurred during block assembly. It is however, a commitment to rework. This has been adopted due to the lack of accurate and reliable weld shrinkage and distortion allowance data. Even though there are some research findings on shrinkage factors it can't be directly apply for the Sri Lankan industry as shrinkage factors may vary from shipyard to shipyard due to facilities, welding equipment, joint design, welding sequence, ambient temperature, and type of material.

This research project provides a comprehensive weld shrinkage factor identification that enables neat construction capabilities for the shipbuilding industry in Sri Lanka. A key component of the research is a predictive weld shrinkage factor based on current ship designs, materials, and construction practices. Through this study, the shrinkage factors will be identified by a statistical analysis of data. It will be done from the development of check sheets, establishing of checking procedures, data gathering, and finally the statistical analysis of data. Since variety of variables can affect the determination of a shrinkage factor, it has to be decided the most crucial factors for particular production process and consider only those factors as the variables. Even though there are three major processes (panel fabrication, block construction, block assembly) in ship building the data was analysed only for data collected from panel fabrication and sample testing. Finally two equations were derived for sample testing and panel fabrication separately by providing dedicated factor for each and every considered variable. The obtained results were validated again by means of another sample testing and the deviation is less than 0.2 mm. The other processes were not considered due to complexity of the structures and data collection difficulty with in limited time frame.

The block construction and assembly processes can be considered for the next step of this research and it can be done with the involvement of modelling software. From the modelling software the differences in each of complex blocks can be identified easily and measured values can be analysed against those differences. Then a comprehensive welding shrinkage compensation factor can be identified and it can be entered to the modelling software at the time of modelling the vessel.

Acknowledgements

I owe a great many thanks to a great many people who helped and supported me during this study.

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1 INTRODUCTION

There are three main stages in construction of a ship hull. Those are pre fabrication, block construction and block erection. These processes are referred to as interim processes. The process of determining shrinkage factors for pre fabrication stage is the task of this study. This can be accomplished by an extensive collection of shrinkage data. The three selected shrinkage types are plate panel shrinkage, hull block assembly shrinkage, and butt erection joint shrinkage. Through this study, the process and methods for gathering shrinkage data were determined for each of the interim processes.

Data collection sheets were specially formatted with all the necessary attributes and independent variables that affect joint shrinkage. Shrinkage data was collected and organized in data sets by the welding process and application. Then the data was statistically analysed and shrinkage factors/formulae were derived.

1.1. Background

This research was carried out based on the activities of new building sector in Sri lankan ship yard. Welding is a fabrication or sculptural process that joins materials, usually metals or thermoplastics. This is often done by melting the work pieces and adding a filler material to form a pool of molten material (the weld pool) that cools to become a strong joint. There are so many types of welding processes, which can be categorized according to the energy source, consumable and the process (Howard, 2005). In ship building industry there are several types of welding processes being used and Flux cored arc welding (FCAW), Shielded metal arc welding (SMAW), Submerged arc welding (SAW) are used in common.

Flux-cored arc welding (FCAW) can be done either in semi-automatic or automatic methods. FCAW requires a continuously-fed consumable tubular electrode containing a flux and a constant-voltage or, a constant-current welding power supply. An externally supplied shielding gas is sometimes used, but often the flux itself is relied upon to generate the necessary protection from the atmosphere (Weman, 2011). The process is widely used in construction because of its high welding speed and portability (Nandkarni, 1992). When considering the application in shipyard, about 90% of the welding is carried out using the FCAW (Table 1).

Table 1: Welding electrode consumption analysis for NC projects in shipyard

Project No.	Weight (T)	UNIT CONSTRUCTION			UNIT ASSEMBLY			TOTAL Welding electrode consumption
		FCAW (Ton)	SMAW (Ton)	TOTAL (Ton)	FCAW (Ton)	SMAW (Ton)	TOTAL (Ton)	
NC 207	741.72	18.95	1.65	20.593	5.73	0.30	6.035	26.628
NC 208	741.72	20.18	2.24	22.425	5.83	0.58	6.410	28.835
NC 211	741.72	18.90	0.99	19.895	6.28	0.55	6.830	26.725
NC 212	741.72	17.40	1.72	19.118	5.89	0.65	6.540	25.658
NC 209	1164.69	26.20	3.57	29.770	16.13	0.85	16.980	46.750
NC 210	1164.69	24.95	2.47	27.417	10.81	1.07	11.874	39.291
NC 215	1468.84	34.00	1.79	35.785	13.51	1.84	15.350	51.135
NC 216	1468.84	32.35	3.20	35.550	19.57	1.94	21.500	57.050
NC 217	1468.84	40.36	3.51	43.865	14.04	1.73	15.770	59.635
NC 218	1468.84	34.88	3.88	38.760	13.08	1.45	14.530	53.290
NC 219	1237.00	32.27	1.70	33.965	9.09	1.24	10.325	44.290
NC 220	1237.00	29.61	2.93	32.535	9.03	0.89	9.920	42.455
NC 224	1524.00	32.03	4.37	36.395	16.45	2.46	18.910	55.305
NC 223	1524.00	32.94	3.26	36.200	13.69	1.52	15.210	51.410
NC 222	1524	32.08	1.69	33.765	14.38	1.25	15.63	49.395
NC 225	1524	29.28	2.90	32.175	12.97	1.44	14.41	46.585
TOTAL Weight	19742	456.36	41.85	498.21	186.46	19.76	206.22	704.44
DATA ANALYSYS		**92%**	**8%**	**71%**	**90%**	**10%**	**29%**	**3.6%**

Source: Project wise welding material consumption data record in selected shipyard

Even though the welding process is quick and reliable method to join metals, it has some draw backs, which will affect the final quality of the product. The main drawbacks in welding are shrinkage and distortion. It is essential to control these two factors to maintain the dimensional accuracy of the product.

When considering the ship building process in shipyard above two factors have become crucial. An additional straightening process has been introduced to the ship construction projects in order to rectify the distortions initiated by the welding. Also there are lots of issues in block erection process due to the shrinkages occurred during panel fabrication and block construction stages. An additional cost and time has to be spent to rectify those issues as there isn't any criteria to control them during the initial stage. If it is possible to introduce some measures to control the shrinkage and distortion the productivity and quality of the process can be improved easily.

Since it is complex to consider all the welding processes for this research, it was decided to select FCAW process and the experiments were carried out only for FCAW process.

1.2. Problem Statement

The material shrinkage during welding is unavoidable and as a result of that dimensional variations in welded stuctures are occur. This is a severe issue in ship building industry as the dimensions should be maintain within the limits given in the ship building standards (IACS, 2010).

Since there isn't sufficient data to predict the welding shrinkage which can occur, the common practise is to provide extra material (50-100 mm) at the plate cutting stage to compensate the welding shrinkages (Figure 1).

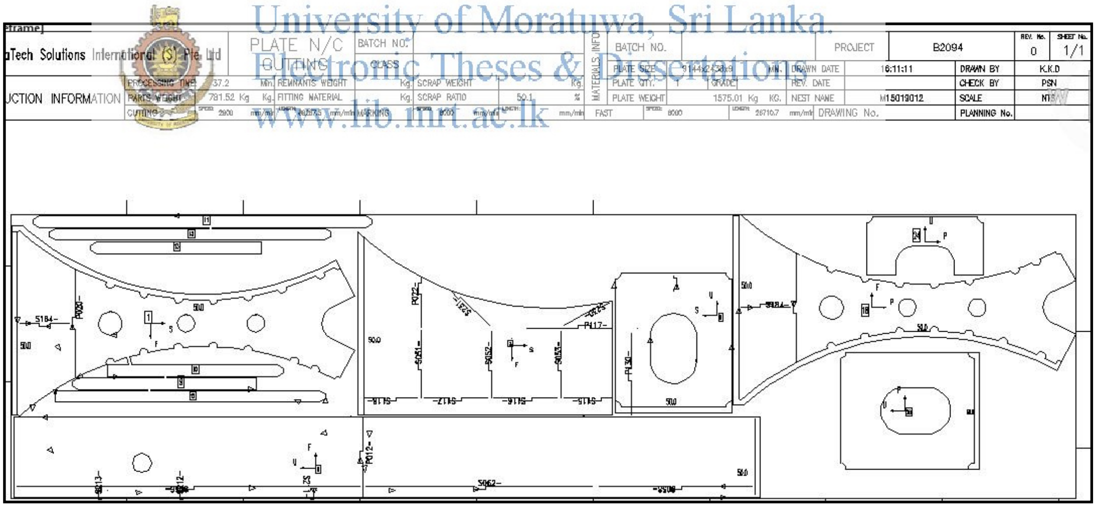


Figure 1: Current nesting drawing with 50 mm extra material

Source: project NC 0231 unit 1501 nesting drawing (DR-NC-0231-102-151N REV.B)

This will leads to lot of steel material wastage. Material cost is a crucial factor in ship building and it is essential to reduce the material wastages. When considering the 3R concept (Reduce, Reuse, and Recycle) the best way to prevent wastage is reducing the usage (Ren, 2013).

Not only the material wastage but also this method creates several additional steps in the production process such as dimensional measurements and marking, manual gas cutting, grinding & rectification. All of those processes involve additional time, labour and consumables such as oxygen and acetylene. Since these processes have to be done manually in the construction stage the quality of the fabrication is also reduced.

The same process has to be done in the block erecting stage (Figure 2) and at that stage it involves lot of preparation works than the panel fabrication stage and due to that high amount of time, manpower, material and consumable being wasted block erecting stage than the panel fabrication stage.

Figure 2: Re cutting of extra material during block assembly

1.3. Aim and Objectives

The aim of this research is to identify welding shrinkage factors for panel fabrication stage in ship hull construction and use it during the design stage in order to prevent dimensional variations at the production stage. The objectives of the research are as follows.

- Analyse about the factors affecting welding shrinkage and methods to control the shrinkage.
- To measure the welding shrinkage for different welding types (Butt weld / Fillet weld) using different plate thicknesses
- Anlysis of welding shrinkage and deriving compensation factors for hull panel fabrication process
- To evaluate the validity of obtained compensation factors /formulae.

1.4. Methodology

The welding shrinkage is mainly varying with the welding method used and this was studied during the literature survey by referring the welding related books, journals, publications and research papers. Since there are many other factors which affect the welding shrinkage, those factors also studied during the literature survey. Sample testing also carried out to find the effect of some major factors. Not only that the methods to minimise the welding shrinkage also studied by conducting a literature survey.

The next objective of this research is to measure the welding shrinkage for different weld types such as butt welds and fillet welds and to achive that a simple sample testing method was adupted and different samples were selected in such a way to cover the all material sizes use in shipyard. A special apparatus was prepared to carry out sample welding and measuring in an effective and efficient manner.

The main objective of this research is to deriving a simple welding shrinkage factors/ formulae for FCAW welding in panel fabrication stage and it was accomplished according to following methodology. Since there are several studies have been carried out in the world related to the welding shrinkage analysis, a literature review has been carried out to find out the results of those researches and the relevance to the sector, which was considered for this study. Ship construction methodology, welding techniques, parameters affecting for the shrinkage and data analysing techniques also studied during the literature review.

The process of determining shrinkage factor can be done in two ways. One method is by theoretical analysis and other method is by experiments. During this study the weld shrinkage factor was determined using experimental methods. The experiments were carried out by measuring of some selected parts during the actual production process.

First the statistical population was defined in order to collect the sample data and inorder to achieve that the analysis was narrow down to a specific process considering the fabrication processes in ship building. Then a welding method and position was selected to make the analysis more specific. Finally the thicknesses of the test pieces were selected considering the appropriateness to the selected process.

The next step is the data collection and data collection methodology was defined considering the final objective. Different measuring techniques for each method were selected to maintain the accuracy of the measurements. Even though the block assembly process did not considered for this analysis, the shrinkage data for block assembly process also gathered in order to provide room for further extension for this research and it wasn't considered for the data analysis.Then relevant data analysing method was identified and the collected data was analysed for each and every process separately. The shrinkage factors /formulae for welding has defined considering the results obtained from the analysis. Finaly the obtained welding shrinkage factors/ formulae were evaluated by a sample fabricated panel welding.

2 LITERATURE REVIEW

When conducting a study to identify the welding shrinkage factor it is important to have proper idea about the available welding technologies and type of special welding techniques used in ship building industry, as the type of welding technology has direct impact on the welding shrinkage. How ever this is not the only factor which affects the welding shrinkage. The weld joint type, joint gap, type of welding, weld position, welding sequence, restraining conditions, base metal temperature and thickness, current and voltage used, travelling speed are the other factors, which affect the welding shrinkage (Leonard, 1991). Due to that it is important to have a proper idea about those items as well.

In the same time of studying the factors affecting the welding shrinkage, the methods to minimise the shrinkage also studied during this literature review. Then the data analysing methods were studied to select a suitable analysing method to analyse the collected data.

Since there are several researches have been done under the same category it is important to study about those researches also. A thorough study about available researches will helps to identify their compatibility with Sri Lankan context, their weakness, and possible improvements to match with the selected application.

2.1. Welding Technology

Welding is a materials joining process, which produces joining of materials by heating them to suitable temperatures with or without the application of pressure or by the application of pressure alone, and with or without the use of filler material (Jeffus, 2009).

The list of processes used in modern metal fabrication and repair, which has published by the American Welding Society (AWS) is shown in the (Figure 3) and it shows the official abbreviations for each process. The primary differences between the various welding processes are the methods by which heat is generated to melt the metal and the method of providing the filler material (The Welding Institute, 1998).

The selection of welding process depends on several factors such as type of metal and their metallurgical characteristics, type of joints and the welding positions, cost of production, size of the structure, desired performance, experience and ability of man power, accessibility for the joint. When considering the above factors with relevant to ship building industry arc welding process is the most suitable one (Khan, 2007).

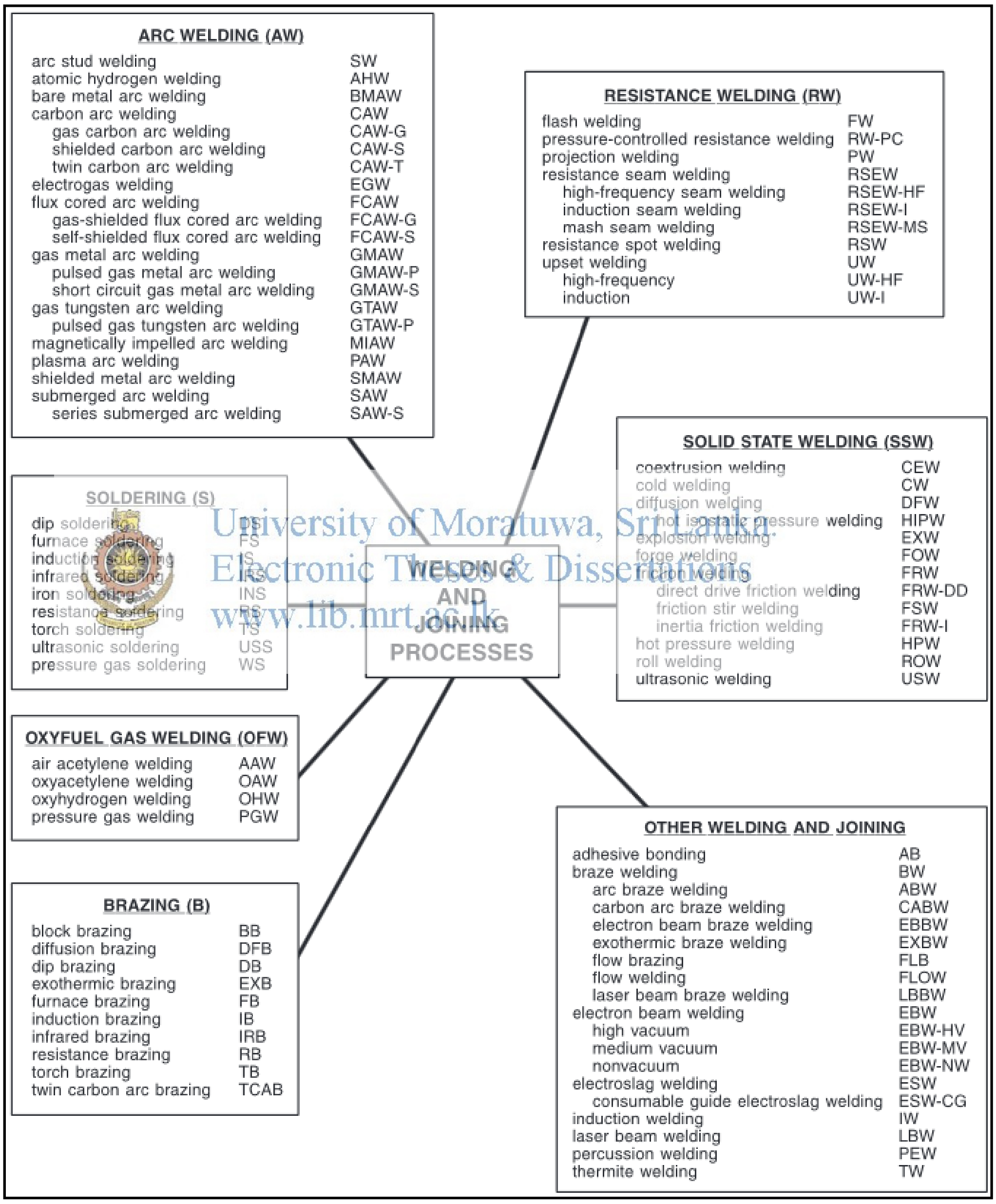


Figure 3: Master Chart of welding and joining processes

Source: Annex D of ANSI Z49.1:2005, Safety in welding, cutting, and allied processes published by the American Welding Society (AWS)

2.2. Special Welding Techniques Used in Ship Building Industry

Out of the available arc welding processes most common welding techniques used in ship building industry are flux cored arc welding (FCAW), shielded metal arc welding (SMAW) and submerged arc welding (SAW) (Turan, 2011).

When considering the application in shipyard, about 90% of the welding is carried out using the FCAW process (source:-Project wise welding electrode consumption data in considered shipyard). Since this research was focused on ship building in sri Lankan shipyard, more attention was provided to study about FCAW process during the literature review.

2.2.1. Flux cored arc welding (FCAW)

Flux cored arc welding (FCAW) is a welding process, which joints metals by heating the metals to their melting point with an electric arc. The arc is between a continuous, consumable electrode wire and the metal being welded. FCAW wire is a hollow or tubular wire that has a flux inside of it. The flux provides a shielding from the air when it is welding. This helps FCAW welder to weld in windy conditions and it increases how much weld can be welded per hour. The powder flux inside also has metal mixed that increase the weld deposit rate. FCAW is the fastest of all of the manual welding processes (Norrish, 2006). FCAW wire has two types.

- Self-shielding
- Dual shielding.

Shelf shielding wire has enough flux inside that and no other shielding source is needed. Dual shield is a wire helps shielding the weld but also needs a source of gas just like in Gas Metal Arc Welding (GMAW) (Davis, 1993).
FCAW can be done in three different ways (Dhulipala, 2014).

- Semiautomatic welding:- equipment controls only the electrode wire feeding. Movement of welding gun is controlled by hand. This may be called hand-held welding.

- Machine welding - uses a gun that is connected to a manipulator of some kind (not hand-held). An operator has to constantly set and adjust controls that move the manipulator.
- Automatic welding - uses equipment, which welds without the constant adjusting of controls by a welder or operator. In some equipment, automatic sensing devices control the correct gun alignment with the weld joint.

Equipment use in FCAW process

Basic equipment for a typical FCAW semiautomatic setup is given in (Figure 5) and the main items of it is as follows (Connor, 1991).

- Welding power source:- provides welding power.
- Wire feeders (constant speed and voltage sensing):- controls supply of wire to welding gun.
- Constant speed feeder:- used only with a constant voltage (CV) power source. This type of feeder has a control cable that will connect to the power source. The control cable supplies power to the feeder and allows the capability of remote voltage control with certain power source/feeder combination. The wire feed speed (WFS) is set on the feeder and will always be constant for a given preset value.
- Voltage sensing feeder:- can be used with either a constant voltage (CV) or constant current (CC) / direct current (DC) power source. This type of feeder is powered off of the arc voltage and does not have a control cord. When set to (CV), the feeder is similar to a constant speed feeder. When set to (CC), the wire feed speed depends on the voltage present. The feeder changes the wire feed speed as the voltage changes. A voltage sensing feeder does not have the capability of remote voltage control.
- Supply of electrode wire.
- Welding gun:- delivers electrode wire and shielding gas to the weld puddle (Figure 4).

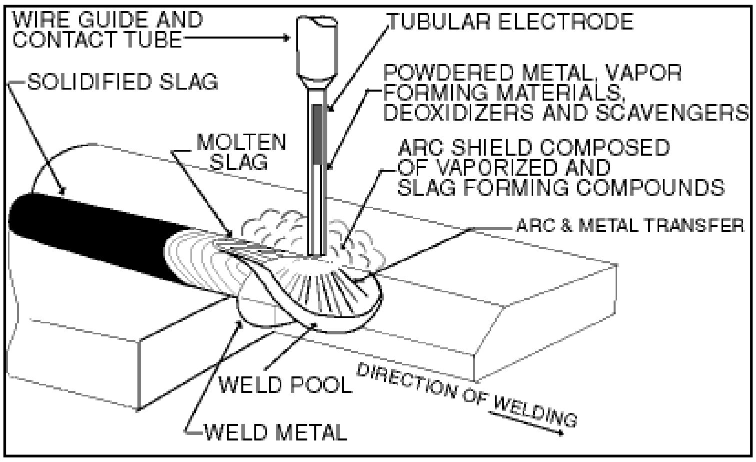


Figure 4: Delivering of electrode wire and shielding gas to weld pool

Source: The procedure handbook of arc welding, 13th edition, (1994), Lincoln Electric Company, Cleveland

- Shielding gas cylinder:- provides a supply of shielding gas to the arc.

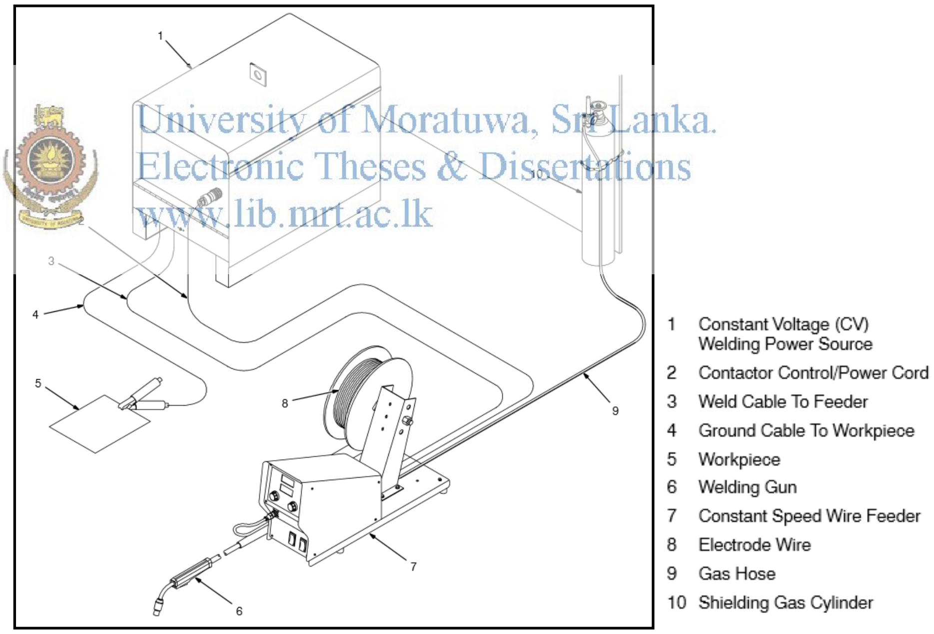


Figure 5: Typical FCAW semiautomatic set up

Source: Guidelines for Gas Metal Arc Welding -GMAW (2010) by Miller Electric Mfg. Co

Parameter setting in FCAW

The parameter setting is one of the most important activities in FCAW. The quality of the product is depend on the parameters selected by the operator. Even though the parameters can be changed from process to process there is a basic guide line to select the welding parameters. The steps of parameter setting is given in Figure 6. The actual parameters can be vary according to material, wire type, joint design, joint fit–up, position and shielding gas (Miller Electric, 2010).

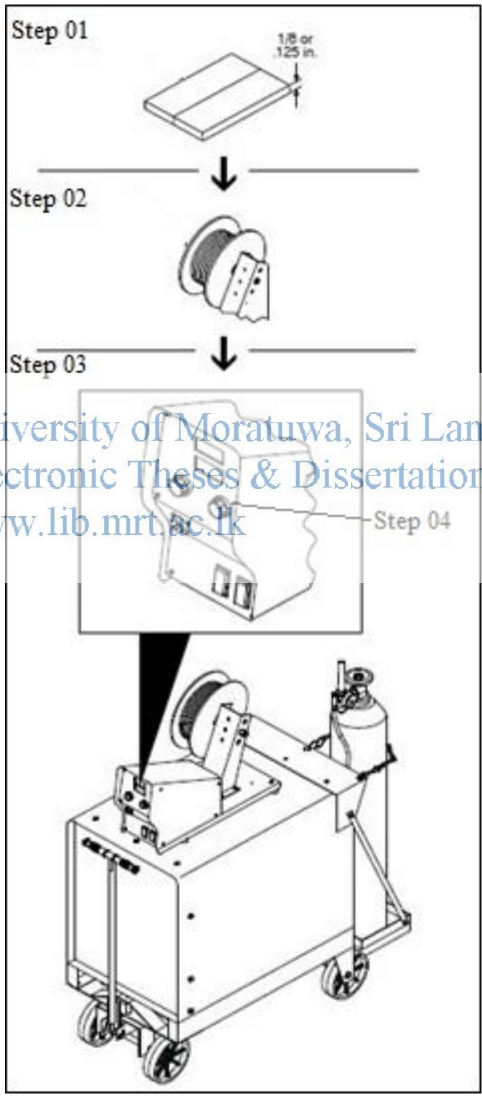


Figure 6: Parameter selection method for FCAW

Source: Guidelines for Gas Metal Arc Welding -GMAW (2010) by Miller Electric Mfg. Co

Step 01:- Convert material thickness to Amperage (A)

0.001 in. = 1 ampere

0.125 = 125 A

Step 02:- Select wire size

Table 2: FCAW Amperage for different feed wire sizes

Wire Size	Amperage Range
0.030 in	40-145 A
0.035 in	50-180 A
0.045 in	75- 250 A

Source: Guidelines for Gas Metal Arc Welding -GMAW (2010) by Miller Electric Mfg. Co

Step 03:- Select the wire speed

Table 3: Selection of welding wire speed for FCAW

Wire Size	Suggested	Wire speed (Approx.)
0.030 in	2 in/ Amp	2*125A= 250 ipm
0.035 in	1.6 in/ Amp	1.6*125A= 200 ipm
0.045 in	1 in/ Amp	1*125A= 125 ipm

ipm = inch per minute

Source: Guidelines for Gas Metal Arc Welding -GMAW (2010) by Miller Electric Mfg. Co

Current 125A is taken considering 0.125 inch (1/8 Inch) material thickness (the amount of amperage is varying according to the material thickness). The penetration rate also controls by the wire speed.

Step 04:- Voltage selection

If the voltage is low weld wire stubs into work and if the voltage is high arc become unstable and create more spatters. So the voltage has selected in such a way to maintain between high and low values. The height and the width of the weld bead can also controled by the voltage.

Advantages of FCAW

- All position capability
- Higher deposition rates than SMAW
- Less operator skill required
- Can automated easily
- Long welds can be made without starts and stops
- Minimal post weld cleaning is required (Leonard, 1991)

Possible welding defects in FCAW

There are several types of defects, which can occur during welding. (Adolfsson, 1999).

- Excessive spatter
- Porosity
- Incomplete fusion
- Excessive penetration
- Incomplete joint penetration
- Burn through
- Waviness of bead
- distortion
- Weld metal crack
- Heat affected zone crack
- Undercut

2.2.2. Shielded metal arc welding (SMAW)

Shielded metal arc welding (SMAW) or Stick welding is a process, which melts and joins metals by heating them with arc between a coated metal electrode and the work piece (Figure 7). The electrode outer coating, called flux, assists in creating the arc and provides the shielding gas and slag covering to protect the weld from contamination. The electrode core provides most of the weld filler metal. When the electrode is moved along the work piece at the correct speed the metal deposits in a uniform layer called bead. The Stick welding power source provides constant current (CC) and may be either alternating current (AC) or direct current (DC), depending on the electrode being used. The best welding characteristics are usually obtained using DC power sources (Miller Electric Mfg. Co., 2013).

The power in a welding circuit is measured in term of voltage and current. The voltage (Volts) is governed by the arc length between the electrode and the work piece and is influenced by electrode diameter. Current is a more practical measure of the power in a weld circuit and is measured in amperes (Amps). The amperage needed to weld depends on electrode diameter, the size and thickness of the pieces to be welded, and the position of the welding. Thin metals require less current than thick metals, and a small electrode requires less amperage than a large one.

It is preferable to weld on work in the flat or horizontal position. However, when forced to weld in vertical or overhead positions it is helpful to reduce the amperage from that used when welding horizontally. Best welding results are achieved by maintaining a short arc, moving the electrode at a uniform speed, and feeding the electrode downward at a constant speed as it melts (Miller Electric Mfg. Co., 2013).

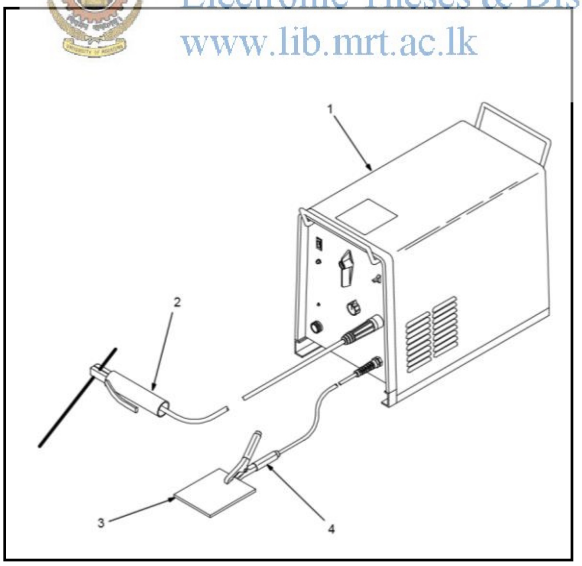


Figure 7: Apparatus used for SMAW

Source: - Guidelines for Shielded Metal Arc Welding (2013) by Miller Electric Mfg. Co.

2.3. Welding Requirement in Ship Building Industry

All the steel joining works in modern ship building are done by welding process. The processes like SMAW, SAW, FCAW, and GTAW are used for that and the selection of the process depend on the application. When considering the hull construction in Sri Lankan yard, the welding processes used are flux cored arc welding (FCAW) and shielded metal arc welding (SMAW). FCAW welding is contributing 90% of the welding works while SMAW contribute for only 10% of the welding works *(Source: Colombo dockyard hull construction department production data)*

The hull construction process consists of three major stages.

- Prefabrication (Figure 8)
- Unit construction (Figure 9)
- Unit assembly (Figure 10)

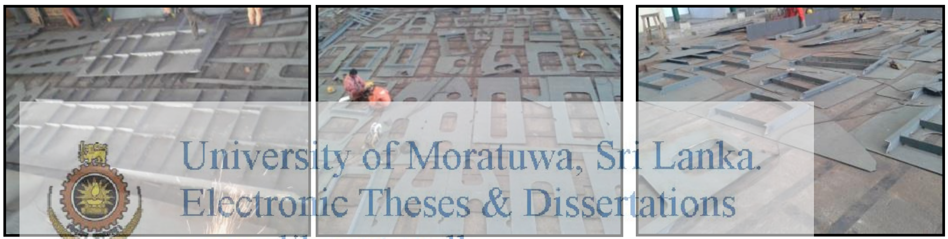


Figure 8: Prefabrication process

Figure 9: Unit construction process

Figure 10: Unit Assembly process

In prefabrication the most common welding methods are down hand fillet weld and butt weld, but in unit construction and unit assembly (Figure 11) both butt welds and fillet welds are applied with several weld positions. The unit construction is the most complex process in hull construction and it is difficult to analyse and find a factor for welding shrinkages in unit construction.

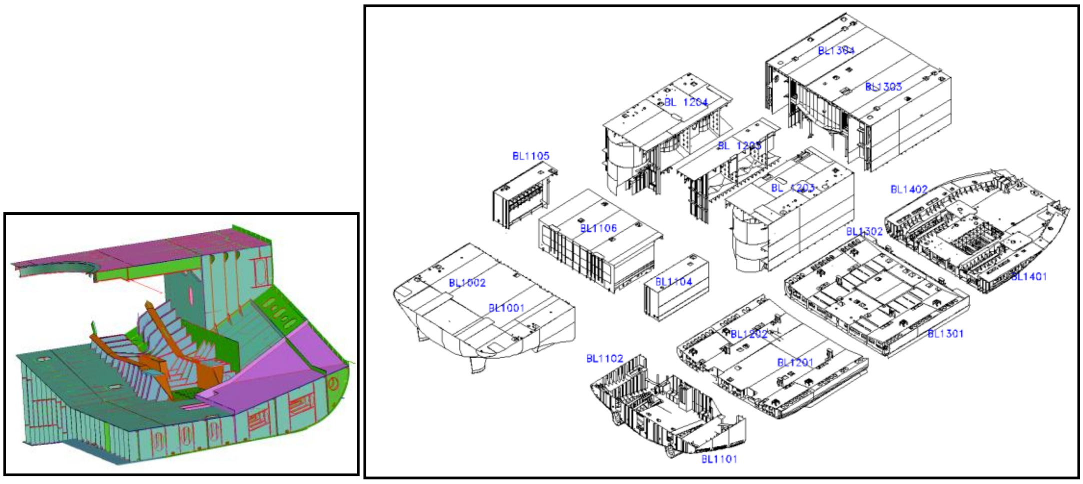


Figure 11: Overall view of a Hull Assembly

2.4. Effect of Welding Attributes on Shrinkage

There are six main welding attributes which affect the welding shrinkage and those are listed below (Navy, 1993). Knowledge of each of these attributes is important to understand the mechanisms that cause weld shrinkage. Changing any one of following attributes would change the characteristics of the process that affect weld shrinkage.

- Joint Design
- Welding Process
- Method of Application
- Joint Position
- Material Thickness
- Independent Variables

2.4.1. Joint design

There are two main types of joints are used in the ship building industry.

- Butt joint
- Fillet joint

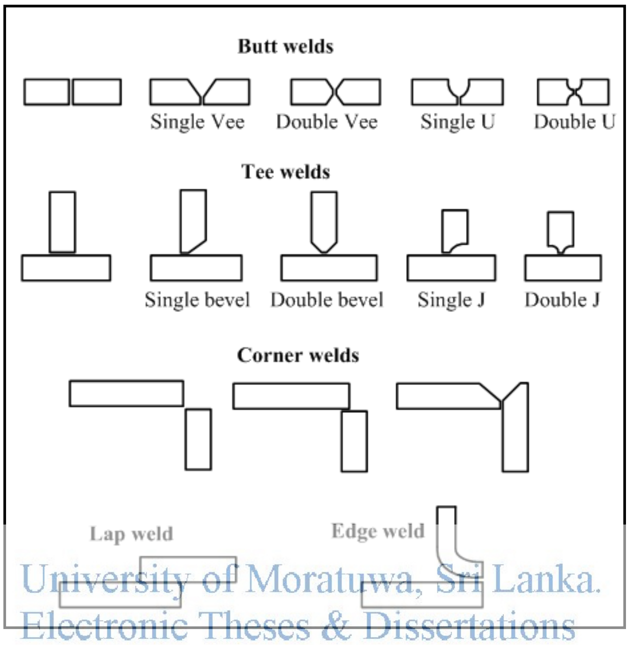


Figure 12: Welding joint designs

Source: - Principles of arc welding by Dr. Dmitri Kopeliovich (www.substech.com)

When considering butt joint there are three main types namely square butt, u groove and V-groove joints (Figure 12). Out of those designs V-groove design is the most common one, which use for the ship building industry. The fillet welding can be categorized according to the throat thickness and it's varying with the material thickness.

2.4.2. Welding process

There are various types of welding processes available and it has described in section "2.1 Welding Technology". The welding processes, SMAW (shielded metal arc welding) and FCAW (flux-cored arc welding) are the most common in ship hull production.

2.4.3. Method of application

Welding processes implemented are then categorized according to the method of application. The application method is defined by (Dhulipala, 2014),

- The type of power source (manual, semi-automatic, and automatic)
- Backing plate usage (with backing or without backing)
- One-sided welding or two-sided welding

2.4.4. Joint position

There are four types of welding positions used for welding of plates (ASME, 2010) (Figure 14). Those are

- Down hand position (1G/ 1F)
- Horizontal position (2G/ 2F)
- Vertical position (3G/ 3F)
- Overhead position (4G/ 4F)

Out of the above positions the down hand position is the most common position and overhead position used rarely. The horizontal and vertical positions are widely used in unit construction and unit assembly stage.

2.4.5. Material thickness

The welding shrinkage varies with the thickness of the material being welded and this is another main attribute which needs to consider when measuring the welding shrinkage.

2.4.6. Independent variables

Factors that affect the degree of weld shrinkage within each specific process are the independent variables. These variables change as a result of the working conditions and decisions made by the welding operator. Each of these variables influences shrinkage independently (Navy, 1993).

Welding parameters

The welding parameters such as voltage, amperage, travel speed, heat input of the welding process is considered under this category. In several applications the welding parameters are adjusted to specified settings by the thickness of the material.

Joint gap

This independent variable determines the weld size for a given material thickness. For a given joint design, the amount of weld metal required to fill the joint is determined by this attribute.

Plate temperature

The difference in base material temperatures recorded at the pre-weld measurement times and the post-weld measurement times is critical for the weld shrinkage. Thermal plate movement from ambient temperature change, if not accounted for, can produce dimensional changes that are as great as the weld shrinkage. To account for this plate expansion or contraction factor, allowances are provided depending upon the plate temperature gradients. Block movement resulting from ambient temperature changes, is caused by thermal expansion and contraction. The pre-weld measurement of a butt joint can shift through the day as a result of ambient temperature changes.

Restraint conditions

The amount of weld joint shrinkage is dependent upon the level of joint restraint. Different forms of restraint counteract the shrinkage forces of a joint being welded. The most obvious form of joint restraint is created by the joint fitting aids. For a V-Groove butt joint for example, reducing the number of strong backs will lessen the restraint conditions creating more allowance for shrinkage.

2.5. Minimisation of Welding Shrinkage

To minimise weld shrinkage, design and welding should be addressed. Weld shrinkage cannot be prevented, but it can be controlled. Following are recommended steps for minimising weld shrinkage according to (Beardsley, 2009).

1. Avoid over welding:- The bigger the weld, the greater the shrinkage. Correctly sizing a weld not only minimises distortion, but also saves weld metal and time.

2. Intermittent welding:- To minimise the amount of weld metal, use intermittent welds instead of continuous welds where possible.
3. Fewer weld passes:- A fewer number of big passes results in less shrinkage than a greater number of small passes with small electrodes. Shrinkage accumulates from each weld pass.
4. Place welds near the neutral axis, or the center of the part:- Distortion is reduced by providing less leverage for the shrinkage forces to pull the plates out of alignment.
5. Balance welds around the neutral axis:- Welding on both sides of the plate offsets one shrinkage force with another, to minimise shrinkage.
6. Use the back step welding technique:- In the back step technique, the general progression of welding may be left to right, but each bead segment is deposited from right to left. This separation is most pronounced as the first bead. With successive beads, the plates expand less and less because of the restraint from the prior welds.
7. Presetting the parts:- Presetting parts before welding can make shrinkage work for you. The required amount of preset can be determined from a few trial welds.

8. Alternate the welding sequence:- A well-planned welding sequence involves placing weld metal at different points of the assembly so that, as the structure shrinks in one place, it counteracts the shrinkage forces of welds already made. An example of this is welding alternately on both sides of the neutral axis in making a complete joint penetration groove weld in a butt joint.
9. Clamping:- Clamps, jigs and fixtures that lock parts into a desired position and hold them until welding is finished are probably the most widely used means for controlling distortion in small assemblies or components. While there is some movement or distortion after the welded part is removed from the jig or clamps, that shrinkage will be lower compared to the amount of movement that would occur if no restraint were used during welding.

10. Thermal stress relieving:- Another method for removing shrinkage forces is thermal stress relieving, i.e., controlled heating of the weldment to an elevated temperature, followed by controlled cooling.

2.6. Data Analysis Techniques

There are many tests that can be used to analyse the data, and which particular one to be used is depends upon expected out put type, what type of data collected and how to collected.

Below are just a few of the more common ones that can be used for quantitative data analysis (Huberman, 1994).

- t-Test
- ANOVA
- Histogram
- Descriptive Statistics
- Correlation
- Covariance
- Exponential Smoothing
- F-Test Two Sample for Variance
- Fourier Analysis
- Moving Average
- Random Number Generation
- Rank and Percent
- Regression
- Sampling
- Z-Test: Two-Samples for Mean

2.6.1. ANOVA (analysis of variance)

ANOVA is one of a number of tests (ANCOVA - analysis of covariance and MANOVA - multivariate analysis of variance) that are used to describe/compare the relationship among a number of groups (Randolph, 2013).

2.6.2. Linear regression

Regression is a more accurate way to test the relationship between the variables compared with correlations since it shows the goodness of fit (adjusted R square) and the statistical testing for the variables. The formulae for one-variable regressions is $y = ax + b$ and for multiple regressions is $y = ax_1^2 + bx_2 + c$.

For $y = ax + b$, y is the dependent variable, x is the causal variable and the intercept is a, indicating the correlation between x and y. If "a" is 0.2 for example, it means when x variable increases 1 unit, y increases 0.2 units. If "a" is negative, meaning y decreases as x increases.

For $y = ax_1^2 + bx_2 + c$, y is the dependent variable, x_1 is causal variable 1 and x_2 is causal variable 2. "a" is the intercept for variable 1 and "b" for variable 2. For example, if $y = 0.6\, x_1^2 – 0.4\, x_2 + 0.23$, it means when x_1 increases 1 unit, y increases 0.6 units and when x_2 increases 1 unit, y decreases 0.4 units (given the variables are statistically significant) (Li, 2013).

2.7. Selecting the Statistical Test

When it comes to the selection of the appropriate test for the research in order to determine the p-value, it is need to base the selection of four major factors, namely:

- The level of data (nominal, ordinal, ratio, or interval).
- The number of groups/samples in the research study (one, two, or more).
- Were the data collected from independent groups/samples or from related groups
- The characteristics of the data (distribution of the data).

Depending on the requirement it is possible to select the appropriate analysing method as shown in Figure 13 (Campbell, 2008).

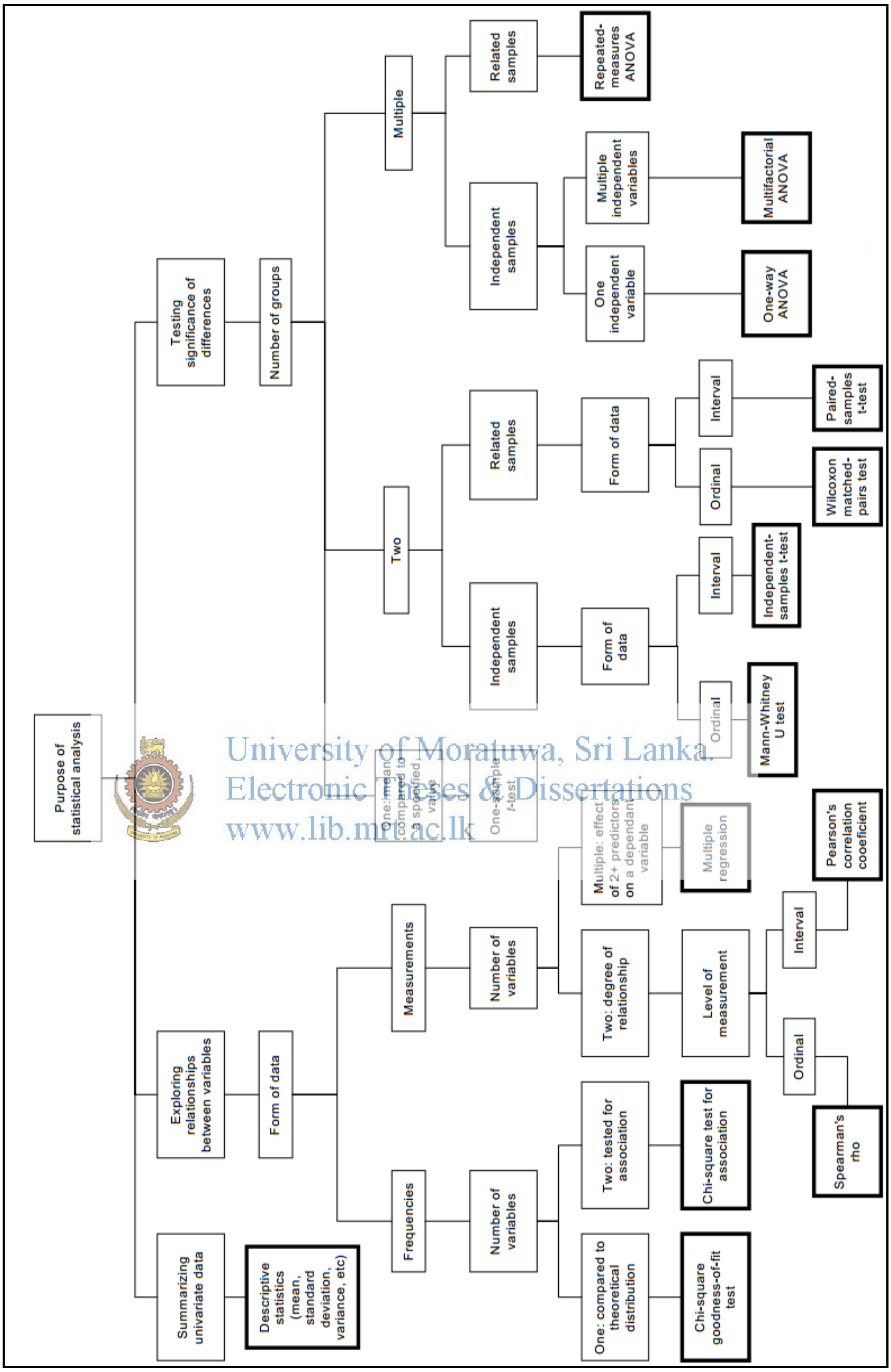


Figure 13: Selection of analysis method based on the purpose

Source: - Quantitative methods in social research by Corston and Colman (2000)

When considering this research the purpose of the analysis is exploring the relationship between the variables. Also the data were collected via measurements and there are multiple variables available.

So according to (Figure 13) multiple regression analysis is the most suitable data analysing method for this research.

There are various types of software available to carry out multiple regression analysis. Fore an example Minitab, SPSS, NCSS, XLSTAT and Microsoft (MS) Excel are some of softwares, which facilitates regression analysis. MS Excel was used to carry out the analysis of this research as it is already available and much user friendly.

2.8. Interpreting the Output of Regression Analysis

A sample output given by regression analysis using Microsoft Excel is given in Table 4 and the interpretation of the parameters are as follows (Andale, 2015).

2.8.1. Regression statistics

- Multiple R:- This is the correlation coefficient. It tells you how strong the linear relationship is. For example, a value of 1 means a perfect positive relationship and a value of zero means no relationship at all. It is the square root of r squared.
- R square:- This is R^2, the coefficient of determination. It tells you how many points fall on the regression line. For example, 80% means that 80% of the variations of y-values around the mean are explained by the x-values. In other words, 80% of the values fit the model.
- Adjusted R square:- The adjusted R-squared adjust for the number of terms in a model. This need to use if there is more than one x variable.
- Standard error of the regression:- An estimate of the standard deviation of the error μ. This is not the same as the standard error in descriptive statistics. The standard error of the regression is the precision that the regression coefficient is measured; if the coefficient is large compared to the standard error, then the coefficient is probably different from 0.

- Observations: - Number of observations in the sample (Andale, 2015).

Table 4: Sample regression analysis output obtained from MS Excel

Regression Statistics	
Multiple R	0.96
R Square	0.93
Adjusted R Square	0.93
Standard Error	0.08
Observations	102

ANOVA

	df	SS	MS	F	Significance F
Regression	4	8.94	2.24	320.63	5.56E-55
Residual	97	0.68	0.01		
Total	101	9.62			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-0.13	0.06	-2.14	0.03	-0.26	-0.01	-0.26	-0.0098
X Variable 1	0.05	0.0034	16.13	3.29E-29	0.05	0.06	0.05	0.06
X Variable 2	0.0003	0.0001	3.42	0.00091	0.0001	0.0005	0.00013	0.0005
X Variable 3	0.40	0.02	17.70	3.89E-32	0.36	0.45	0.36	0.45
X Variable 4	-0.06	0.04	-1.48	0.14	-0.13	0.02	-0.13	0.02

2.8.2. ANOVA

1. SS:- Sum of Squares.
2. Regression MS:- Regression SS / Regression degrees of freedom.
3. Residual MS:- Mean square error (Residual SS / Residual degrees of freedom).
4. F:- Overall F test for the null hypothesis.
5. Significance F:- The associated P-value.

The second part of output that get in Excel is rarely used, compared to the regression output above. It splits the sum of squares into individual components. So it can be harder to use the statistics in any meaningful way. If basic linear regression is tested (and have no desire to delve into individual components) then this section of the output can be skipped (Andale, 2015). For example, to calculate R^2 from this table,

$$R^2 = \frac{1 - \text{residual sum of squares (SS Residual)}}{\text{Total sum of squares (SS Total)}}$$

2.8.3. Regression coefficients

This section of the table gives very specific information about the components that chose to put into the data analysis. Therefore the first column will say something different, according to the data which have put into the worksheet (Andale, 2015).

The columns are:

1. Coefficient:- Gives you the least squares estimate.
2. Standard Error:- the least squares estimate of the standard error.
3. T Statistic:- The T Statistic for the null hypothesis vs. the alternate hypothesis.
4. P Value:- Gives you the p-value for the hypothesis test. The p value indicates the probability that would obtain the present results if the null hypothesis were true. If the p value is very small, the null hypothesis can be rejected.
5. Lower 95%:- The lower boundary for the confidence interval.
6. Upper 95%:- The upper boundary for the confidence interval.

2.9. Related Research

Since welding is the main material joining process in ship building industry the quality and efficiency of welding is directly affecting the productivity of the process. The welding shrinkage and distortion in this industry have led to lot of production losses and hence there are lot of researches has been carried out to eliminate or control shrinkage and distortion during welding process.

Most of those researches have been carried out along three main streams, which are described below.

1. Modelling and weld simulation using finite element methods (FEM)
2. Numerical investigations based on theories and formulae
3. Combination of numerical and experimental methods

Finally outcome of those researches have been verified using experimental results. The use of computer simulative techniques has the potential to significantly reduce the cost of welded fabrications by allowing for predictions to be made long before a single weld bead is put down on the workshop floor. Therefore, computer models that are aimed at predicting welding phenomena not only need to be accurate, but must also be affordable and capable of making predictions within industrial time frames if they are to be used by fabricators (Bachorski, 2000).

2.9.1. Weld simulation using FEM

Finite-element prediction of distortion during gas metal arc welding using the shrinkage volume approach

This research has been carried out from the Department of Mechanical Engineering, The University of Adelaide, under the supervision of Bachorski, Painter, Smailes, Wahab (2000).

The Shrinkage Volume Method is a linear elastic finite-element modelling technique that has been developed to predict post-weld distortion. By assuming that the linear thermal contraction of a nominal shrinkage volume is the main driving force for distortion, the need to determine the transient temperature field and microstructural changes is eliminated. In so doing, the model solution times are reduced significantly and the use of linear elastic finite-element methods permits large, highly complex welded structures to be modeled within a reasonable time frame. Verification of the modeled results was carried out by an experimental program that investigated the distortion of plain carbon steel plates having differing V-butt preparations

Thermo mechanical analysis of the welding process using the finite element method

This research paper was published by Mr. Friedman, in the Journal of Pressure Vessel Technology - Volume 97. During this research analytical models are developed for calculating temperatures, stresses and distortions resulting from the welding process. The models are implemented in finite element formulations and applied to a longitudinal butt weld. Non uniform temperature transients are shown to result in the characteristic transverse bending distortions. Residual stresses are greatest in the weld metal and heat-affected zones, while the accumulated plastic strain is maximum at the interface of these two zones on the underside of the weld.

The finite element approach has been shown to be a powerful tool both for determining the welding thermal cycle and for evaluating the stresses and distortions generated as a result of the temperature transients. The analysis procedures are applicable to planar or axisymmetric welds under quasi stationary conditions. The method used for determining temperatures is featured by a direct iteration procedure to accurately account for the latent heat liberated during solidification of the weld. The finite element calculations enable, in particular, the effects of the heat input distribution on the heat flow patterns through the thickness of the weld to be determined. The short-time thermal response, which yields the dimensions of the fusion and heat affected zones, thus greatly affects the resulting non uniform shrinkage in these zones.

Numerical simulation of welding distortion in large structures

This was carried out by Mr. Dean Deng from Research Center of Computational Mechanics, Inc and Hidekazu Murakawa & Wei Liang from Welding Research Institute, Osaka (2007).

In this study, based on inherent strain theory, an elastic finite element method is developed to precisely predict welding distortion during the assembly process considering both local shrinkage and root gap. First, thermal elastic–plastic finite element method is employed to estimate inherent deformations for different typical welding joints. Then experiments are carried out to verify the simulated results. The effectiveness of the proposed elastic FEM is confirmed using experimental results.

2.9.2. Numerical modelling of welds

A numerical analysis of the void-shrinkage process controlled by surface-diffusion

This research was carried out in Department of Welding and Production Engineering, Osaka University, Japan by Takahashi, Ueno and Nishiguchi (1998).

Void-shrinkage is analysed by computer simulations to visualize and predict the process of diffusion bonding. It is assumed that the atom-transport from boundary to void-surface is controlled by surface diffusion, that is, the coefficient of surface diffusion is much less than that of boundary diffusion. The shrinkage processes of isolated and arrayed voids on a boundary are respectively analysed. For simplicity, the initial voids are assumed to be cylindrical with symmetrical cross sections. The computer simulations conducted to visualize the process of the void shrinkage indicate that a void shape changes its shape continuously. The void-shrinkage depends on geometrical parameters such as void-spacing, void-height and void-width as well as the external process parameters of temperature and pressure. It is found that the activation energy for the void-shrinkage can be obtained by (Equation 1).

Equation 1: Activation energy for the void-shrinkage

$L_n\ (T/t_v) - 1/T$, where

t_v = time required to attain the void-shrinkage of a certain volume

T = absolute temperature

It is also indicated that the stress-exponent n to t_v gradually increases from −0.85 to −0.3 with decreasing bonding pressure.

Analysis of welding distortion using qualitative and semi quantitative techniques.

This was carried out by Zhou (1995). During this research following formulae have been used to calculate the welding shrinkage.

Table 5: Formulae for prediction of transverse shrinkage

Formula	Variable description
Malisius's formula $S = \lambda_1 K \frac{Q}{S_1} + \lambda_2 b$	S: axial Shrinkage perpendicular to the weld (mm) λ_1:linear thermal expansion of the base material (about 0.004) λ_2: linear thermal expansion of the weld (about 0.0093) Q: cross section of the weld including reinforcement (mm^2) S_1: average thickness of the base material (mm) b: average breadth of the material (mm) K: constant depending on the thermal output of the welding process and thermal conductivity (about 45-55 for arc welding electrode)
Capel's formula $\Delta l = \frac{KW10^3}{su}$	Δl: transverse shrinkage (mm) s: thickness of the layer of weld metal (mm) u: welding speed (cm/min) W: electric power of welding arc K: constant depend on material (17.4 for carbon steel)
Cline's formula $\Delta l = 0.1(\sqrt{t} - 0.230)$	Δl: transverse shrinkage (mm) t: plate thickness (mm)

Source: - Predictive formulae for weld distortion: A critical review by G. Verhaeghe (1999)

2.9.3. Combination of numerical and experimental methods

A simplified approach to estimating welding shrinkage assumes the plate being welded contains a thermo elasto-plastic zone and a fully elastic zone.

This was carried out by Dr. Mandal and Sundar and they have done a theoretical analysis of transverse shrinkage in a welded butt joint (Mandal, 1997). The mathematical model used in this analysis is based on the assumption that the plate undergoing welding is made up of a thermo elasto-plastic zone and a fully elastic zone. The analysis provides a simplified approach for estimating welding shrinkage.

Equation 2: Simplified equation for theoretical analysis of weld shrinkage

$$\delta r_{max} = \left[\frac{\alpha T_m T_p}{2T_m - T_p} - \frac{\sigma Y_0}{E_0}\right] L$$

Where,

σY_0 –Yield stress

E_0 –Modulus of elasticity

α –Thermal strain coefficient

T_p –Peak temperature

T_m –Melting temperature

The calculation was done for selected samples and the results were verified with the actual values obtained. The results obtained during this research was given in the (Table 6)

Table 6: Comparison of results obtained from theoretical and practical experiments

	Plate dimensions				SAW Parameters			Shrinkage		
Sample	length (mm)	breadth (mm)	Thick (mm)	Material	Current (A)	Voltage (V)	Speed (cm/s)	Actual (mm)	Calculated (mm)	Deviation %
1P6	1000	240	6	MS	520	26	1.80	0.6	0.626	4.30
2P6	1000	240	6	MS	520	28	1.60	1.02	1.140	11.76
3P6	1000	240	6	MS	540	27	1.80	0.52	0.556	6.9
4P6	1000	240	6	MS	440	30	1.83	0.49	0.508	3.67
1P12	1000	240	12	MS	480	32	0.93	0.26	0.278	6.92
E1	12000	3000	16	AH32	1180	33	1.13	0.80	0.750	6.25
E2	12000	3000	19.5	AH32	1230	33	1.05	0.80	0.795	0.62

Source: - A simplified approach to estimating welding shrinkage assumes the plate being welded contains a thermo elasto-plastic zone and a fully elastic zone by Dr. Mandal and Sundar

The analysis of longitudinal shrinkage in butt weld joint

This research was published by M. Iranmanesh and S. Babakoohi (2008, January).

For this study an equation for the longitudinal shrinkage has derived (Equation 3) and the results are verified using sample testing also.

Equation 3: Formula for longitudinal shrinkage in butt weld joint

$$\delta r = \delta y_0 = -\left[\frac{\sigma y_0 L}{E_0 K_r}\right]$$

Where,

K_r = spring constant divided by flat bar constant = (2K) / (E_oS/L)

σy_o= yield stress

E_o = modulus of elasticity at room temperature

L= length

The comparison of the results during numerical analysis and experimental methods are given in the following

Table 7: Parameters and comparison of results

Sample	I (A)	Ep (V)	V (mm/s)	Lep (mm)	Krc	δr (mm) model	δr (mm) Sample
1	100	25	2.5	22.6	5.74	0.28	0.34
2	170	27	2.4	43.3	2.52	0.63	0.54
3	200	30	2.2	61.77	1.47	1	0.70
σy_0 =350Mpa, E_0= 200Gpa							

Source: - The analysis of longitudinal shrinkage in butt weld joint, by M. Iranmanesh and S. Babakoohi in Department of Marine Engineering, Amirkabir University of Technology

3 EXPERIMENT, DATA COLLECTION & ANALYSIS

3.1. Identification of the Sample

3.1.1. Selection of the process

For the convenience of this experiment total hull construction process was divided in to three main sectors considering the differences in application and process. Those are,

1. Panel fabrication (Figure 8)
2. Block construction (Figure 9)
3. Block assembly (Figure 10)

Through this study, the process and methods for gathering shrinkage data were determined for each of the interim processes. However the study was mainly focused on the panel fabrication stage as 60% (Considering the job wise electrode consumption data extracted from shipyard management information system) of the welding works in a ship building project are related to panel fabrication.

During this research the shrinkage data during the block construction also collected and it was done to get an idea about the shrinkage effect for the production and to use as a base line for further continuation of this research.

3.1.2. Selection of welding method and the position

Since 90% of the welding in a ship building project in Sri Lankan shipyard is carried out using the FCAW process (Table 1) the FCAW welding process has selected as the welding method to be used during this study.

When considering above 3 main processes in ship building the type of welding utilization is different for each process. The panel fabrication involves 100% of down hand welding (1G/1F) (Figure 14) and more fillet welding utilization than the butt welding. For the block construction vertical and horizontal fillet welding is utilised more (2F/3F). The block construction is the most complex process in hull construction and it is difficult to analyse and find a factor for welding shrinkages in block construction. In the block assembly process, butt welding is more utilised than the fillet welding and in that case amount of vertical and horizontal welding (2G/3G) is high.

Since the panel fabrication process is focused during this study the down hand welding position (1G/1F) has selected as the welding position for the study.

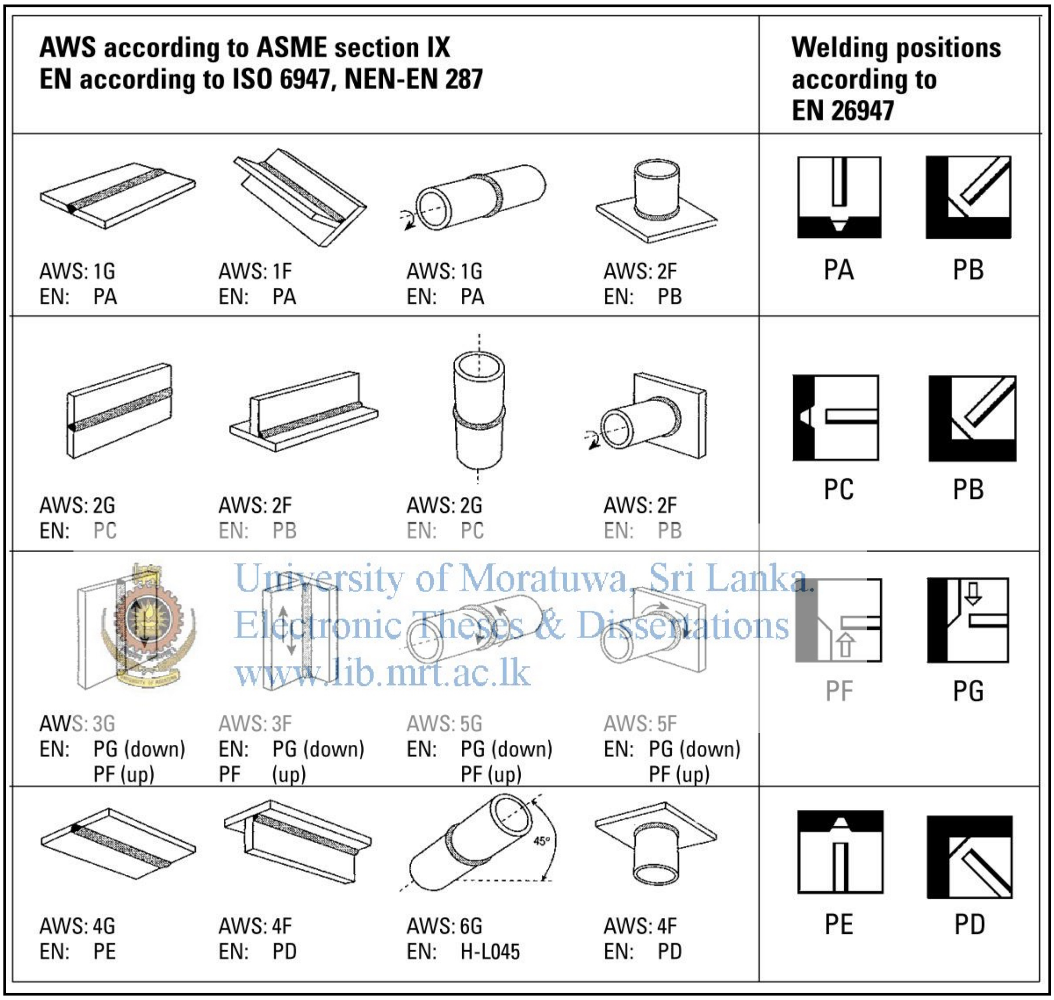


Figure 14: Standard Welding positions

Source: - www.sumitwaghmare.files.wordpress.com/position.jpg (2011/02)

3.1.3. Selection of the test pieces

The steel palates of various thicknesses (From 5mm to 50mm) are used in hull construction works in shipyard. Since it is difficult to collect data for each of above thicknesses, some sample thicknesses were selected for the testing purposes.

The sample thicknesses were selected considering the consumption frequency of them and it was selected in such a way to represent at least 90% of the total plate usage (Table 8).

Table 8: Steel plate consumption for NC projects

Plate requirement per vessel																
Thickness	5	**6**	7	8	**9**	10	11	**12**	14	15	16	20	22	25	40	50
Usage	54	71	47	263	193	125	68	168	41	10	18	16	0	2	1	1
Total for category	172			581			277			48						
% from total	16			54			26			4						
	96									4						

Source: -Project material usage data in CDLMIS (Colombo Dockyard PLC Management Information System)

3.2. Data Collection Methodology

Special data collection sheets were prepared to collect shrinkage data of above each and every process. The data collection sheets were formatted with all the necessary attributes and independent variables that affect joint shrinkage. The shrinkage data relevant to each and every test was collected and organised in data sets according to the welding process and application

The data was collected using two methods for this experiment. First method is sample testing and the second method is taking on the job measurements. Even though testing of welding shrinkage in panel fabrication can be done using above mentioned methods, the shrinkage measurement in block construction and block erection have to be done during the actual production process.

3.3. Measuring Techniques

3.3.1. Measuring of dimensions in actual production environment

Two different types of measuring techniques were used for the measurement taken of butt welds and fillet welds during the sample testing. When taking measurements of the welding shrinkage during actual production process, it is difficult to separate fillet and butt welds and the dimensions are related to combination of those welds. Standard measuring tapes were used to measure the larger dimensions (distance of a pre-fabricated panel, distances of a block) during the actual production process.

3.3.2. Measuring of butt weld shrinkage in test samples

Use 150*250 mm test pieces to carry out the butt joint welding. The root gap was selected according to the plate thickness (Table 9).

Table 9: Root gap variation with the thickness of plate

Plate thickness	Root gap
6 mm	2 mm
9 mm	4 mm
12 mm	6 mm

Source: Shipyard welding procedure hand book

A special test piece holding device was prepared for mounting and holding the test piece during the welding and inspection process (Figure 15). This was done to eliminate the measurement errors due to warping of the plates during welding process (Figure 17). The measurements were taken from three points along the weld (Figure 20) and during three stages. Those are before welding (Figure 16), after root welding (Figure 18), after final welding (Figure 19). The measuring points were marked using center punch before starting the welding and the distances were measured using digital venire caliper. After recording the measurements carry out the root run and again the distances were measured after completing the root run. Again the data was recorded and finish the welding with final capping run. Keep the test piece to cool and then the final distances were measured and recorded.

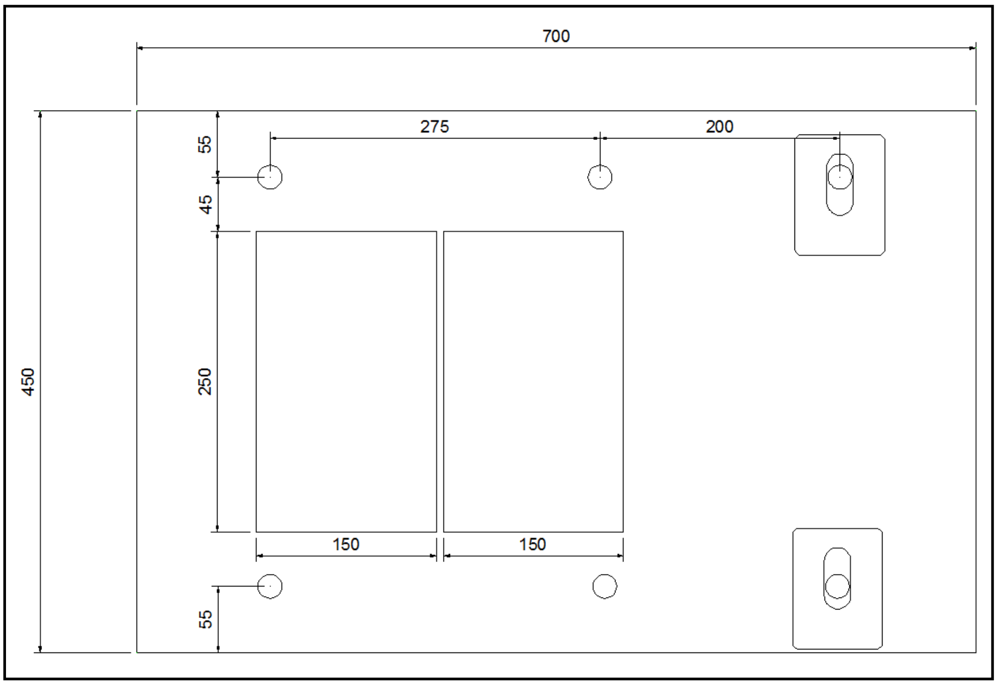


Figure 15: Test piece holding device

Figure 16: Clamping of test piece for measurements

Figure 17: Carry out welding of test pieces

Figure 18: Taking measurements after root welding

Figure 19: Taking measurements after final welding

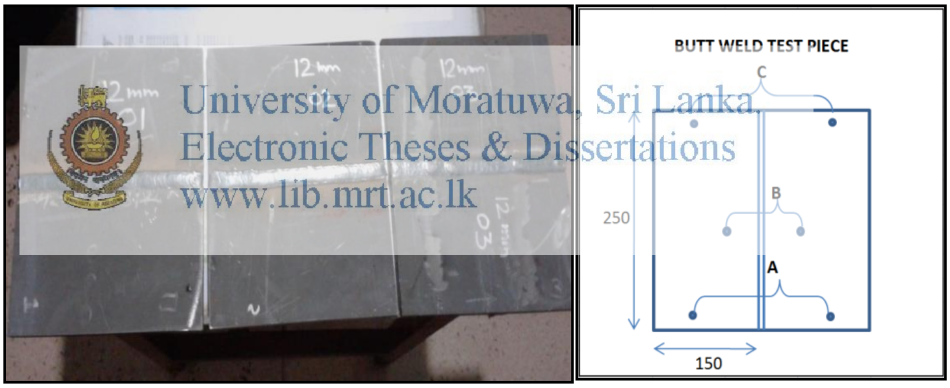


Figure 20: Butt welding test piece

3.3.3. Measuring of fillet weld shrinkage in test samples

To measure the shrinkage in fillet weld, 500 mm*250 mm plate is used as the base plate and 3 no’s of 100 mm flat bars were welded to that using a fillet weld (Figure 21). In this case also the plate thicknesses for the sample testing were selected in such a way to represent at least 90% from the total plate consumption of a project. The welding throat was selected as per the plate thicknesses used (Table 10). It is important to measure and control the throat thickness as it is directly affecting the welding shrinkage. The throat thickness was measured using the welding gauges (Figure 22).

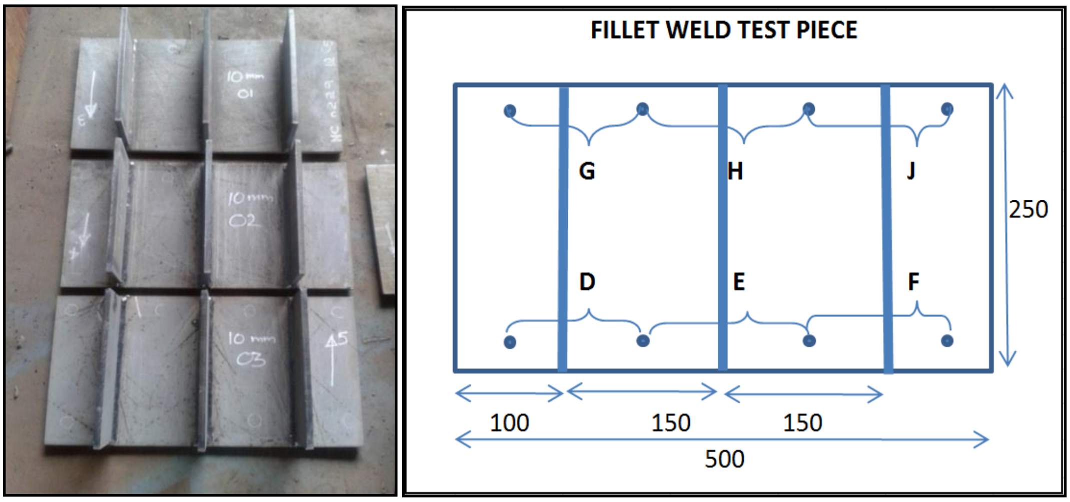


Figure 21: Fillet welding test piece

Table 10: Throat thickness variation with the thickness of plate

Plate thickness	Throat thickness
6-8 mm	3 mm
9-12 mm	4 mm
13-20 mm	5 mm

Source: Shipyard welding procedure hand book

In this case also the measurement taking points were marked using the center punch before starting the welding. Then the initial distances were measured using divider and the digital vernier caliper.

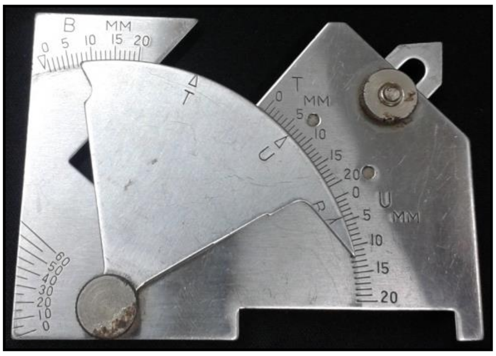


Figure 22: Welding gauges

The welding was carried out under the controlled conditions and final dimensions were taken after allowing some time for the cooling. Final dimensions were taken from the same positions using the same procedure used for before welding measurement taken.

3.3.4. Measuring of shrinkage during panel fabrication

Since it is costly to carry out sample testing for panel fabrication stage, the measurement were taken during the production process. Some fabricated panels with different welding combinations were selected for this purpose and the dimensions were taken using measuring tapes (Figure 23). Each of dimensions was taken at two stages, namely before welding and after welding.

Figure 23: Taking measurements of fabricated panels

3.3.5. Measuring of shrinkage during block construction

This is the most complex fabrication process in ship building process. Large number of welding runs with different types and different positions are consisting in a single unit. So it is difficult to do a proper analysis and it was decided not to consider the block construction stage for this study. However dimensions of few units were taken at the before welding and after welding stages in order to get an idea about the impact of welding shrinkage for unit construction and as an encouragement to proceed with that in future study. The distances of the units were measured using the laser distance meter (Figure 24).

Figure 24: Laser distance meter

3.3.6. Measuring of shrinkage during block erection

This is the final stage of ship construction process and the total length of the ship is depend on the shrinkage occurs in this stage. The distances (before welding and after welding) related to this process also have to be taken during the actual production. The distances can be measured across the weld seam with in 1000 mm span (Figure 25). Due to the complexity of the process this stage also wasn't considered for the study.

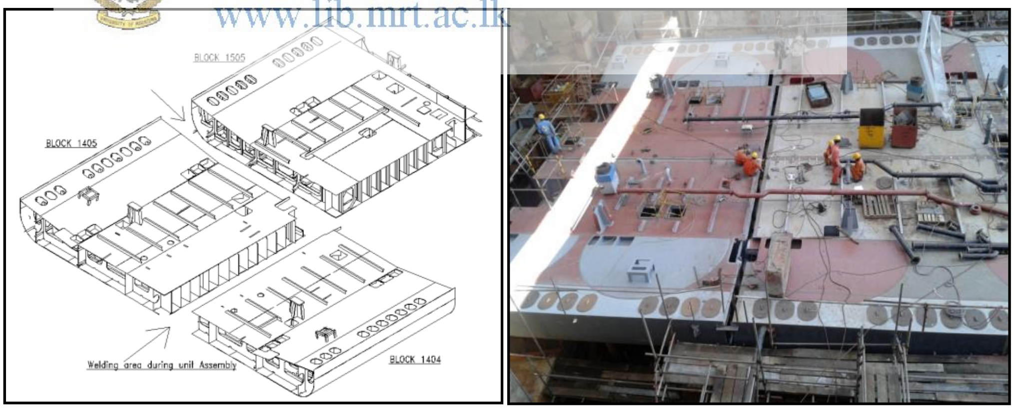
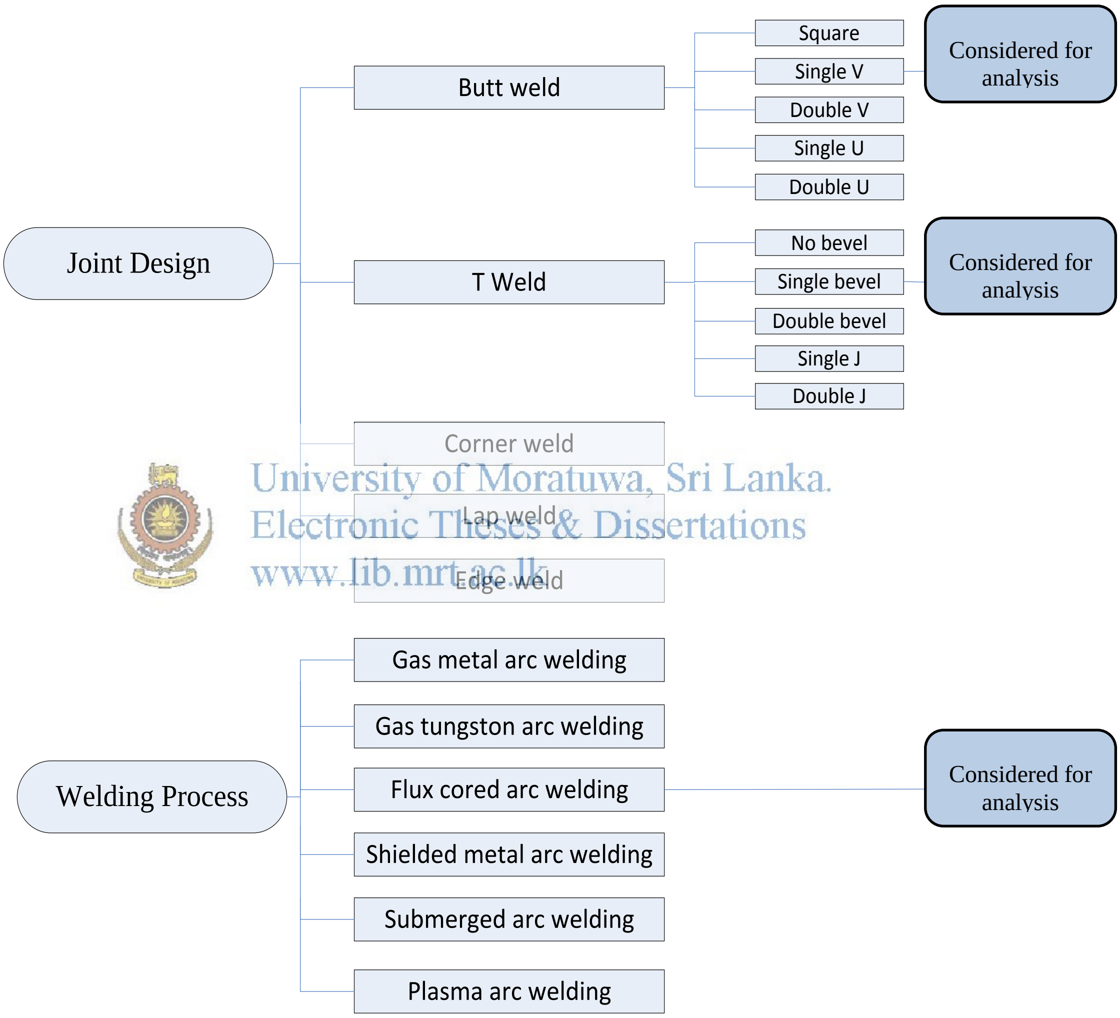


Figure 25: Unit assembly process

3.4. Methodology of Data Analysis

As described in the section "1.4 Methodology ", for the convenience of the study the ship building process divided in to three main processes and the shrinkage factor for each process was analysed separately. During this study the main focus was on panel fabrication stage and comprehensive analysis was done for that process. Even though raw data were gathered for unit construction processes, they were not properly analysed and it was done as an initiative for the future works in those areas.

Since the welding attributes described in "2.4 Effect of Welding Attributes on Shrinkage" has an impact on the shrinkage data it is necessary to define the fixed and variable attributes and the considered and omitted parameters (Figure 26) at the beginning of the study.



To be continued…

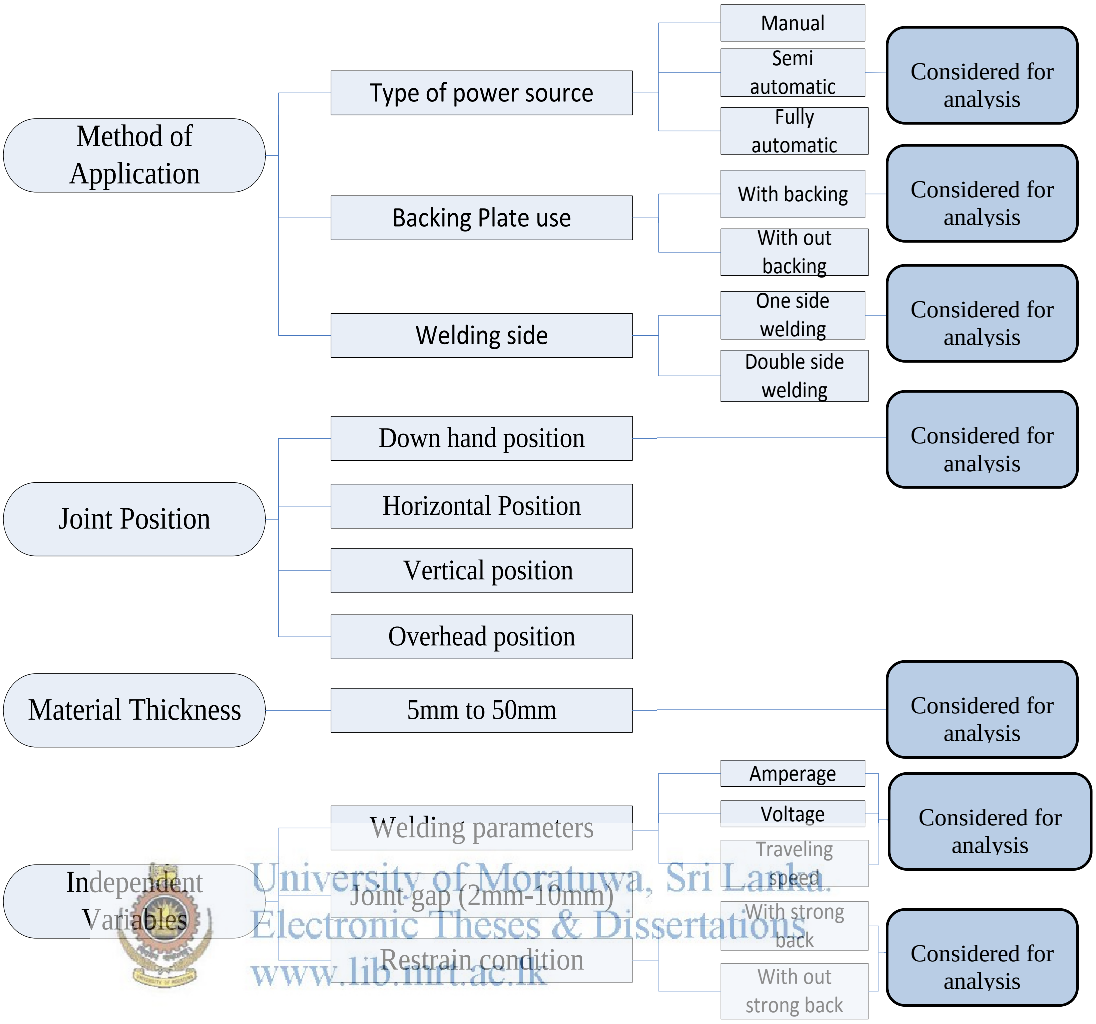


Figure 26: Welding parameters considered for the analysis

3.5. Representation of Data

3.5.1. Data collected in sample testing

A comprehensive set of data was collected during the sample testing. It is easy to control all the variables during sample testing and it can be used to obtain shrinkage values for each and every combination by controlling the variables. Since 90% of the welding in ship building is done using FCAW method (Table 1), the shrinkage data of sample testing were taken only for FCAW semi-automatic welding method. The plate thicknesses use for the testing was selected in such a way to represent more than 90% of the plate consumed in ship building industry (Table 4). The joint gap is also considered as a fixed parameter for a particular plate thickness use and for the testing standard joint gaps were used (Table 9). The other parameters such as Amperage, Voltage and travelling speed also considered as fixed parameters for a particular thickness as those parameters vary mainly with the material thickness (2.2.1Flux cored arc welding (FCAW)). The summary of the parameters defined for sample testing is described in (Table 11).

Table 11: Summary of parameters defined for sample testing

Parameter	Parameter identification	Sub categories	Category identification
Joint design	F1	Butt weld	2
		Fillet weld	1
Welding process	F2	FCAW	0
Application method	F3	Semi-automatic	0
Welding position	F4	Down hand	0
Material thickness	F5	6 mm	0
		9 mm	1
		12 mm	2
Welding parameters (Amperage, Voltage, Traveling speed)	F6	Fixed for selected plate thickness	0
Joint gap	F7	Fixed for selected plate thickness	0
Restraining condition	F8	With strong backs	1
		Without strong backs	2

The testing combinations were decided base on above parameter selection. For each parameter combination 3 numbers of test pieces were tested and there shrinkages were recorded. When considering above parameters 9 numbers of combinations (Table 12) were obtained and the shrinkage data gathered for each combination separately.

Table 12: Testing combinations for sample testing

Category	F1	F2	F3	F4	F5	F6	F7	F8
1	2	0	0	0	0	0	0	1
2	2	0	0	0	0	0	0	2
3	2	0	0	0	1	0	0	1
4	2	0	0	0	1	0	0	2
5	2	0	0	0	2	0	0	1
6	2	0	0	0	2	0	0	2
7	1	0	0	0	0	0	0	1
8	1	0	0	0	1	0	0	1
9	1	0	0	0	2	0	0	1

For each of above combination three test pieces were tested and 102 numbers of data set were collected (

Table 13). The collected data under each category was summarised.

Table 13: Shrinkage data collected during sample testing

Test No:	Thick	Position	Distance from start	Restrain condition	Weld type	Distance before weld	Distance after weld	Shrinkage (mm)
1	12	A	25	2	2	200	198.87	1.13
	12	B	125	2	2	100	98.82	1.18
	12	C	225	2	2	200	198.54	1.46
2	12	A	25	2	2	200	198.85	1.15
	12	B	125	2	2	100	98.73	1.27
	12	C	225	2	2	200	198.48	1.52
3	12	A	25	2	2	200	198.83	1.17
	12	B	125	2	2	100	98.57	1.43
	12	C	225	2	2	200	198.62	1.38
4	9	A	25	2	2	200	198.88	1.12
	9	B	125	2	2	100	98.87	1.13
	9	C	225	2	2	200	198.7	1.3
5	9	A	25	2	2	200	198.99	1.01
	9	B	125	2	2	100	98.81	1.19
	9	C	225	2	2	200	198.79	1.21
6	9	A	25	2	2	200	198.88	1.12
	9	B	125	2	2	100	98.86	1.14

	9	C	225	2	2	200	198.6	1.4

Test No:	**Thick**	**Posi tion**	**Distance from start**	**Restrain condition**	**Weld type**	**Distance before weld**	**Distance after weld**	**Shrinkage (mm)**
7	6	A	25	2	2	200	199.36	0.64
	6	B	125	2	2	100	99.12	0.88
	6	C	225	2	2	200	199.09	0.91
8	6	A	25	2	2	200	199.38	0.62
	6	B	125	2	2	100	99.26	0.74
	6	C	225	2	2	200	199.18	0.82
9	6	A	25	2	2	200	199.29	0.71
	6	B	125	2	2	100	99.24	0.76
	6	C	225	2	2	200	199.16	0.84
10	12	A	25	1	2	200	199.21	0.79
	12	B	125	1	2	100	99.18	0.82
	12	C	225	1	2	200	199.16	0.84
11	12	A	25	1	2	200	199.18	0.82
	12	B	125	1	2	100	99.16	0.84
	12	C	225	1	2	200	199.14	0.86
12	12	A	25	1	2	200	199.22	0.78
	12	B	125	1	2	100	99.18	0.82
	12	C	225	1	2	200	199.16	0.84
13	9	A	25	1	2	200	199.39	0.61
	9	B	125	1	2	100	99.36	0.64
	9	C	225	1	2	200	199.32	0.68
14	9	A	25	1	2	200	199.38	0.62
	9	B	125	1	2	100	99.37	0.63
	9	C	225	1	2	200	199.35	0.65
15	9	A	25	1	2	200	199.32	0.68
	9	B	125	1	2	100	99.29	0.71
	9	C	225	1	2	200	199.28	0.72
16	6	A	25	1	2	200	199.43	0.57
	6	B	125	1	2	100	99.42	0.58
	6	C	225	1	2	200	199.42	0.58
17	6	A	25	1	2	200	199.48	0.52
	6	B	125	1	2	100	99.46	0.54
	6	C	225	1	2	200	199.43	0.57

To be continued…

To be continued..

Test No:	Thick	Posi tion	Distance from start	Restrain condition	Weld type	Distance before weld	Distance after weld	Shrinkage (mm)
18	6	A	25	1	2	200	199.44	0.56
	6	B	125	1	2	100	99.42	0.58
	6	C	225	1	2	200	199.41	0.59
19	8	D	25	0	1	150	149.68	0.32
	8	E	25	0	1	150	149.67	0.33
	8	F	25	0	1	150	149.69	0.31
	8	G	225	0	1	150	149.67	0.33
	8	H	225	0	1	150	149.68	0.32
	8	I	225	0	1	150	149.66	0.34
20	8	D	25	0	1	150	149.7	0.3
	8	E	25	0	1	150	149.67	0.33
	8	F	25	0	1	150	149.69	0.31
	8	G	225	0	1	150	149.67	0.33
	8	H	225	0	1	150	149.69	0.31
	8	I	225	0	1	150	149.67	0.33
21	10	D	25	0	1	150	149.64	0.36
	10	E	25	0	1	150	149.62	0.38
	10	F	25	0	1	150	149.63	0.37
	10	G	225	0	1	150	149.63	0.37
	10	H	225	0	1	150	149.62	0.38
	10	I	225	0	1	150	149.6	0.4
22	10	D	25	0	1	150	149.61	0.39
	10	E	25	0	1	150	149.6	0.4
	10	F	25	0	1	150	149.59	0.41
	10	G	225	0	1	150	149.6	0.4
	10	H	225	0	1	150	149.59	0.41
	10	I	225	0	1	150	149.59	0.41
23	10	D	25	0	1	150	149.58	0.42
	10	E	25	0	1	150	149.59	0.41
	10	F	25	0	1	150	149.58	0.42
	10	G	225	0	1	150	149.57	0.43
	10	H	225	0	1	150	149.58	0.42
	10	I	225	0	1	150	149.57	0.43

To be continued…

Test No:	Thick	Posi tion	Distance from start	Restrain condition	Weld type	Distance before weld	Distance after weld	Shrinkage (mm)
24	14	D	25	0	1	150	149.44	0.56
	14	E	25	0	1	150	149.46	0.54
	14	F	25	0	1	150	149.44	0.56
	14	G	225	0	1	150	149.46	0.54
	14	H	225	0	1	150	149.45	0.55
	14	I	225	0	1	150	149.45	0.55
25	14	D	25	0	1	150	149.39	0.61
	14	E	25	0	1	150	149.41	0.59
	14	G	225	0	1	150	149.39	0.61
	14	H	225	0	1	150	149.4	0.6
	14	I	225	0	1	150	149.39	0.61
26	14	E	25	0	1	150	149.42	0.58
	14	F	25	0	1	150	149.42	0.58
	14	G	225	0	1	150	149.42	0.58
	14	H	225	0	1	150	149.43	0.57
	14	I	225	0	1	150	149.43	0.57

Note :- All dimensions are in mm

Graphical interpretation of data

After collecting the data a graphical analysis was done to understand the behavior of welding shrinkage with the thickness of the material (Figure 27).

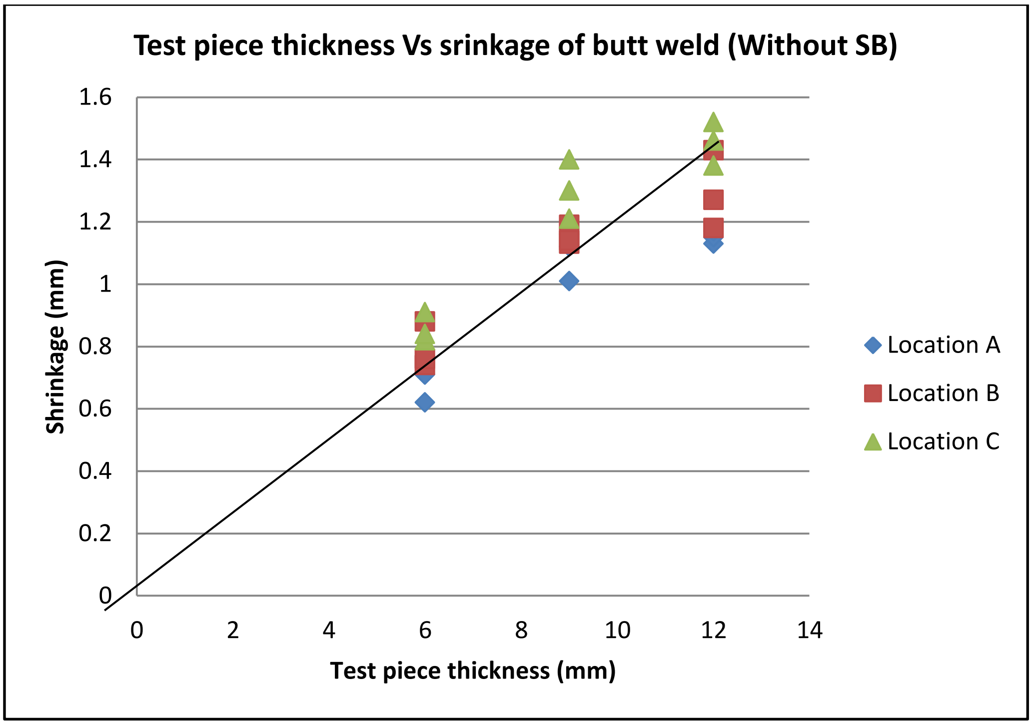


Figure 27: Butt welding shrinkage vs material thickness (without strong back)

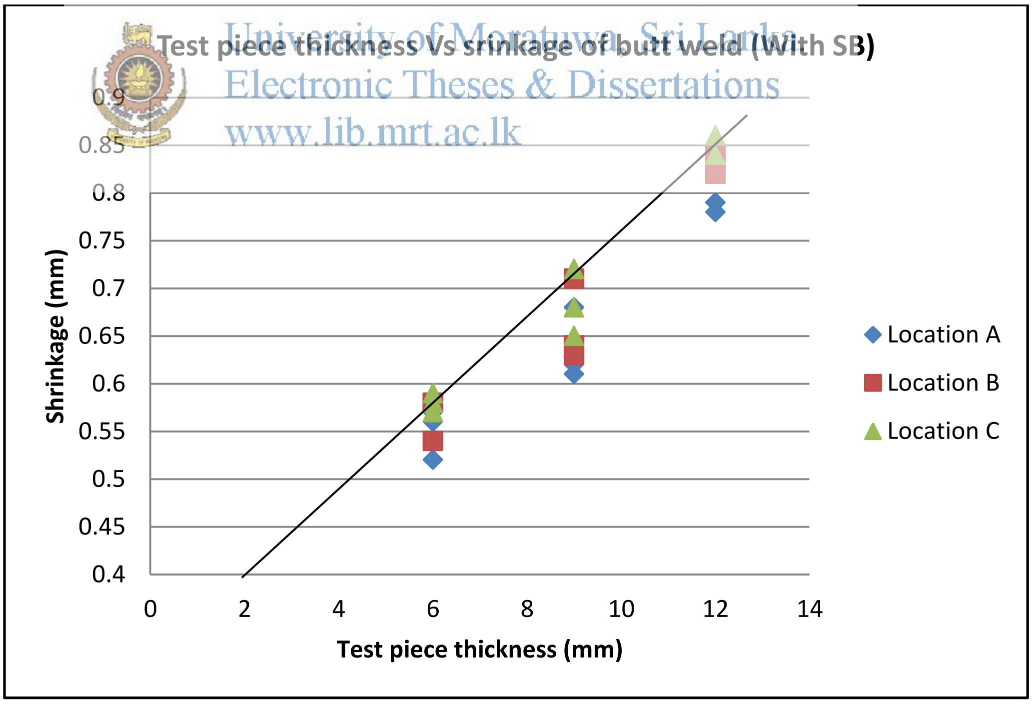


Figure 28: Butt welding shrinkage vs material thickness (without strong back)

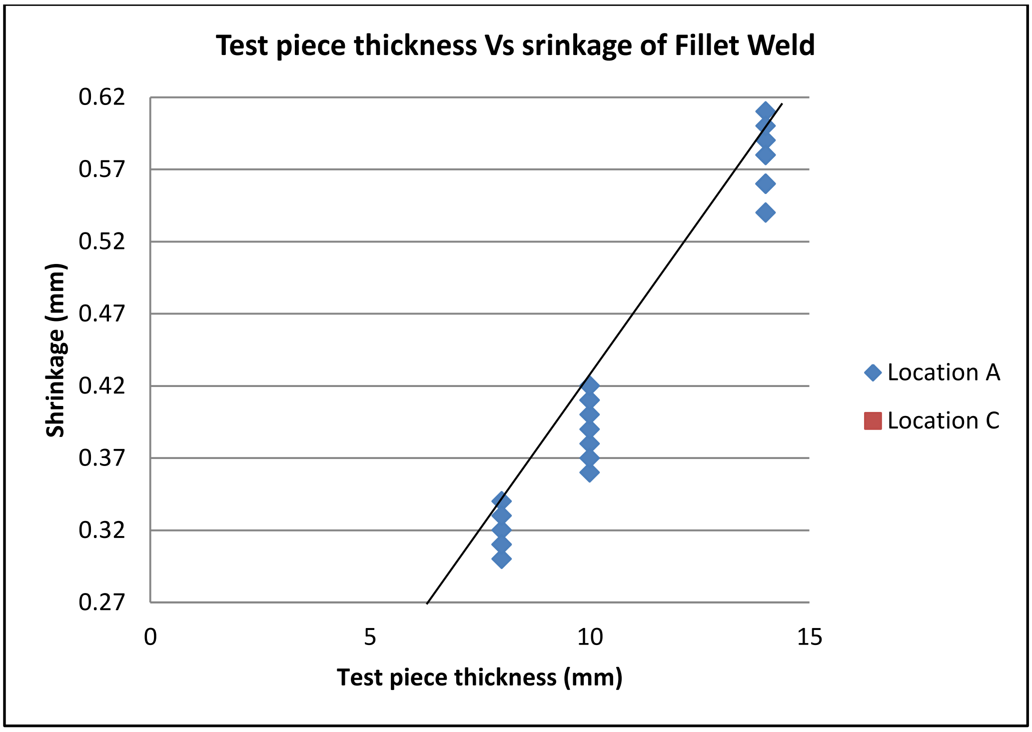


Figure 29: Fillet welding shrinkage variation with material thickness

Since the variation of the shrinkage is almost linear, multivariate regression models can be used to find the relationship between identified variables and the welding shrinkage.

3.5.2. Data collected in panel fabrication

As described in the section "3.2 Data Collection Methodology" the shrinkage data for the panel fabrication was collected during the production process. In that case it was difficult to carry out different tests for butt welding and fillet welding separately. In practical situation the both joint design types have to use to complete welding of a panel (Figure 30). For the convenience of the analysis few main attributes considered (Table 14) during the analysis of shrinkage in panel fabrication.

Table 14: Attributes consider during data collection for panel fabrication

Test No:	Material thickness		Number of fillet welds		Number of butt welds	
	Plate	Stiffener	Transverse	Longitudinal	Transverse	Longitudinal
1						
2						
3						
4						
5						
6						

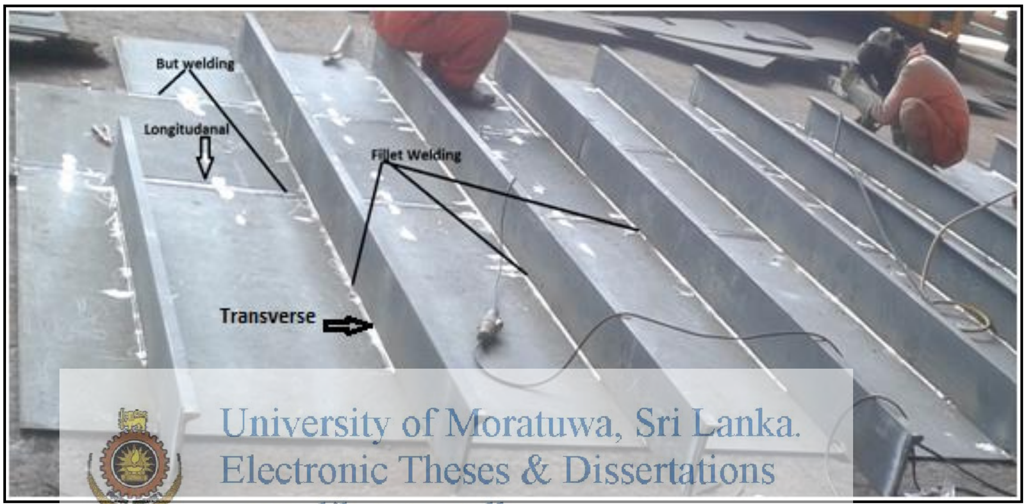


Figure 30: Joint design types use during panel fabrication

Under this category 20 numbers of panels were tested and 42 numbers of data set were collected. The collected data was summarised in Table 15 and all dimensions are in millimeters.

Table 15: Welding shrinkage data of panel fabrication

Test No:	Part No:		Thick		Perpendi.		Parallel		Measurement		Shrinkage
			Plate	Stif	Fillet	But	Fillet	But	Before	After	
1	1	NC-229, 304P-LB8500P	7.5	7	5	0	1	1	3650	3648.8	1.2
2	1	NC-229, 304P-LB8500P	7.5	7	5	0	1	1	3530	3528.7	1.3
3	1	NC-229, 304P-LB8500P	7.5	7	1	1	5	0	1800	1798.6	1.4
4	1	NC-229, 304P-LB8500P	7.5	7	1	1	5	0	1870	1868.8	1.2
5	2	NC-229, 22C-CEN BHD	10	8	2	0	0	0	1470	1469.4	0.6
6	2	NC-229, 22C-CEN BHD	10	8	0	0	2	0	1510	1509.5	0.5
7	3	NC-227, 1303-4700 ABL	8	8	4	0	0	0	3170	3168.7	1.3
8	3	NC-227, 1303-4700 ABL	8	8	0	0	4	0	1120	1119.6	0.4

To be continued…

Test No:	Part No:		Thick		Perpendi.		Parallel		Measurement		Shrinkage
			Plate	Stif	Fillet	But	Fillet	But	Before	After	
9	4	NC-227, 1801-FR102	8	8	0	2	3	0	3035	3033.3	1.7
10	4	NC-227, 1801-FR102	8	8	3	0	0	2	1610	1608.9	1.1
11	5	NC-227, 1804-FR105	8	8	16	2	0	1	12971	12966.2	4.8
12	5	NC-227, 1804-FR105	8	8	0	1	10	2	2511	2509.4	1.6
13	6	NC-227, 1802-FR102	8	8	0	2	3	0	3440	3438.2	1.8
14	6	NC-227, 1802-FR102	8	8	3	0	0	2	1840	1838.9	1.1
15	7	NC-229, 22C- LB3300 S	10	8	7	1	0	1	4250	4247.9	2.1
16	7	NC-229, 22C- LB3300 S	10	8	0	1	7	1	2990	2988.8	1.2
17	8	NC-229, 22C- LB5100 S	10	9	7	1	0	1	4280	4278.1	1.9
18	8	NC-229, 22C- LB5100 S	10	9	0	1	7	1	3200	3198.8	1.2
19	9	NC-227, 1101-FR 13	8	8	5	0	2	0	3230	3229	1
20	9	NC-227, 1101-FR 13	8	8	0	2	7	0	3310	3308.5	1.5
21	10	NC-229, 22C- FR-04	8	7	14	0	0	2	8750	8746.9	3.1
22	10	NC-229, 22C- FR-04	8	7	0	2	14	0	2840	2837.8	2.2
23	11	NC-229, 13-2C- LB6400	12	10	5	1	0	2	3340	3337.9	2.1
24	11	NC-229, 13-2C- LB6400	12	10	0	2	5	1	1740	1738.2	1.8
25	12	NC-227, 1803-H010	6	7	7	1	0	1	4270	4267.8	2.2
26	12	NC-227, 1803-H010	6	7	0	1	7	1	2105	2103.7	1.3
27	13	NC-227, 1803-P151	8	7	4	1	0	1	2440	2438.3	1.7
28	13	NC-227, 1803-P151	8	7	0	1	4	1	1420	1418.8	1.2
29	14	NC-227, 1902-P071	10	9	8	1	0	1	5120	5117.4	2.6
30	14	NC-227, 1902-P071	10	9	0	1	8	1	1830	1828.6	1.4
31	15	NC-227, 1405-P014	6	6	6	0	0	1	3810	3808.5	1.5
32	15	NC-227, 1405-P014	6	6	0	1	6	0	1410	1408.9	1.1
33	16	NC-227, 1502-P124	7	8	6	0	0	2	4210	4208.3	1.7
34	16	NC-227, 1502-P124	7	8	0	2	6	0	2830	2828.2	1.8
35	17	NC-229, 17-12C-LB3900	12	10	6	1	0	2	3840	3837.7	2.3
36	17	NC-229, 17-12C-LB3900	12	10	0	2	6	1	2430	2427.9	2.1
37	18	NC-229, 12C-FR3-P017	14	12	4	1	0	1	2610	2607.8	2.2
38	18	NC-229, 12C-FR3-P017	14	12	0	1	4	1	3140	3138.4	1.6
39	19	NC-229, 12C-FR3-P022	10	8	3	0	0	1	2210	2209	1
40	19	NC-229, 12C-FR3-P022	10	8	0	1	3	0	2640	2638.9	1.1
41	20	NC-227, 1901-FR114	9	8	8	2	2	3	5220	5216.6	3.4
42	20	NC-227, 1901-FR114	9	8	2	3	8	2	3140	3137.1	2.9

Note :- All dimensions are in mm

After collecting the data they were graphically interpreted in order to understand the influence of each category for the final shrinkage. Since there are more than one variables it is possible to get only rough idea. Sometimes effects of few variables may not be shown in the graph (Figure 31) due to influence of other prominent variables.

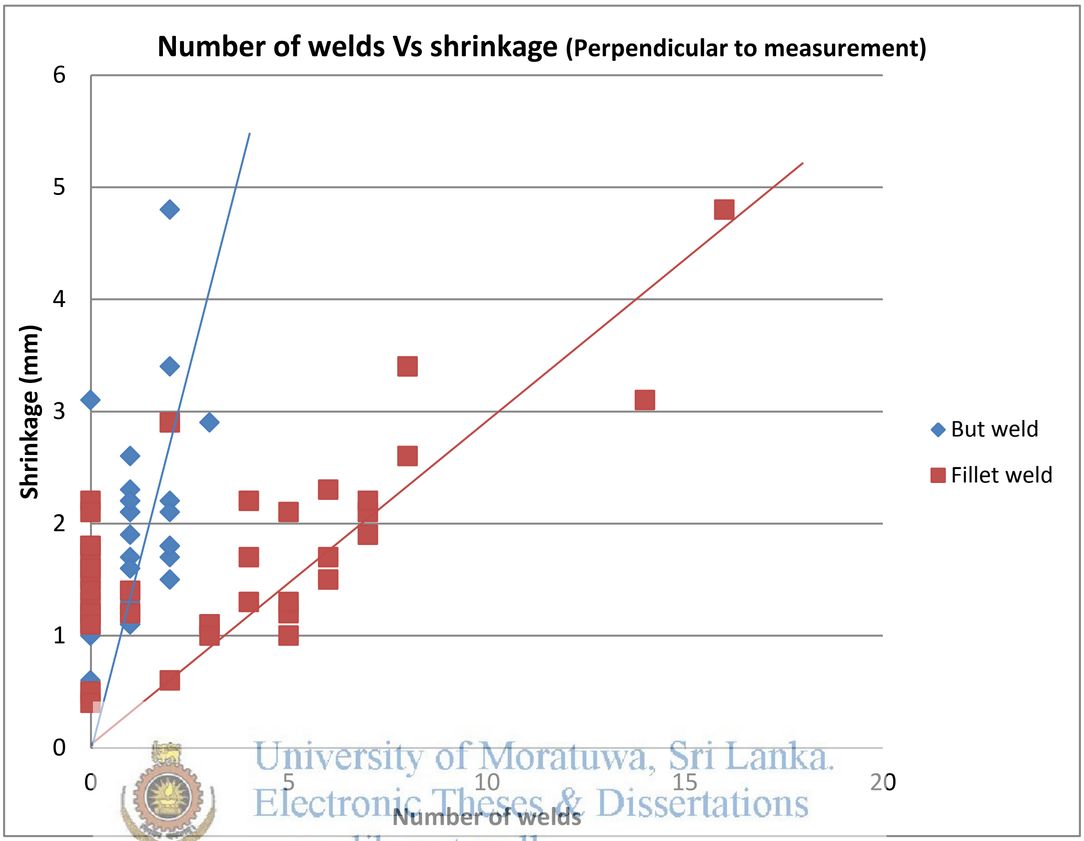


Figure 31: Shrinkage vs. number of welds (perpendicular to direction of measurement)

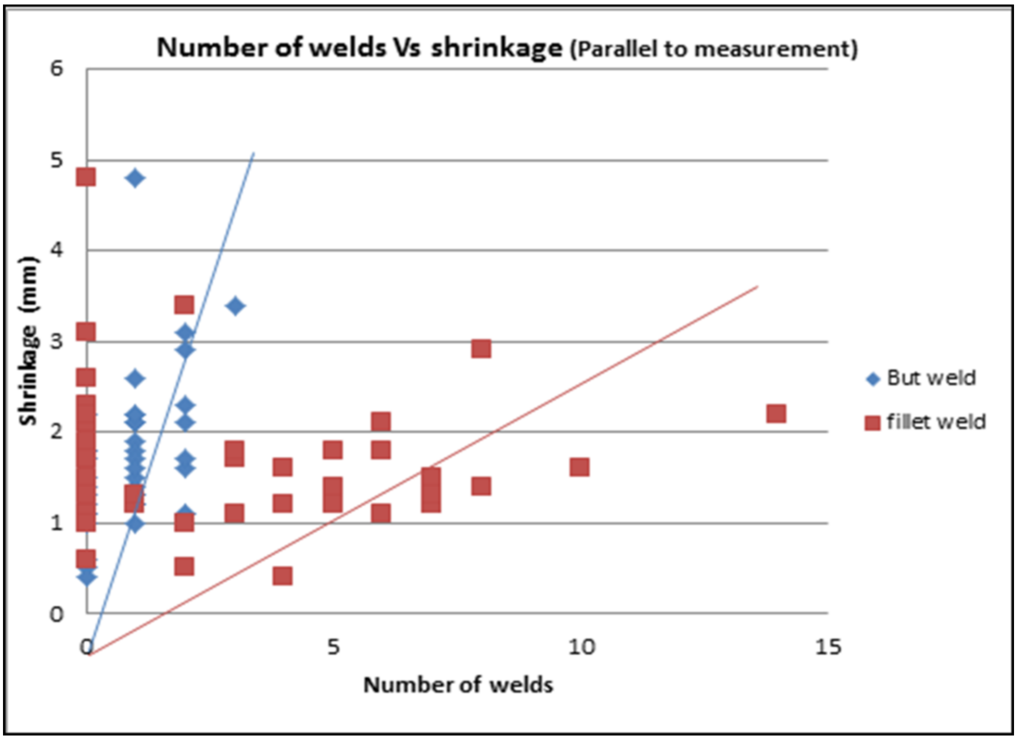


Figure 32: Shrinkage vs. number of welds (parallel to direction of measurement)

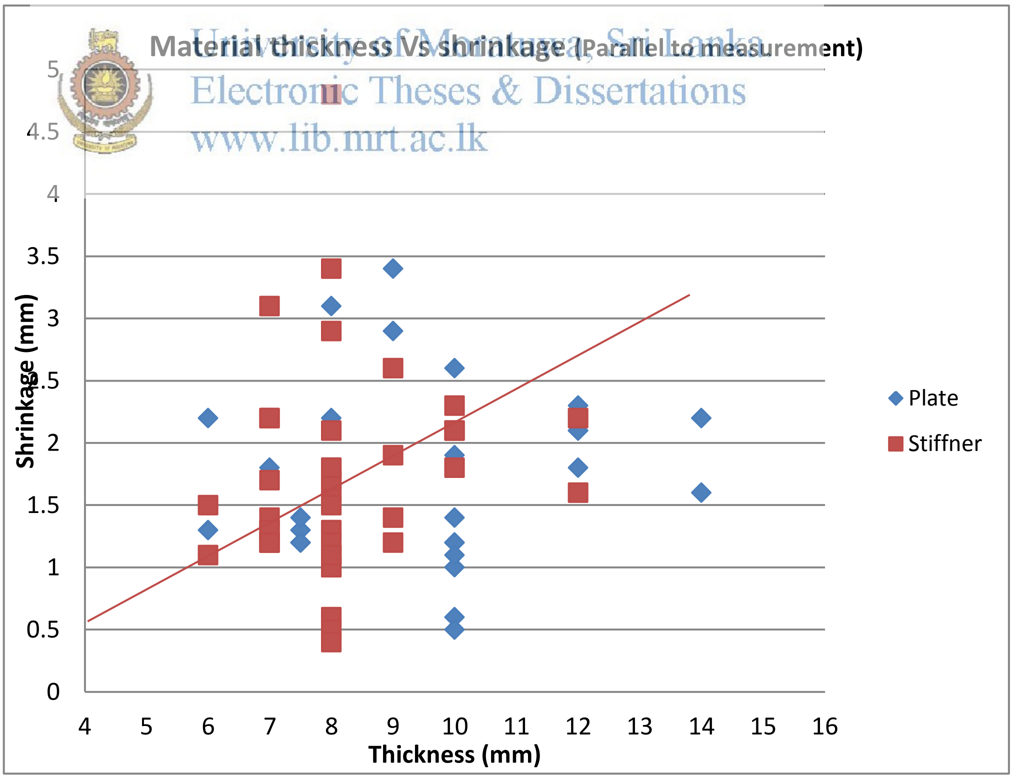


Figure 33: Shrinkage variation with the material thickness

3.5.3. Data collected in unit construction

When considering ship building process in shipyard a vessel is erected as a combination of around 50 units (Figure 34). In order to check the shrinkage in unit construction 48 units of a project was considered and then length and width of each unit were measured before welding and after welding.

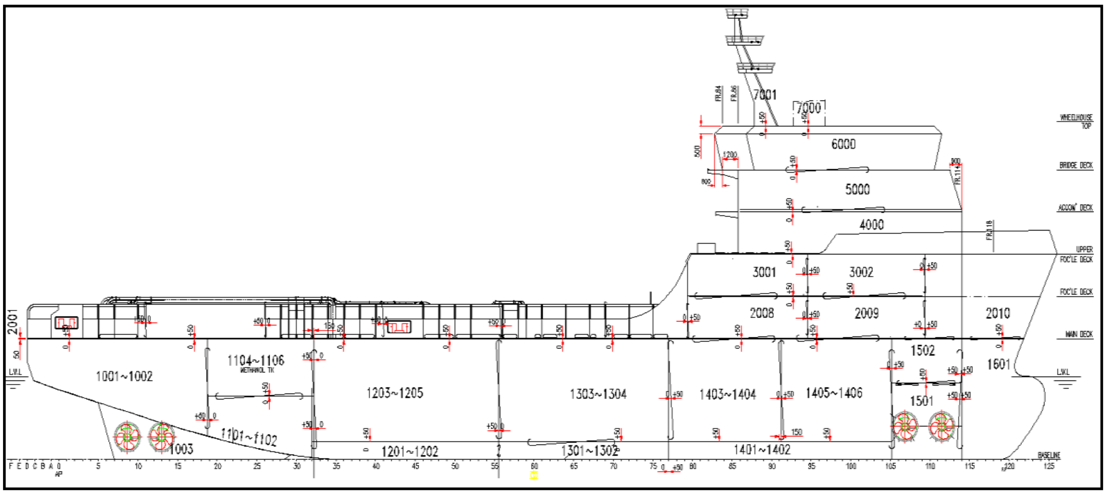


Figure 34: Unit numbering of the considered project

Three months of time period were taken to complete a unit and around 10 months were taken to complete the data collection process of following units. The collected data was given in the Table 16. Those data was not subjected to analysis and it was collected to get an idea about the welding shrinkage in heavy structures. However these data can be used as a base line for further development of this research.

Table 16: Welding shrinkage data of unit construction

Unit Number	Weight (Ton)	Before weld		After weld		Shrinkage	
		Length (mm)	Width (mm)	Length (mm)	Width (mm)	Length (mm)	Width (mm)
1001	76.325	13700	7800	13682	7794	18	6
1002	66.67	13700	9200	13682	9196	18	4
1003	21.016	15700	1960	15687	1960	13	0
1101	34.3829	8100	9200	8085	9195	15	5
1102	29.8795	8100	7800	8085	7795	15	5
1104	8.9079	8000	2520	7987	2518	13	2
1105	10.5034	8000	2520	7987	2518	13	2
1106	55.6628	7820	12000	7806	11995	14	5
1201	51.7116	14000	9200	13986	9192	14	8
1202	43.94	14000	7800	13986	7793	14	7
1203	83.305	15500	8650	15482	8645	18	5
1204	81.646	15500	8350	15482	8346	18	4
1301	52.05	13000	9200	12984	9192	16	8
1302	44.35	13000	7800	12984	7793	16	7
1303	89.752	13000	8650	12983	8645	17	5
1304	85.173	13000	8350	12983	8345	17	5
1401	63.33	16750	9200	16724	9191	26	9
1402	52.557	16750	7800	16725	7794	25	6
1403	37.077	8400	8650	8389	8646	11	4
1404	34.213	8400	8350	8388	8346	12	4
1405	41.548	8350	8650	8337	8644	13	6
1406	39.92	8350	8350	8337	8345	13	5
1501	47.472	5150	14000	5142	13994	8	6
1502	17.583	5150	16500	5146	16497	4	3

3.6. Results

3.6.1. Results of sample testing study

The collected data during the sample testing was analysed using the multiple regression method in MS Excel and following (Table 17) output was received.

Table 17: Regression analysis output for sample testing data analysis

Regression Statistics	
Multiple R	0.96
R Square	0.93
Adjusted R Square	0.93
Standard Error	0.08
Observations	102

ANOVA

	df	SS	MS	F	Significance F
Regression	4	8.94	2.24	320.63	5.56E-55
Residual	97	0.68	0.01		
Total	101	9.62			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-0.13	0.06	-2.14	0.03	-0.26	-0.01	-0.26	-0.0098
X Variable 1	0.05	0.0034	16.13	3.29E-29	0.05	0.06	0.05	0.06
X Variable 2	0.0003	0.0001	3.42	0.00091	0.0001	0.0005	0.00013	0.0005
X Variable 3	0.40	0.02	17.70	3.89E-32	0.36	0.45	0.36	0.45
X Variable 4	-0.06	0.04	-1.48	0.14	-0.13	0.02	-0.13	0.02

In this analysis the variables have defined as follows.

X Variable 1 (X_1) = Thickness of the test piece

X Variable 2 (X_2) = Distance to measurement point from weld start

X Variable 3 (X_3) = Restrain condition

X Variable 4 (X_4) = Weld type

After considering above results following clarifications can be done regarding the sample testing data.

Multiple R is 0.964. This is the correlation coefficient and it gives indication of strength of the relationship. Since this is closer to 1, there is a strong positive relationship between variables and the results.

Adjusted R square is 0.926. This is the coefficient of determination. Since there is more than one variable this value has to use instead of R square value. It tells how many points fall on the regression line. In this case 93% of the results are fall in the regression line. So using the above regression line 93% of the Y values can be described by variables.

Standard error is 0.083. The standard error here refers to the estimated standard deviation of the error term and since this is very small we can consider the regression line is representing the relationship between variables and the output.

Significance F = 5.5646 E-55, this gives the associated P values of null hypothesis $X_1 =0$, $X_2=0$, $X_3=0$, $X_4=0$. The significance level considered for this analysis is 0.05. Since this significance P value is less than 0.05 the null hypothesis can be rejected.

3.6.2. Results of panel fabrication study

The collected data during panel fabrication was analysed using the multiple regression method in MS Excel and following (Table 18) output was received.

Table 18: Regression analysis output for panel fabrication

Regression Statistics	
Multiple R	0.98
R Square	0.97
Adjusted R Square	0.96
Standard Error	0.16
Observations	42

ANOVA

	df	SS	MS	F	Significance F
Regression	6	26.24	4.37	170.33	2.13E-24
Residual	35	0.90	0.03		
Total	41	27.14			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-0.23	0.20	-1.15	0.26	-0.63	0.18	-0.63	0.18
X Variable 1	-0.02	0.03	-0.56	0.58	-0.08	0.05	-0.08	0.05
X Variable 2	0.09	0.05	1.81	0.08	-0.01	0.18	-0.01	0.18
X Variable 3	0.19	0.01	18.69	8.686E-20	0.17	0.21	0.17	0.21
X Variable 4	0.60	0.04	14.91	9.879E-17	0.52	0.68	0.52	0.68
X Variable 5	0.04	0.01	3.61	0.0010	0.02	0.07	0.02	0.07
X Variable 6	0.09	0.04	2.56	0.01	0.02	0.17	0.02	0.17

In this analysis the variables have defined as follows.

X Variable 1 (X_1) = Thickness of the plate

X Variable 2 (X_2) = Thickness of the stiffener

X Variable 3 (X_3) = Number of fillet weld perpendicular to measurement direction

X Variable 4 (X_4) = Number of butt weld perpendicular to measurement direction

X Variable 5 (X_5) = Number of fillet weld parallel to measurement direction

X Variable 6 (X_6) = Number of butt weld parallel to measurement direction

After considering above results following clarifications can be done regarding the panel fabrication testing data.

Multiple R is 0.983. This is the correlation coefficient and it gives indication of strength of the relationship. Since this is closer to 1, there is a strong positive relationship between variables and the results.

Adjusted R square is 0.96. This is the Coefficient of Determination. Since there is more than one variable this value has to use instead of R square value. It tells how many points fall on the regression line. In this case 96% of the results are fall in the regression line. So using the above regression line 96% of the Y values can be described by variables.

Standard error is 0.160. The standard error here refers to the estimated standard deviation of the error term and since this is very small we can consider the regression line is representing the relationship between variables and the output.

Significance F = 2.1315 E-24, this gives the associated P values of null hypothesis $X_1 = 0$, $X_2=0$, $X_3=0$, $X_4=0$, $X_5=0$, $X_6=0$. The significance level considered for this analysis is 0.05. Since this significance P value is less than 0.05 the null hypothesis can be rejected.

When considering individual P values it can be observe that all the P values except for X1 and X2 has P values less than significance level 0.05. So the null hypothesis $X_3=0$, $X_4=0$, $X_5=0$, $X_6=0$ can be rejected and $X_1=0$, $X_2=0$ cannot be rejected. Considering above results it can be found that plate thickness and stiffener thickness has very low impact for welding shrinkage during panel fabrication.

4 DETERMINATION OF WELDING SHRINKAGE FACTORS

4.1. Obtaining the shrinkage factors / formulae

Preliminary 26 numbers of test pieces also tested to find out the effect of material thickness, weld type and restrain condition on the shrinkage. As a result it was found that the shrinkage is higher when there is no restrain is used before starting the welding and shrinkage during butt weld is higher than the shrinkage during fillet welding.

As simple summary of the above output the fitted line for the shrinkage during test piece welding is given in Equation 4

Equation 4: Regression line for shrinkage in sample testing

$$Y = -0.1342 + 0.054\,X_1 + 0.0003\,X_2 + 0.4022\,X_3 - 0.057\,X_4$$

Where,

X_1 = Thickness of the test piece

X_2 = Distance to measurement point from weld start

X_3 = Restrain condition

X_4 = Weld type

The weld shrinkage data model for fabricated panels was developed by regression analysis of data collected from 20 production panels. Since this was done considering the panels used for actual production process it was difficult to check effect on weld shrinkage by changing one variable at time. As a result of that effect of some variables were not highlighted during this analysis. For an example the null hypothesis for variables of material thickness and stiffener thickness cannot be rejected as they are showing P values higher than 0.05 (significance level). However those were identified as factors for welding shrinkage during test piece weld shrinkage testing.

From this analysis it was identified that butt welds and fillet welds, which are perpendicular to measuring direction has more impact on weld shrinkage.

As simple summary of the above output the fitted line for the shrinkage during panel fabrication is given in Equation 5

Equation 5: Regression line for shrinkage in panel fabrication

$$Y = -0.2285 - 0.0169X_1 + 0.0864\,X_2 + 0.1856\,X_3 + 0.5985\,X_4 + 0.0426\,X_5 + 0.0942\,X_6$$

Where,

X_1 = Thickness of the plate

X_2 = Thickness of the stiffener

X_3 = Number of fillet weld perpendicular to measurement direction

X_4 = Number of butt weld perpendicular to measurement direction

X_5 = Number of fillet weld parallel to measurement direction

X_6 = Number of butt weld parallel to measurement direction

4.2. Validation of the obtained shrinkage factors/ formulae

After obtaining the shrinkage factors and formulae they were validated by conducting another sample testing. Three numbers of samples (Figure 35, Figure 36, Figure 37), which are having combination of fillet welds and butt welds were selected and the parameters related to each test sample were given to the obtained welding shrinkage formula to obtain the expected welding shrinkage. Then those test pieces were welded and there actual shrinkage was calculated by measuring the before weld distance and after weld distance. The parameters and the measured values, which were obtained during validation testing are given in the Table 19 and the shrinkage deviation between predicted and actual amout were ploted against the test number in order to evaluate the variation (Figure 38). By refering to the graph it was understood that the shrinkage deviation is varying around the zero value and the maximum deviation is 0.17 mm.

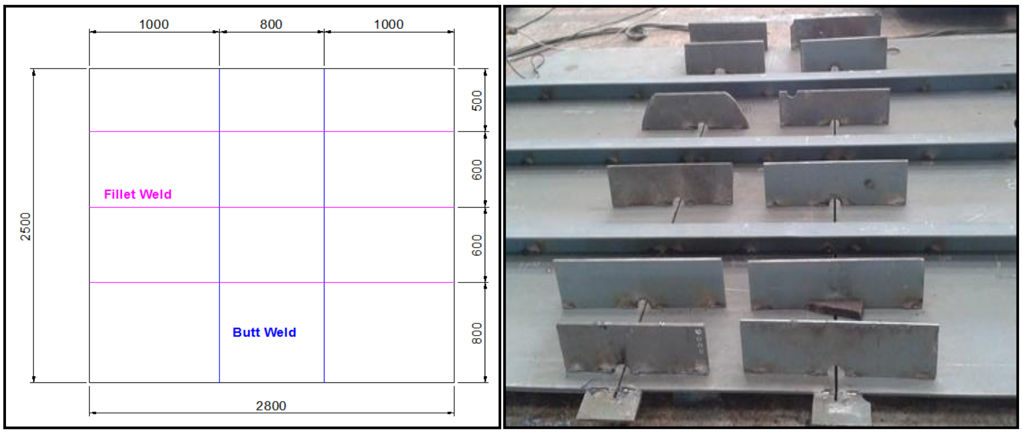


Figure 35: Sample 01 for result validation

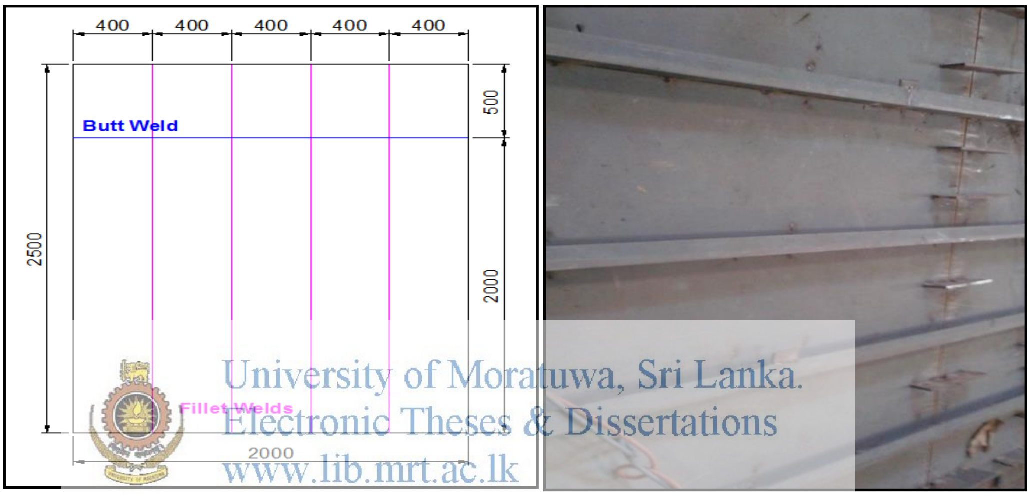


Figure 36: Sample 02 for result validation

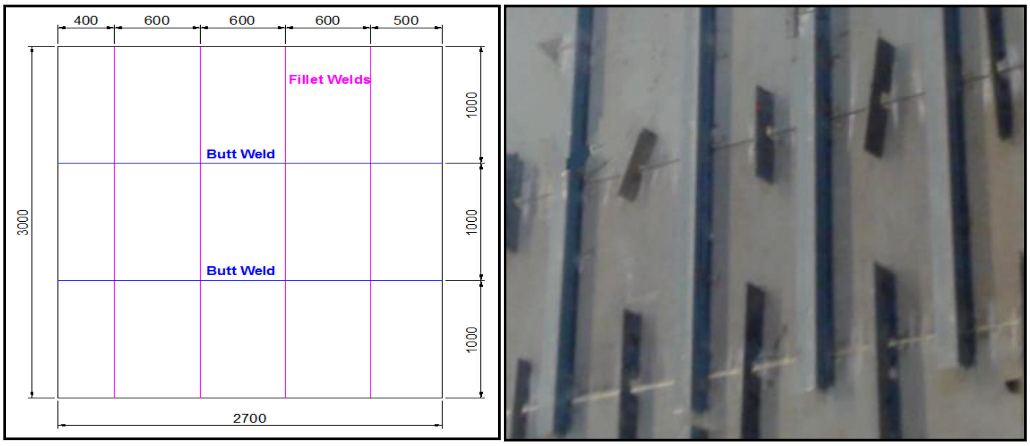


Figure 37: Sample 03 for result validation

Table 19: Deviation between predicted and actual shrinkage

Sample Number		Welding parameters						Predicted Shrinkage	Before weld Measure ment	After weld measure ment	Shrinkage	Deviation Actual - Predicted
		Plate Thickness	Stifner thickness	Perpendicular direction		Parallel direction						
				Fillet weld	But weld	Fillet weld	But weld					
		X1	X2	X3	X4	X5	X6	mm	mm	mm	mm	mm
		-0.02	0.09	0.19	0.60	0.04	0.09	-0.23				
Sample 01	1	12	8	0	2	3	0	1.58	2800	2798.30	1.70	0.12
Sample 01	2	12	8	3	0	0	2	1.01	2500	2499.10	0.90	-0.11
Sample 02	3	9	8	0	1	4	0	1.08	2500	2498.80	1.20	0.12
Sample 02	4	9	8	4	0	0	1	1.15	2000	1998.70	1.30	0.15
Sample 03	5	14	10	0	2	4	0	1.77	3000	2998.40	1.60	-0.17
Sample 03	6	14	10	4	0	0	2	1.33	2700	2698.80	1.20	-0.13

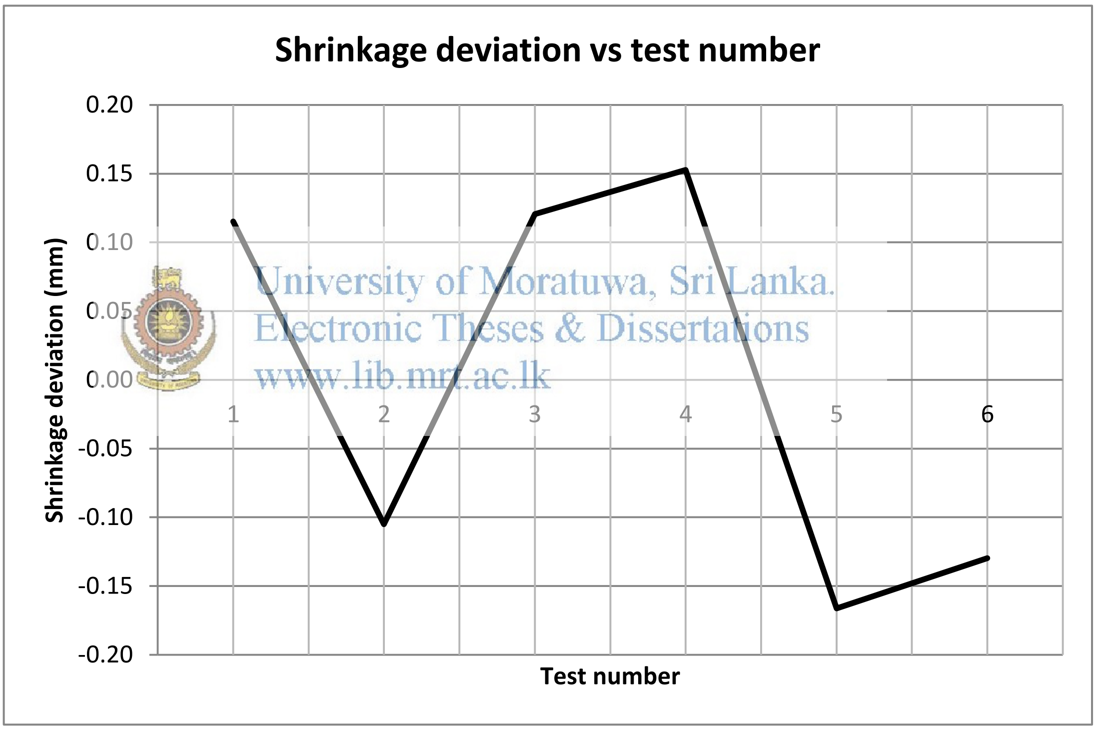


Figure 38: Shrinkage variation vs. test number

5 DISCUSSION AND CONCLUSION

5.1. Discussion

The prediction of welding shrinkage in ship building is of great important from the point of dimension control. There are many researches have been carried out under this topic and most of them were based on mathematical modelling as that was the simple and easiest method. Apart from that there are few researches have been carried out based on experimental methods. Since the welding attributes are not identical from shipyard to shipyard the weld shrinkage factors developed in one yard using experimental methods, cannot be implemented in another yard, without analysis. So the results obtained from this analysis is unique to the ship building operation of considered shipyard.

When developing the research methodology, some related researches (analysis of longitudinal shrinkage in but weld joint by Babakoohi, analysis of welding shrinkage by Mandal) have been used as a referance. After studying those researches and their pros & cons, this research was carried out as a improved version and a unique one to match with Sri Lankan context.

There are 06 main welding attributes and around 20 numbers of variables, which affect the welding shrinkage level (Figure 26). If all of the above variables were considered for the analysis there will be 180 numbers of combinations and the analysis the become more complex. So inorder to reduce the complexity of the research some of variables have been considered as fixed and for this research consider only fillet welds and butt welds with single V joint preparation while FCAW has considered as the welding process. From the various methods of application it has considered only semi automatic, downhand one side welding with use of backing strip and assume as welding parameters are fixed for the selected material thickness.

Even though there are three processing stages in hull construction, only panel fabrication stage was considered for this analysis. This is due to the complexity of other processes and difficulty to carry out proper analysis for them without an involvement of software module. Due to large number of attributes that influence on the amount of weld shrinkage in block construction and block assembly, it is difficult to calculate the expected shrinkage by numerical investigation or finite eliment modelling. For those processes the reasonable approach, which leads to practical solutions to compensate shrinkage is using existing shrinkage data from already built ship assemblies for each of the processes and analysing them with the aid of a modelling software.

The standard measuring tapes have been used to get the dimensions of the fabricated panels and smallest dimension of that is 0.5 mm. However the actual shrinkage value can be vary from the amount which is less than to 0.5 mm, with the changing of some attributes and due to that the effect of some attributes can be neglected. Inorder to overcome that fine measurement taking methods such as laser beam measuring has to be used.

To take the shrinkage measurements of the fabricated panels, the actual parts of the vessel have been used as the samples. This was done to reduce the cost of the experiment and due to that intentional changing of parameters become difficult. During one test several attributes were changed and the obtained shrinkage value is a result of each of those attributes. In this situation the effect of some minor attributes can be masked by the dominent attributes and it is difficult obtain the correct factor related to those minor attributes. Inorder to find out the accurate effect of each and every attributes, sample fabricated panels have to be prepared by changing only one attribute per sample.

While carring on welding in fabricated panels welding distortion is unavoidable. Eventhough precautions were taken during the welding, still considereble amount of distortion which will affect the final dimensions can be occur. Inorder to get the perfect result those distortions also to be considered and the measurments have to be adjusted accordingly. This can be done by taking three dimensional measurements of panels using the equipments like total stations. However during this research it wasn’t done due to unavailability of such sophisticated equipments.

5.2. Conclusion

During this research welding attributes such as material thickness, type of weld, using of restraints, number of butt welds and number of fillet welds were considered as variables. Then the impact to welding shrinkage from each of those variables was evaluated.

After conducting the experiment using test pieces it was identified that the restrain condition is having the highest effect on shrinkage. There is about 50% of shrinkage reduction can be obtained using the restraining plates (strong backs). The results of the test piece testing reveals that higher the plate thickness the shrinkage value also become high. This is mainly due to the welding current and the joint gap, which was varied only with the plate thickness. From the results of above test it can also be understood that the shrinkage in butt welding is higher than the shrinkage in fillet welding.

Using the results obtained from the panel fabrication testing it can be prove that higher the number of welds (fillet or butt), higher the shrinkage amount. The results clearly illustrate that the welding in perpendicular direction to the measuring direction has more impact on the shrinkage than the welding parallel to the measuring direction.

Using the results obtained from the experiment, shrinkage factors for each and every considered variable were derived. Finaly an evaluation has been done to evaluate the validity of the obtained formula and the average error is less than 0.17mm. Since this deviation is insignificant when considering the ship hull fabrication works, the obtained formula is valid to use for the shrinkage calculation in panel fabrication.

5.3. Future Work

During this research analysis has been done only for the test piece welding and panel fabrication. The shrinkage data during unit construction was gathered and it can be continued as a second phase of this research to find out a shrinkage data model for the complex unit construction. Also, there is a possibility of deriving shrinkage model for third interim process block assembly. A data collection methodology for block assembly has described during this research and the data gathering and analysis can be done as the next stage of this research.

Further to that for data collection and analysis, Microsoft Excel spread sheets have been used and only the main parameters were considered for the analysis. Other variable remain as constants, which may be vary at the actual production process. As a extension of this research it is possible to consider all the variables including material type, plate thickness, stiffener shape, spacing, and length, and overall panel dimensions. The user can also provide fabrication details, such as the welding process, weld sizes, welding parameters, and the use of fixtures. The Excel spread sheet can be enhanced to allow a user to input complex-panel features, inserts, multiple plate thicknesses, and non-rectangular-shape panel. After considering the all above variable a common model can be derived to match with all interim processes namely panel fabrication, block construction and unit assembly. After that, the complex-panel shrinkage data model has been implemented into Ship Constructor (a modelling software use in shipyards for designing works) to calculate shrinkage from a software during the designing stage.

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