Thermal Technology for the Straightening and Relieve of Residual Stresses in Steel Welded Panels

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“Whether you function as welders or inspectors, the laws of physics are implacable lie-detectors. You may fool men. You will never fool the metal.”

- Lois McMaster Bujold
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Resumo

Esta dissertação teve dois principais objetivos. O primeiro foi criar um modelo simples para simular a existência de Tensões Residuais em placas metálicas soldadas. O segundo foi, utilizando como ponto de partida o modelo criado no primeiro ponto, simular o arrefecimento forçado da zona soldada, de modo a testar se as Tensões Residuais eram mitigadas.

De modo a simular o processo de arrefecimento, um Modelo de Elementos Finitos foi criado. O modelo criado utiliza uma geometria de placa a 2 Dimensões e é feito um aquecimento gradual, com uma variação de temperatura dependente do tempo, aplicada uniformemente ao longo do comprimento da placa.

O modelo foi validado comparando a distribuição de Tensões Residuais com o modelo teórico. Várias modificações ao modelo forma experimentadas. O modelo foi depois modificado para simular uma descida de temperatura até uma temperatura negativa escolhida, antes de ser levada à temperatura de referência.

Os resultados do arrefecimento forçado foram comparados com os resultados obtidos na validação do modelo, onde não foi aplicado arrefecimento forçado.

Palavras-chave: Tensões Residuais, Relaxamento de Tensões Residuais, Análise de Elementos Finitos, Soldadura de Placas simples, Soldadura de placas reforçadas
Abstract

This dissertation had two main goals to reach. The first was to create a simplified model to simulate the existence of Residual Stresses in metallic structures. The second one envisioned the usage of this simple model to simulate the introduction of a cooling charge directly on the welding area, to mitigate the residual stresses in the geometry.

In order to simulate the cooling process, a Finite Element Analysis was performed to a model. The model that was created uses a 2-Dimensional geometry and a heat input with a time-dependent temperature increase. The input is uniform along the welding path.

The model was validated by comparing the distribution of the residual stresses to the theoretical model. Several modifications were implemented and tested. The model was then modified to have a decrease in temperature to several chosen negative temperatures before it was brought back to the reference temperature.

The results of the simulation of the cooling process were compared to the results obtained for the validation of the model.

Keywords: Residual Stresses, Residual Stress Relaxation, Finite Element Analysis, Welding of flat plates, Welding of stiffened plates
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Nomenclature

Greek Symbols

\( \phi \)  Strength
\( \varepsilon \)  Strain
\( \eta \)  Ratio between the thickness of the plate and the strip under traction
\( \alpha \)  Thermal Expansion Coefficient
\( \beta \)  Plate Slenderness
\( \Delta \)  Interval
\( \omega \)  Wave Height

Roman Symbols

\( l \)  Length of the Plate
\( w \)  Width of the Plate
\( t \)  Thickness of the Plate
\( E \)  Young’s Modulus
\( T \)  Temperature
\( k \)  Generic coefficient
\( m \)  Mode of Imperfection (Longitudinal)
\( n \)  Mode of Imperfection (Transversal)

Suffixes

\( e \)  Effective Strength
\( y \)  Longitudinal Direction
\( o \)  Yield Stress
\( r \)  Residual Stress
\( t \)  Transversal
\( m \)  Compressive Strength
\( b \)  Generalized Strength
\( 0 \)  Wave Amplitude
## Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>BC</td>
<td>Boundary Condition</td>
</tr>
<tr>
<td>BISO</td>
<td>Bilinear Isotropic</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>GTAW</td>
<td>Gas Tungsten Arc Welding</td>
</tr>
<tr>
<td>SAW</td>
<td>Submerged Arc Welding</td>
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<tr>
<td>SMAW</td>
<td>Submerged Metal Arc Welding</td>
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</tbody>
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Chapter 1

1. Introduction

1.1 Motivation
Transportation of goods around the world exists since the discovery of India in the end of the XV Century. Ships have been the main mean of transportation of goods ever since. The original Portuguese man-of-war guaranteed the moving of spices, tea, and other goods up to Europe. In that time, the only option was to use sail-powered, wood-constructed ships. With the passage of time, ships lost their sails, and by the time of the Industrial Revolution, ships were powered by steam engines. The Industrial Revolution also saw the substitution of wood by steel in the construction of the ship’s structure. Back then, metal was joined together via steel nails. That created ships with added strength, but these ships would also prove to be considerably heavy.

In 1940, Ingalls Shipbuilding, a shipyard in Mississippi delivered its first ship, the SS Exchequer. This was the first ship ever to be constructed entirely using welding as a sole joining technique. This ship, later the USS Pocomoke, after being acquired by the U. S. Navy and converted to a seaplane tender, helped the U. S. build up their fleet of ships prior to the beginning of the Second World War.

With the Second World War in its start, and with the rapid sinking of many British and American ships by the German submarines, these nations needed to build ships faster. Hence, the appearance of majorly welded ships in shipbuilding. Welding was a faster way to join long plates and made the ships considerably lighter. The U. S., in the early 1940s, were responsible for building 2710 ships for the war. These were called the “Liberty Ships” and were cargo ships constructed to transport armament munitions to the warzones.

The welding type used was submerged arc welding (SAW). This method of welding was faster than most other methods. Automation was also implemented to alleviate the load on workers welding the longer joints and speed up the process even more. With the end of the war, this type of shipbuilding turned to commercial ships. Welding became mainstream. Shipyards grew also with the growth in size, and welders became more and more essential.

Nowadays still, commercial ships, given their size, are constructed almost entirely of steel. These ships, which have grown in size since the 1950s, with a period of an incredible increase in
deadweight in the 70’s due to the interest in moving petroleum. The material used, as such, needed to be cheap, easy to handle and shape, and easy to be joined together. Steel accomplishes that, and since the beginning that ships are made of it. Moreover, the growth of ships means longer welds. SAW welding is of great use, since most welding of plates and profiles is straight, making possible the use of fully automated SAW welding machines.

The problem with welding is that, by heating a specific part of the material, there is an introduction of residual stresses. Those residual stresses create deformations in the plates, which need to be corrected. That costs the shipyard labour and time.

However, the biggest problem with the introduction of residual stresses is the reduction in strength that the plate may be subjected to, constituting a problem to the safety of the structure in general. Moreover, weld seams are prone to mechanical failure, being identified as one of the most critical part for failure in cyclical loads. It is important, in the structural design phase, to compensate for the losses of strength in the welded plate.

Many studies were made since the 1960s to predict the magnitude and general effects that the introduction of residual stresses constitute. Guedes Soares and Soreide (1983) studied the design of plate strength. The authors show the calculations that need to be conducted in order to predict the loss of strength of stiffened panels. The methods used provide a possibility to be used systematically in different stiffened panels.

Later, Guedes Soares (1988a) put the equations for the plate strength of Carlsen, Faulkner, Soreide and Czujko, Ueda et al. and Ueda and Yao to comparison against experimental data retrieved in the field. This shed a light on how true the results were obtained by the different equations. Gordo and Guedes Soares (1988) showed that the plate slenderness was the only important factor that influenced plate strength.

Guedes Soares (1992) also created probabilistic methods to determine the plate strength distribution on plates. This has proven to be important, given the uncertainty associated with plate imperfection to the assessment made to the degradation of the plate strength caused by the residual stresses. This, in relation to the Plate Buckling model of uncertainty provided by Guedes Soares (1988b) shed a light on the effects of the initial imperfections of plates. Plate slenderness being the sole reason for the value of the plate strength.

More recently, a study (Gordo, 2015) was made using FEM to estimate the strength of plates with imperfections. These imperfections were modelled using a sinusoidal function, function that is more common to see in reality. This study concluded that imperfections contribute to up to 20% in decrease of plate strength. Initial strength is predominantly dependent of the mode of the initial imperfections.
Nowadays, SAW is used as a sole method of joining flat plates to each other, and also “T” joint to join stiffeners in order to construct stiffened panels, given the length that most of the welds have. The speed that most of these machines is estimated to be averaged at 5.42 m/h (Gordo et al., 2006), far bigger that the speed achieved by any of the manual or semi-automatic method of welding. The sheer girth of the plates to be joined in some cases can be of several meters. As such, plates are rested on a roller bed. These facilitate the movement and alignment of the soon-to-be joined plates.

1.2 Objectives

The scope of this dissertation is to analyse the possibility of developing a method of relaxation of the residual stresses by the means of thermal technologies. The principle is based on the idea of injecting a cooling charge directly on the plate right after the welding. This method was designed to be used with fully automated submerged arc welding for butt welds, and later converted to be used for “T” joint welds as well in the simulations. This method also predicts the use of steel as the sole material of the plates. The analysis it to be conducted using only Finite Element Analysis (FEA). In addition, other types of welding can also be analysed since the input to be made to the plates in order to obtain the residual stresses is the temperature.

Firstly, a model was created to simulate the residual stresses. Several different thicknesses were considered. This model simulates the joining of two plates of 6, 10 and 20 milimetres, as these are thicknesses commonly found in welded structures of ships. As an initial analysis, the model is to be tested using two plates of 10 metres in length by 2.5 metres in width each. This is to ensure that the results obtained in the centre of the plate are sufficiently far from the end of the edges of the plate. The validation is made by comparing the result of the distribution of residual stresses to the theoretical model commonly used in studies. With the validation of the FEM, the model is scaled down to a simulation of two plates of 2 metres in length by 0.4 metres in width each. The thicknesses are kept the same as the ones in the first model. In the second model, imperfections are added to better simulate reality. These imperfections are simulated using the model in the study of Gordo (2015). An analysis of plates with similar dimensions found in the study from Khameneh (2018) are also conducted, and the results compared.

Finally, a simulation of the thermal techniques is conducted using FEA. These simulations are performed using the same geometries created for the validation of the model. Two models, one with one “T” join, and the second with two “T” join welding of stiffeners are also tested. The profiles of the stiffeners chosen are ones commonly chosen for the thicknesses of the plates used. With the results of the simulations, a review of the feasibility of the process is made.
1.3 Thesis Outline

This dissertation covers the aspects of implementation of a method capable of reducing the distribution of residual stresses that are introduced on welded structures upon welding. This was done solely by the means of FEM simulations.

In the Chapter 2 - State of the Art, the existing methods and theoretical approaches to address the characterization and subsequent FEM implementation of residual stress are introduced. An introductory theoretical approach is conducted as to explain the concept behind the method implemented in FEM.

A validation of the model was conducted, in order to attest the adequability of the method used to induce the correct distribution of residual stresses in 3 - Validation Model for the Input of Residual Stresses. This validation was made using the model of a plate with 10 by 5 metres in dimension, and a uniform heat loading. Secondly, an additional, smaller model was created, to attest the veracity of the results obtained for the first model. Several modifications were considered, including the introduction of initial geometric imperfections on the plates, and the results were compared.

Additionally, an analysis of the method was made on a geometry of a reinforced plate one stiffener, in 3.5 - Welding of Stiffeners on Flat Plates. This model was then modified to accommodate two stiffeners, as to attest the influence that an additional stiffener has on the first. A comparison between the two models was made.

In 4 - FEM Simulation of the Cooling Process, the cooling process was introduced and compared to the initial simpler model that have not got into account the process of residual stress relaxation.

Finally, in 5 - Conclusion, the final concluding remarks are shown, as well as the remarks on future work and implementation of the method in real life.
Chapter 2

2 State of the Art

In Chapter 2, in order to give a better understanding of how the welding is analysed, a review of the main aspects revolving around the analysis of welding is presented. The general scope of this review is to analyse both the methods used to simulate the welding process using FEM and the equations that regulate the welding process.

Firstly, the approximation considered for the stress-strain curve is introduced. This makes possible the usage of the following equations that describe the distribution of the residual stresses. Secondly, the model for the distribution of the residual stresses, along with the considerations taken into account for the validation of the model, are presented. This analytical model of the distribution of the residual stresses gives a baseline for the comparison of the resulting distribution simulated in the FEM. In addition, the approach considered for the reduction in strength caused by initial imperfections present in the plates is introduced. The equation and modelling considered is a vital key to better simulate reality in FEM, as it is not possible to have real plates with no initial imperfections.

Lastly, the general considerations taken into account in both the geometry of the model, the modelling of the heat input to simulate the welding process are addressed. These approximations are important, and need to be fully understood, as they constitute a major influence on the interpretation of the results, as well as value deviation in comparison to experimental results.

2.1 Thermally-induced Residual Stress Distribution in Welded Plates

2.1.1 Stress-strain Curve Approximation

Gordo and Guedes Soares (1993) proposed a simplified approach to calculate analytically the distribution and values of the Residual Stresses. For this method, the authors considered a bilinear isotropic elastic-plastic approximation (BISO). This consideration has proven to be more than acceptable in cases like the one being studied. The equation that models this behaviour is defined by branches and is the one seen in (1).

\[
\phi_e = \begin{cases} 
-1 \leq \varepsilon < -1 \\
-1 < \varepsilon < 1 \\
+1 \leq \varepsilon > 1 
\end{cases}
\]  

(1)
This equation not only considers the material in traction, but also in compression. As it will be seen later, this consideration is very important to the calculation of the interval of temperatures needed in order to achieve the desired effect.

2.1.2 Behaviour of the Plate in Compression

As it can be deducted from (1), the behaviour of the material under traction, in the elastic area, can be simplified by a straight curve uniting the origin of the graph, where the tension is equal to zero, to the yield strength of the material.

However, when it comes to metals, especially for ductile steels, the behaviour of the material in the plastic domain can be described as unstable. As such, it is not simple to characterize the instability of the plasticity of ductile steels mathematically, let alone implement it in a Finite Element model (FEM). As such, the plastic domain of the stress-strain curve can be simplified using a linear correction, more specifically, a constant straight line.

In the Figure 2.1 can be seen the resulting curve of the correction for stress-strain curve that characterizes the behaviour of the material under traction and compression due to the existence of residual stresses. It can also be seen that a correction can be made for plates that are under cyclic loads. However, this is not going to be considered, since the plates that are being considered are to be used on a new construction and as such have not been put under cyclic loads.

![Figure 2.1 – Correction for the material behaviour under tension and compression, Gordo (2014)](image)

What can also be seen from Figure 2.1 is that the curve is mirrored for the compressive domain, with the same yield strength considered and the same Young Modulus. This was the stress-strain curve considered through the entire dissertation.
2.1.3 Residual Stress Distribution

During welding, the temperature between the sides of the plate, which maintain an even temperature along its width equal to the environment temperature, and the area near the welding, can be severely different. Welded marine structures present a complex distribution of residual stresses. These are caused by the butt joint welds of adjacent plates and “T” joints of stiffeners to the plate. According to Masubuchi (1980), the residual stresses that appear on a plate can be of two types:

a. Residual welding stresses that are produced directly by the thermal difference during the welding;

b. Residual stresses caused by external restraint.

Masubuchi and Martin (1965) devised an equation for the distribution of residual stresses in the longitudinal direction along the width of the plate. This equation can be seen depicted in (2).

\[ \sigma_y(x) = \sigma_m \left[ 1 - \left( \frac{x}{w} \right)^2 \right] e^{-\frac{1}{2} \left( \frac{x}{w} \right)^2} \]

(2)

This equation considers the area of the plate in traction, as well as the area in compression. The value for the \( \sigma_m \) can be as high, and is often regarded as equal to the yield stress. The distribution of residual stresses given by equation (2) can be seen in Figure 2.2.

Figure 2.2 - Residual stresses’ distribution parallel to the welding direction

This distribution, as can be seen in Figure 2.2, has a distinct area in which the stresses change from tensile to compressive. The value of the width of the band under traction loads is commonly
referred to as $\eta$. This value can be easily obtained by substituting the value for the longitudinal residual stress by zero in the equation and solve for $x$.

However, it is usual to consider a model, with a simplified distribution of residual stresses along the width of the plate. With that, it is possible to define the residual stresses in tension as being located in a strip of width $\eta t$, with $\eta$ being the ratio between the plate’s thickness $t$ and the strips’ width. The remaining $w - 2\eta$ width of the plate is in compression.

For the value of $\eta$, Guedes Soares and Soreide (1983) state that, although commonly varying from 2 to 8, it is common even to consider values below that. As such, a value of 1.5 was set, and used along the calculations and on the model used for the FEA. Since the model used considers two adjacent plates, the total width of the strip is equal to $2\eta t$. It is in this area that the residual stresses are significantly bigger. These are more predominant in the longitudinal direction, and their value can be obtained using equation (3).

$$\sigma_r = \sigma_o \frac{2\eta t}{w - 2\eta t}$$  

Similarly, for the transversal direction, the equation given is (4).

$$\sigma_{rt} = \sigma_o \frac{2\eta t}{a - 2\eta t}$$  

However, given the latter’s small dimension in comparison to the former, these are usually neglected. With the value obtained for the residual stresses. Timoshenko and Goodier (1982) asserts that a plate experiencing a gradient of temperature along its width is bound to develop residual stresses, which are characterised by equation (5).

$$\sigma_y = \frac{1}{2w} \int_{-w}^{+w} \alpha T E \, dy - aT E$$  

This even distribution can be obtained considering the Principle of Saint-Venant, in which at sufficient distance from the edges of the plates the effect of this singularity is not felt.

Since that, at sufficient temperature, the variation in length of plates, given that the sides of the plates are practically at room temperature and as such do not have an increase in volume, impede the heated part of expanding longitudinally. With that, the only direction in which the heated strip can expand freely is the vertical one. The lack of longitudinal expansion in the area of the plate at room temperature, in addition to the necessity for the metal to grow in length in the heated area creates a distribution of stresses characterised by the pulling of the non-heated area by the heated area. Stresses appear as such to counteract this effect, and the equation (5) can be transformed in equation (6), that can be seen below.

$$\sigma_y = k\alpha \Delta T E$$  

(6)
After the welding, and the cooling process is initiated in the welding region, the strips subjected to the welding heat start to shrink, originating tensile stresses. These are caused by the disparity in length between the heated strips and the remainder of the plate, causing the residual stresses to appear.

The peak value appears in the middle of the weld path and has a drastic reduction to zero, where the stresses change from traction to compression. The compression stresses then, with the growth of distance to the centre of the weld, start to dissipate, with the distribution asymptotically approaching zero. As for the peak value, it is common to assume a value equal to the yield stress of the material at room temperature (Gordo and Guedes Soares, 1993).

However, for simplicity purposes on performing calculations, a theoretical model has been created. This model features a constant distribution for both the traction residual stresses and compression residual stresses. In Figure 2.3 the resulting distribution is represented. This is the theoretical model implemented throughout this dissertation, and it is the one to which the results are compared.

2.1.4 Strength Reduction Caused by Initial Imperfections

As it happens in reality, plates never have the perfect geometry as intended. These imperfections have consequences to the strength of plates. These imperfections need to be taken into account when performing the analysis of the welding process. However, firstly it is necessary to understand how these imperfections can be modelled, and how plate slenderness influences the behaviour of the plates. Faulkner proposed the design and reduction in strength of plates in his study (1965), based on the concept of plate slenderness defined by the equation (7) as $\beta$. 
\[ \beta = \frac{w}{t \sqrt{\frac{\sigma_o}{E}}} \]  

(7)

As it can be seen in equation (7), the slenderness only depends on the ratio between the width, \( b \) and the thickness of the plate, \( t \). \( E \) is the Young modulus and \( \sigma_o \) is the yield stress of the material used. For this theory, a BISO approximation of the stress-strain curve is assumed, with no hardening after yielding. Faulkner also proposed an equation for the reduction of the strength of the plate. According to the proposal, the strength of a rectangular plate comes as \( \phi_F \) in equation (8).

\[ \phi_F = \frac{\sigma_m}{\sigma_o} = \phi_b - \Delta\phi_b \]  

(8)

The \( \sigma_m \) and \( \sigma_o \) in (8) are the compressive strength and yield stress, respectively, \( \phi_b \) is the strength of a non-welded plate, and lastly \( \Delta\phi_b \) represents the degradation of strength due to welding residual stresses. The degradation of strength is represented as seen in (9).

\[ \Delta\phi_b = \frac{\sigma_m E_t}{\sigma_o E} \]  

(9)

Finally, the strength of the plate \( \phi_b \) can be described by the equation, as Faulkner (1965) proposed.

\[ \phi_b = \frac{a_1}{\beta} - \frac{a_2}{\beta^2} \]  

(10)

For the values of \( a_1 \) and \( a_2 \), which are constants that take into account the supports for the plate, it is often considered an approximation with \( a_1 = 2.0 \) and \( a_2 = 1.0 \) for simply supported plates, and \( a_1 = 2.5 \) and \( a_2 = 1.56 \) for plates supported by clamps.

### 2.1.5 Characterization of Initial Imperfections

As stated in 2.1.4 - Strength Reduction Caused by Initial Imperfections, the initial imperfection present in plates is a major aspect influencing the strength, and therefore influencing the performance of the plate. As such, it is important to have in consideration this aspect when dimensioning the structure, so it becomes crucial to model the initial imperfections when running a simulation. The initial imperfections of a plate may be decomposed in a Fourier series where each component is characterised by the equation (11).

\[ \omega = \omega_o \sin \frac{m\pi x}{w} \sin \frac{m\pi y}{l} \]  

(11)
Where $w_0$ is the amplitude of the wave, $m$ is the number of half waves present in the plate in the longitudinal direction, with $n$ being the same in the transversal direction, and $l$ and $w$ are the length and width of the plate respectively. It is common to consider values for the number of half waves from $m = 1$ to $m = 2 \times \alpha$, with $\alpha$ being the aspect ratio of the plate ($l/w$). The values above, as it can be seen in the study performed by Gordo (2015), are similar to the values obtained for the number of half waves equal to $2\alpha$, and as such have little significance to this study. Gordo also states that the plates experience a more significant reduction in strength with imperfections for $m = 1$, which is the critical mode.

2.2 Modelling of the Welding Process in FEM

2.2.1 Modelling of the Heat Source

Many efforts have been made to simulate the process of welding. Given that the process of welding has a phenomenon of liquid metal, and as such without solid-state stresses, slightly above fusion temperature, the reality is quite difficult to emulate. This phenomenon is usually neglected, and the analysis is concentrated on the heat flux directed to the plate on the welded zone. The heat source, as such, can be of two types: fixed or moving. The fixed heat source does not move in time, and is usual to model this heat source by applying heat evenly to the weld chord area for a fixed period of time. This approach, although more easily computed and less time-consuming to analyse, produces the worse results. For results that emulate better the process of welding, it is common to use moving heat sources. These heat flux sources can be described analytically in three ways.

The first one to be described is the approximation proposed by Rosenthal (1946). The analytical theory of Rosenthal is based on a concentrated heat source. The study predicts the movement of the heat source, as it happens in reality in welding. However, the study did not predict the variation of the properties of the metal across the temperature range, and as such, it presented variations in comparison to the experiments made.

Later, Friedman (1975) presented the Gaussian Distributed heat source, as to express an approximation of the heat flux of the moving heat source. This heat source was, as it can be seen in Figure 2.4, bell-shaped and had radial symmetry. It was used and produced the most precise results for gas tungsten arc welding (GMAW) and submerged metal arc welding (SMAW). However, these techniques of welding are known to be in average slower than SAW. With that in mind, results for the faster SAW are considerably less precise in comparison to the experimental results.
More recently however, a study (Goldak, Chakravarti and Bibby, 1985) proposed the usage of a Double-Ellipsoidal moving heat source. As it can be seen in Figure 2.5, this theory takes into consideration the trail of heat that the stiffness of the welding produces. As such, the trailing part of the heat source is significantly longer than the one in front.

It is important to study thoroughly the moving heat source and the quantity of heat introduced, in order to obtain the best results. Different heat inputs with different welding speeds have a direct effect on not only in the results, but in the simulation and computation as well. Heinze, Schwenk and Reithmeier (2012) have studied this phenomenon, which compares different heat inputs with the results obtained.

2.2.2 Geometry of the Finite Element Model

The FEA of the welding process is often defined as a thermo-mechanical coupled analysis. Generally, there are three methods to simulate the welding process.
The first method is the most straightforward of the three methods used. It consists in applying directly the temperature input to the plate, with its geometry already defined with structural elements, to calculate directly the distribution of residual stresses and the plate deformation. The temperatures are defined as body loads, and the plate is heated and cooled along time as such. However, more often than not it is difficult to have the temperature distribution. This method is effectively seldom used. For this analysis, the element that was commonly used in ANSYS® was SHELL93 for the two-dimensional analysis (2D), and the SOLID185 for the three-dimensional (3D) analysis.

The two more used methods are known as the direct and indirect methods. The direct method, as the name implies, is characterized by the usage of elements that make possible both a thermal and a structural analysis. This method is known to produce very acceptable results. The thermal analysis has a direct and preponderant influence on the structural analysis, while the structural has a smaller effect on the thermal analysis, which tends to be neglected. It is the method used in bidirectional-coupled simulations. For this method, the geometry normally used was the 3D. However, this type of simulation is not as common as the indirect.

The indirect method, which is the single most used method in simulations of this type, uses a semi-coupled approach. This approach predicts two different steps in the calculations, one in which the heating process is simulated, and elements which only have thermal degrees of freedom are used. The resulting values for the temperatures in each node for several different instances of time are recorded. The resulting temperature field along time is then used to make a purely structural analysis. In this method, it is not possible to revert the analysis, making it unidirectional. The results are very acceptable. This approach was used in studies from Chen (2011), Chen, Adak and Guedes Soares (2011), and later Chen and Khameneh (2013) to study the deformations welding causes to specimens with 300 mm by 260 mm and 6 mm in thickness.

The geometry used is commonly accepted to be the three-dimensional in general for all simulations. However, it is especially difficult and time-consuming to compute 3D plates with initial imperfections. In these cases, it is common to use a 2D simulation. When using ANSYS® and regarding the indirect method of computation, the element usually used is the SOLID70, which is an 8-node 3D thermal 3D element. This element then needs to be converted to an element with the same number of nodes. It is considered common practice to convert the SOLID70 element to a SOLID185, as both of these have the same geometry and approximations to the calculations.

Regarding mesh size, when performing an analysis of the deformation due to the heat of the welding process, it is common to use a more refined mesh in the area of the welding chord, and directly near it, as done in the study performed by Chen (2011). For a more refined simulation, dynamic meshes can be used. In general, dynamic meshing consists of having moving meshes solidary to the moving heat source. This saves computation time. Runesson and Skyttebol make a brief case of the methodology used to perform analysis of the welding process in their study (2007).
2.2.3 Boundary Conditions

In modelling the welding process, it is crucial to make the right choice regarding the boundary conditions for the model being simulated. The boundary conditions affect drastically the outcome of the results. It is of the biggest importance to have the boundary conditions in mind when performing the simulations. With that in mind, when it comes to choosing the boundary conditions, in terms of the structural analysis, it is common for the plates to be simply supported, clamped, or free. There are also some cases in which the plates have the edges linked to springs. This is especially important when considering that the plates will have other plates welded to them, with each acting as a spring, due to their elastic behaviour. These results tend to provoke increase of the residual stresses, since the plate is being pulled by the plates adjacent to it when in the structure. A study has been made (Fu et al., 2014) to simulate this effect. The authors compared these boundary conditions to the other cases. It was found that the boundary conditions that restrained more the plate have less strain, but tend to have more residual stresses.

For the clamped case, there are two methods in which the clamping can be simulated. In the study made by Deng (2015), the clamping is simulated by applying a friction coefficient and a force to specific nodes. This technique, however, requires the knowledge of the friction coefficient between the plate and the bases of the clamps, as well as the force applied by the clamps, which is usually difficult to obtain. The simplest case is to lock the nodes in the areas in which the clamps are attached to simulate clamping, since the movement on the clamping is minimum and can usually be neglected. This approach was used in the study performed by Fu et al. (2014), with the results obtained being more than acceptable.

2.3 Description of the Model

As a concluding Sub-chapter of 2 - State of the Art, the characteristics of the model are described briefly throughout.

Firstly, the FEM will make use of a two-dimensional (2D) geometry, where elements of shell type were used. In ANSYS®, elements of the type SHELL281 were used. A quadrangular mesh was used, in which the mesh is finer in the middle, where the welding toe is located, and coarser in the edges, were low refinement can be considered.

The material behaviour is described by the Equation (1), where the Bilinear Isotropic (BISO) correction to the Elasto-Plastic domain was used, with no plastic hardening considered, as seen in Figure 2.1. This behaviour was considered for both traction and compression.

Regarding the heat source, a time-dependent Heat Source was considered, which is uniform along the length of the welding path, to promote speed in the computational process. Various temperatures were considered, as it can later be seen in 3.1.3 - Loading.
Finally, concerning the Boundary Conditions, two cases were considered. The first one features a fixation of the nodes located on the longer edges of the plates, where these cannot move. This was considered to promote symmetry, as leaving one edge free would create asymmetry on the resulting geometry. For the first case the shorter edges were left free, whereas in the second case, the shorter edges are allowed only to move as a rigid line, as to simulate a welded plate on these shorter edges.

### 2.4 Temperature Difference

With the common approach to the distribution of the residual stresses in mind, and using equation (6) presented in 2.1.3, it is possible to arrive to a temperature interval between the weld-induced temperature and room temperature. The assumption is that reducing the temperature almost immediately after the welding process will allow it to have a significant impact in reducing the residual stresses.

For this approach, and later to characterise the properties in the *FEM* model, a material needed to be chosen. The steel used was *ASTM 36 Structural Steel*. Its characteristics (Lyman, 1948) are given in Table 2.1, and were the ones considered throughout this study. This steel is commonly used in the naval industry, which makes it a suitable choice, as the vast majority of naval welded steel structures are composed by this type of steel.

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</tr>
</thead>
<tbody>
<tr>
<td>273</td>
<td>480</td>
<td>60</td>
<td>7880</td>
<td>15.9</td>
<td>210</td>
<td>0.280</td>
<td>1.10</td>
<td>380</td>
</tr>
<tr>
<td>373</td>
<td>500</td>
<td>50</td>
<td>7880</td>
<td>16.5</td>
<td>200</td>
<td>0.285</td>
<td>1.15</td>
<td>340</td>
</tr>
<tr>
<td>473</td>
<td>520</td>
<td>45</td>
<td>7800</td>
<td>17.3</td>
<td>200</td>
<td>0.290</td>
<td>1.20</td>
<td>315</td>
</tr>
<tr>
<td>673</td>
<td>650</td>
<td>38</td>
<td>7760</td>
<td>20.1</td>
<td>170</td>
<td>0.310</td>
<td>1.30</td>
<td>230</td>
</tr>
<tr>
<td>873</td>
<td>750</td>
<td>30</td>
<td>7600</td>
<td>24.6</td>
<td>80</td>
<td>0.330</td>
<td>1.42</td>
<td>110</td>
</tr>
<tr>
<td>1073</td>
<td>1000</td>
<td>25</td>
<td>7520</td>
<td>31.4</td>
<td>35</td>
<td>0.330</td>
<td>1.45</td>
<td>30</td>
</tr>
<tr>
<td>1473</td>
<td>1400</td>
<td>28</td>
<td>7300</td>
<td>53.6</td>
<td>15</td>
<td>0.360</td>
<td>1.45</td>
<td>20</td>
</tr>
<tr>
<td>1573</td>
<td>1600</td>
<td>37</td>
<td>7250</td>
<td>61.2</td>
<td>10</td>
<td>0.380</td>
<td>1.45</td>
<td>18</td>
</tr>
<tr>
<td>1873</td>
<td>1700</td>
<td>37</td>
<td>7180</td>
<td>84.8</td>
<td>10</td>
<td>0.390</td>
<td>1.45</td>
<td>15</td>
</tr>
</tbody>
</table>

As stated above, using the equation (6) for the calculation it is possible to find a temperature interval that makes the metal reduce its temperature just enough so that the residual stresses do not surpass the yield stress.

Considering a temperature of 20° Celsius, the yield stress of this particular steel is equal to \(\sigma_y = 370 \text{ MPa}\). Now, it is important to acknowledge that, since the material is heated, with that its yield stress changes drastically with heating, it is important to acknowledge that the yield stress will lower. For that, two iterations were done to ensure the correctness of the resulting temperature
difference. As such, the first temperature difference calculated was equal to $\Delta T = 160.17 \, K$. That temperature was used to find a second yield stress. Considering a room temperature of 20º Celsius, the yield stress is equal to $\sigma_0 = 325 \, MPa$. This value was considered using the Table 2.1. The thermal expansion coefficient can be also iterated and is equal to $\alpha = 11.3 \times 10^{-6} \, K^{-1}$.

The final temperature difference is equal to $\Delta T = 140.88 \, K$. It is important to bear in mind that this is a higher value for an interval starting at a free condition. With that in mind, the interval of temperature differences is given as:

$$\Delta T = [0 \, ; \, 140.88 \, ] \, K$$

With this value is possible to have an initial assumption as to what temperature would be required to acquire a drop in the residual stresses along the plate. As it will be seen later in 4.2, the temperature interval used was significantly bigger, as to obtain relevant comparable results between the model with the cooling process and the model without it.

In fact, having into account the graph present in Figure 2.1, where the stress-strain curve is approximated for both traction and compression by mirroring the curve on the origin, we can conclude that the final stress differential present on the plate after the welding is complete is double the yield stress in total. As such the final temperature interval should be from zero to double the maximum value.
Chapter 3

3 Validation Model for the Input of Residual Stresses

With the distribution of the residual stresses characterized in 2.1.3 - Residual Stress Distribution, a FEM could be created, in order to obtain the necessary curve to then obtain a relaxation of the residual stresses. In 3 - Validation Model for the Input of Residual Stresses, the FE model is firstly described, and finally is validated. This validation is done by comparing the results for the distribution of residual stresses with the curve shown in 2.1.3 - Residual Stress Distribution.

3.1 Plate with 10x5 metres and no initial imperfections

In order to validate the feasibility of the two-dimensional (2D) approach for the application of weld-induced residual stresses, a test model was devised. For the model to be accurate, a couple of parameters needed to be met. Only with a valid modelling of the residual stresses would the simulated model provide a decent starting point to then add the cooling process and make a comparison between the two.

The dimensions of the plates to be welded were thoroughly chosen as an equal in dimensions to the dimensions of the real plates used in ship construction. These are commonly rectangular-shaped and have a length of up to 15 metres in length, and a width of up to 7.5 metres. Regarding the thicknesses used in ship construction, it is common for ships to have plates of no less than 6 millimetres in thickness. To have a general idea of the influence that the thickness has on the variation of the residual stresses on this method of modelling, two more thicknesses were chosen.

Secondly, the boundary conditions needed to be chosen carefully, as to depict more correctly what can be observed experimentally.

Finally, since this model is to be a simpler form of modelling the residual stresses, the loading is made using only a direct heat input along the full length of the welding path. This heat input is also conducted in the full width of the area of the plate subjected to a traction stress. As it will be seen later, this method introduces an error in the distribution of the residual stresses in the longitudinal direction.

3.1.1 Geometry

As it was described above, in order to better depict the reality, the model is composed of two equal plates with 10 metres in length by 2.5 metres in width, a plate size commonly found in ship construction. The plates have an aspect ratio of 4. This was chosen with the specific intent of
having a significant width of the plate in compression, in comparison to the width in traction, given by equation (3).

As such, the resulting geometry is of a plate with 10 by 5 metres, with the welding path directly in the middle of the plate. In the Figure 3.1 is show the geometry of the final plate for a better understanding.

As it can be seen in Figure 3.1, the plate is separated in 6 different areas. These were chosen as to create a mesh that grows the further it is from the centre. The first and last areas, the ones further from the centre, have 1 metre in width. The centre ones have $\eta t$ in width each. As stated in 2.1.1, the value for $\eta$ chosen is equal to 1.5. In Figure 3.2 can be found a zoomed image of the centre areas.
Figure 3.2 - Zoom of the centre areas of the 10 m by 5 m plate

As it can be seen above, both areas subjected to traction stresses are very slim. Regarding the thickness of the plate, as mentioned in 3.1, a plate of 6 millimetres was chosen. With that, two additional plates with 10 millimetres and 20 millimetres were also considered. These thicknesses are common in shipbuilding and were considered in order to find if there is a correlation between the plate slenderness and the accuracy of the results for the model.

Since the width of the strip subjected to traction stresses varies with thickness, the following widths were calculated for each plate thickness, all using a value corresponding to $\eta = 1.5$, as can be seen in Table 3.1.

<table>
<thead>
<tr>
<th>Thickness $t$ [mm]</th>
<th>Width of the strip in traction $\eta t$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
</tr>
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</table>

The plate was then divided in elements. Since the strip subjected to traction stresses is three orders of magnitude smaller than the dimensions of the plate, this creates an additional problem regarding element size. In order to obtain a considerable number of nodes in the centre area, while maintaining the limit of nodes that ANSYS Student has, which is of 32000, a coarser mesh would be required in the areas farther from the welding toe. As such, six different areas were created specifically with that in mind.
Firstly, the mesh in the centre area was created, and the remaining mesh was created from the centre outwards. The mesh in the centre area is conditioned by the width of the strip subjected to traction stresses. The programme used can have difficulties working with elements with one dimension more prevalent than the others, and that can influence the results obtained. With that in mind, the mesh in the two centre areas has an average size of 20 centimetres. The following areas have an average element size of 30 centimetres, with the outer areas having an average element size of 50 centimetres. The resulting mesh can be seen in Figure 3.3, were this is worked from the centre outwards.

Figure 3.3 - Mesh for the plates with 10 m by 5 m

The resulting mesh has a total of 1560 elements obtained from 4753 nodes. This is far below the 32000-nodes limit but ensures a fast solution time. As it will be seen later, this has an impact on the distribution of the residual stresses on the width of the plate, specifically in the area subjected to traction.

### 3.1.2 Boundary Conditions

The boundary conditions chosen need to ensure that the plate has freedom to move, since this exact analysis simulates the welding that occurs while the plate is still in the rollerbed. As such, the edges of the plate were left free.

However, in order to obtain symmetry transversally to the welding path, the longer edges were constrained on the transverse direction, in the x direction. Figure 3.4 shows the constrain used on the plate with a thickness of 10 millimetres. This approach can be used, as the stress, and
consequently the strain on the x direction can be neglected, in comparison to the stress and strain on the longitudinal direction, which are far bigger in value.

Figure 3.4 - Constrains on the edges of the plate with 10 m by 5 m

Also, in a second approach, and to simulate the welding on the transversal edges, a constrain of rigid edge in the longitudinal direction was created. Both edges were left free to move. In Figure 3.5 can be seen the constrains applied in this second approach.

Figure 3.5 - Constrains for the second approach on the 10 m by 5 m plate
3.1.3 Loading

Khameneh, in her study (2018), gathered experimental data from welding two plates with 150 millimetres by 200 millimetres each by the longer side. With that a temperature distribution was computed. Below, in Figure 3.6, can be seen the temperature distribution created in the study along the width of the plate for different moments of time retrieved form the experimental work.

![Figure 3.6 - Temperature distribution along time near the welding toe, Khameneh (2018)](image)

It can be seen that the temperature goes up to 700º Celsius, but stays in that peak for a fraction of the total time.

As it has been stated in 2.2.1, the modelling of the heat source for the loading of the plate can be made to resemble the welding path and shape of the heat source. However, given the that this model is to maintain its overall simplicity, the modelling of the heat source in this instance was done using a uniform heat source along the length of the welding path.

With that in mind, in order to choose a suitable uniform temperature, an iterative process was performed, with the gathering of the longitudinal residual stresses' distribution in the width of the plate. An analysis of the results from inputting peak temperatures of 200º, 300º, 400º, 500º and 600º Celsius were analysed, and put to comparison.

Regarding the heat source, this was modelled by applying directly the temperature as a body force to the plate, forcing the temperature in the nodes. The temperature input in itself was made using a time-dependent table, with the variation made using a ramped increase. In Figure 3.7 the temperature as a function of time can be seen. As it can be retrieved form the figure below, the temperature increases to 500º Celsius in 500 seconds, with a decrease to the 20º Celsius. The uniform temperature chosen was of 20º Celsius.
It is important to acknowledge that the simulation runs to 1200 second, although the temperature variation finishes at 1000 seconds, in order to accommodate the simulation of the cooling process in those final 200 seconds for the latter simulation.

The same principle was used for the several remaining peak temperatures, with only the maximum value being changed. In the Table 3.2 the values gathered for the longitudinal residual stresses along the width of the plate can be found. These values are from a path that follows the line that separates the plate in two equal parts along its width. It is important to understand that only half the plate was used, since the boundary conditions used ensure the symmetry of this distribution.
As it can be seen in Table 3.2, with a temperature of only 300° Celsius, the error is never above 0.18%. However, since these have a difference in value never bigger than 0.2%, 500° Celsius were used along the simulations. It is important to keep in mind that a temperature is applied along the full length of the welding toe at the same moment of time.

With these conditions established, it was possible to simulate the residual stresses and validate the model created.
3.1.4 Validation of the model

In order to validate the model, firstly the deformed shape was analysed, keeping in mind the overall deformation that needed to be obtained. In the Figure 3.8 can be seen the overall deformation of the plate obtained, with the initial shape also shown for comparison.

![Figure 3.8 - Deformed Shape of the 10 m by 5 m plate after the heating process for a plate 10 mm thick](image)

It can be noticed a slight shrinkage on the longitudinal direction near the edges, while a big shrinkage in the centre of the plate is present. Two distinct spikes can be found on the edges of the welding path. This is because there is no addition of material during the simulation, as it happens in welding in reality. This part of the plate would be in a liquid state, which it is not accounted for in this simulation. Since the material does not have internal stresses in liquid state, only in solid state, some additional plastic stresses can be found in the results that would not be present in reality.

It can also be seen that there is no movement on the transversal direction, as the longer edges of the plate are restrained from translation in the transversal direction. Symmetry was maintained as such.

Regarding the distribution of residual stresses, the paths chosen were five: three transversal paths and two longitudinal paths. The three transversal paths are located at mid-length, quarter-length and eighth-length of the plate. These were used to compute the distribution of longitudinal residual stresses. The two longitudinal paths were used to compute the transversal residual
stresses. These are located in the middle of the welding toe, and at a distance $\eta \times \epsilon$ of the middle of the welding toe.

Firstly, the residual stresses in the longitudinal direction were analysed. The Figure 3.9 depicts the distribution of the residual stresses along the width of the plate at mid-length. It can be noticed that the distribution resembles the theoretical approach, presented in the Figure 2.2. in 2.1.3, as initially intended. It is also noticeable that the peak stress occurs in the middle of the plate and has a value similar to the yield stress of the material being analysed. Symmetry is also present, as it would be expected.

However, the overall width of the area in traction is substantially bigger than the one expected. This is made possible since the amount of heat introduced in the plate in each point is drastically higher than the one introduced by a moving heat source, which allows for the heat to have time to dissipate to the sides of the plate, broadening the area subjected to traction stresses.

![Figure 3.9 - Distribution of the Residual Stresses in the longitudinal direction at mid-length for a plate with 10 mm](image)

Regarding the distribution in the paths at quarter and eighth-length, the picture is similar. In the Figure 3.10 and Figure 3.11 is depicted the distribution of the longitudinal residual stresses in these two paths, respectively. It is noticeable a further broadening of the strip subjected to traction stresses.
It is also important to acknowledge that, while the path at an eighth-length is located relatively near the end of the plate, is not severely influenced by the singularity present at the latter location. With the path at an eighth-length located at 1.25 metres of the shorter edge of the plate and having little to no influence from the edge of the plate, where there is a singularity, this method can be used to simulate the welding of shorter plates. This is an important observation, as the
plates later analysed are substantially shorter and slimmer. Finally, the transversal residual stresses were analysed. Below, in the Figure 3.12 and Figure 3.13 are depicted the distribution of the residual stresses on the transversal direction.

Figure 3.12 - Distribution of the Residual Stresses in the transversal direction at the welding toe for a plate with 10 mm

Figure 3.13 - Distribution of the Residual Stresses in the transversal direction at a distance of $\eta \times t$ for a plate with 10 mm

As it can be seen above, the distribution of the transversal residual stresses has the expected curve, with regards only for the point near the edges, which present abnormal peaks. These can
be explained by the fact that, since the model does not involve addition of material in the liquid form, and all of the material is already present at the beginning of the simulation, this acquires an abnormal value for strain, which in turn then influences the stresses near the edges.

As a simple comparison test, the second boundary condition case described in 3.1.2, with the shorter edges moving as a rigid line, was also computed. The temperature used, as stated in 3.1.3, being equal to 500º Celsius. In Figure 3.14 can be seen the deformed shape for this case of BC's. The thickness of the plate used was equal to 10 mm for illustrative purposes only.

![Figure 3.14 - Deformed shape of the plate with 10x5 metres with the shorter edges constrained](image)

As it can be seen in Figure 3.14, the shorter edges of the plate remain perpendicular to the longer edges. However, the plate suffers a shrinkage of its total length. This is a result of the heating of the central part of the plate, part which then shrinks when the temperature drops to 20º C, causing the outer parts of the plate to shrink in concordance. In Figure 3.15 can be seen the residual stress distribution in the longitudinal direction along the mid-length path.

The peak value for the residual stresses, as it can be collected from Figure 3.15, is equal to 373 MPa, where the lowest value for the compressive stresses is equal to −4.5 MPa. However, using an $\eta = 1.5$ on the equation (3), with a width of 5 metres and thickness of 10 mm, the resulting compressive stress is equal to 2.25 MPa. This value, although quite different from 4.5 MPa, is in the same order of magnitude, which is fairly acceptable for the purpose of this experiment.
Figure 3.15 - Distribution of longitudinal residual stresses for the second case of BC's

It is noticeable that the compressed parts of the plate experience a constant distribution of stresses. This is due to the constrain on the shorter edges of the plate, which distribute the compressive stresses through the width of the plate.

Lastly, it was important to validate the influence of the thickness of the plate on the final results. For that two additional thicknesses of 6 and 20 millimetres were used. The results were computed and put to comparison in the Figure 3.16.

Figure 3.16 - Comparison between the distribution of longitudinal residual stresses along the width for a path at mid-length for different thicknesses
In this simulation, the plate had its shorter edges constrained to act as a rigid line. As such, the strips of the plate under compression have a constant value throughout their width. It is noticeable that the distribution varies fractionally with the variation of thickness. It is important to acknowledge that with the increase of thickness comes an increase of the maximum stress, measured in the middle of the plate. With an increase in thickness also comes an increase of the absolute value in the part of the plate subjected to compressive stresses. The width of the area at traction is also bigger with an increase of thickness. That can be explained by the fact that the width of the heated strip varies with the thickness $t$, being wider the thicker the plate, and thus resulting in a wider strip of plate under traction.

As a first concluding point, it can be seen that this 2D method can be used to simulate the welding process with enough accuracy to provide a starting point to simulate the cooling process. Later, in 3.2, the plate was shortened in order to have a better refinement of the mesh, while maintaining the relatively rapid simulation time. As it was seen in 3.1, at a distance of 0.5 metres from the edges of the plate, there were still very few signs of influence from the singularity, which means that a length of 2 metres would not constitute a problem for the simulation.

Additional refinement to the value of $\eta$ would be of consideration, in order to have a more significant value for the compressive stresses in the outer parts of the plate.

### 3.2 Plate with 2x0.8 metres and no initial imperfections

As referred in the Sub-chapter 4.1., the plate with 2 metres in length by 0.8 metres in width in total was created to accommodate a finer mesh, without losing computational speed. This model was also created to later be modified to model initial geometric imperfections. That aspect is dwelled into in 3.3, where it is described more thoroughly.

#### 3.2.1 Geometries, Boundary Conditions and Loading Cases

As stated above, this model is composed by two plates with 2 by 0.4 metres, welded together by their longer edge, creating a plate with 0.8 metres in width, with the welding toe in the middle. As far as boundary conditions are concerned, this simulation has the same two cases as 3.1.2. An additional case was then added, for comparison reasons, to simulate additional conditions. Additionally, a stepped loading case was created. This stepped loading is consisted by a division of the length of the welding toe in four different parts, with each part being heated in different moments of time, as to simulate the travelling of the heat source.
3.2.2 Plate with added 100 by 100 mm on the edges of the welding toe

The additional case was created to simulate the addition of a plate in the beginning and end of the welding toe. This is usual in shipbuilding, as the initial and final parts of the welding have imperfections. To simulate this case, two plates with 100 millimetres by 100 millimetres were added on each end of the welding toe, and heated together with the plate. Regarding loading, the same distribution of temperature was used as in 3.1.3. The Figure 3.17 illustrates the geometry of the model with plates to initiate the welding.

Figure 3.17 - Geometry of the plate with added 100 mm plates

It is also noticeable in the figure that the plate was only constrained form translation in the transversal direction on the longer edges. The simulation resulted in the deformed shape depicted in the Figure 3.18.
As it can be seen in Figure 3.18, the plates added also deform. What is interesting is that the 2 by 0.8 metres plate has a smaller deformation in the longitudinal direction near the area of the welding toe.

For the distribution of residual stresses, the paths chosen were the same as the ones in 4.1., where in this case the longitudinal paths also have into account the length of the small added plates. From Figure 3.19 until Figure 3.21 are shown the results from the distribution of longitudinal residual stresses along the paths chosen, which are similar as the ones in 4.1.
As it can be seen for the longitudinal residual stresses along the width, the distribution pairs resemblance to the distribution of the plates with the former boundary conditions used on the validation. As it can be seen, at the path at 0.25 metres, at eighth-length, in the Figure 3.21, the
distribution is influenced by the singularity at the edge of the plate. However, the influence is bigger than in the plate with 10 metres in length.

For the longitudinal paths, the distribution for the transversal residual stresses is illustrated in Figure 3.22 and in Figure 3.23 for the distribution at a distance $\eta \times t$ from the welding toe.

![Figure 3.22 - Transversal residual stresses along the welding toe for a plate with 2 by 0.8 m](image1)

![Figure 3.23 - Transversal residual stresses at a distance $\eta \times t$ for a plate with 2 by 0.8 m](image2)
As is can be seen in Figure 3.22 and in Figure 3.23, the distributions have peaks near the edges. However, the peaks occur on the additional 100 by 100 mm plates. It is also important to acknowledge that these plates are removed after the welding is completed. This process is not replicated in the simulation, as such it bears little more utility than to prove the worthiness of the method employed.

3.2.3 Plate with Stepped Heat Source

In order to have a more realistic simulation, a model with a moving heat source was developed. This was achieved with the division of the welding toe into four different equal-length segments. The segmentation was implemented so that each segment would have its own time-dependent temperature distribution loading. Each of these loadings would be employed at a different moment of time, giving the effect of movement. As such, the method does not use a traditional moving heat source. Instead, it is better characterised as a stepped heat source.

To employ the stepped heat source, the initial geometry was modified. The areas were divided in four different parts and meshed afterwards accordingly. In the Figure 3.24 can be seen the final mesh used for this simulation. The mesh suffers a substantial growth in size as it gets further from the heated area.

![Figure 3.24 – Mesh of the model with a stepped heat source](image)
The BC’s used were the ones used in the first simulation, with only the longer edges being kept from moving in the transversal direction. As far as the loading is concerned, four different time-dependent temperature distributions were devised. These can be seen in Figure 3.25.

![Figure 3.25 – Temperature distribution for the stepped simulation](image)

The distributions start with a 250 second gap from each other, since the peak of each distribution occurs 250 seconds after the climb in temperature, each rise starts when the one before starts to cool down.

Regarding the BC’s, in order to have the best comparison between the current model, and the model with the uniform heating along the length of the welding toe, the current model has the same BC’s. As such, the resulting deformed shape is the one seen in Figure 3.26. This resulting shape is similar to the one show above as a result of the uniform heating input.

The distribution of residual stresses was done using the same paths defined in 3.2.1, the three paths along the width of the plate in the mid, quarter and eighth-length of the plate, and the longitudinal paths along the middle of the welding toe and at a distance $\eta \times t$ from the middle of the welding toe. From Figure 3.27 to Figure 3.29 the distribution of longitudinal residual stresses is depicted.
Figure 3.26 – Resulting deformed shape for the stepped heat input

Figure 3.27 - Longitudinal residual stresses along the width of the plate at mid-length for the stepped model
The distributions for the longitudinal residual stresses resemble the model with uniform heat source, as it was expected, since the model has the same boundary conditions. However, when it comes to the distribution of transversal residual stresses along the length of the plate, the graphs
obtained in the paths chosen have dramatic peaks in the areas where the plate is divided into segments.

Figure 3.30 - Transversal residual stresses along the middle of the welding toe of the plate for the stepped model

Figure 3.31 - Transversal residual stresses along the length at a distance of $\eta \times t$ of the middle of the plate for the stepped model
As it can be seen in Figure 3.30 and Figure 3.31, the distribution resembles the characteristic curve predicted theoretically. However, the peaks were formed in the areas where the plate is divided, given by the fact that the line that separates the heated segments is heated two times. As such, this approach introduces additional errors to the model, errors that the simpler model with the uniform heat source do not have at all, and does not constitute a better choice to model the residual stress distribution.

3.3 Plate with 2x0.8 metres and initial imperfections

In order to try and bring the simulation closer to reality, the plate with 2 metres by 0.8 metres was modelled with initial imperfections added prior to the heating process. These imperfections can be found in real plates, which cannot be made with a perfect geometry. The results obtained were compared to the simulation without initial imperfections and between each other.

3.3.1 Geometry, BC’s and Loading

For the modelling of the initial imperfections, the same geometry used in 3.2 was considered, but with the addition of initial imperfections to the geometry. These were characterized by the equation (11). For the values of $m$ and $n$, values ranging from 1 to 3 were used, as it constitutes a sufficient number of values to develop a tendency in the results. Two additional models with a value of 1.5 for $l$ and $b$ each were also considered, in order to introduce asymmetry to the geometry. The BC’s used were similar to the two simpler cases presented in 3.1.2. As for loading, the simpler model with the uniform loading was used. The resulting geometry can be seen in Figure 3.32, where the mode with $m = n = 2$ is the one employed below, in a MATLAB® graph.

![Figure 3.32 – Geometric initial imperfections for the mode with $m = n = 2$](image)
The value for the amplitude of the wave was set at a $w_0 = 0.001$ m, for the plate with 10 mm in thickness, which constitutes 1/10 of the thickness. For the remaining thicknesses the same rule was used.

### 3.3.2 Results

The results for this chapter are initially put to comparison between the modes compiled, and the results from the perfect plates. A total of 21 plates with imperfections were compared along with the 3 perfect plates. As an illustrative note, the resulting geometry, for a plate with mode equal to $m = 1$ and $n = 1$ can be found in Figure 3.33.

![Figure 3.33 – Deformed geometry of the plate in the first mode of imperfections for both directions](image)

As it can be seen in Figure 3.33, the plate suffers a longitudinal shrinkage in the strip subjected to the heat load. The shrinkage, however, is less prominent. Also, in addition to the expected shrinkage, the plate gains curvature. The plate also bends upwards. This is an effect of the heating occurring off the xy-plane.

Regarding the distribution of residual stresses, the results were computed only for the longitudinal direction, in the middle of the plate, since the distribution is scarcely affected by the position of the path chosen, as concluded in 3.1.4, as long as it is far enough from the edges of the plate.

In the Figure 3.34 can be seen the distribution of the residual stresses in the longitudinal direction, for the different modes of initial imperfections. This graph was made using a plate with 10 mm in thickness. As it can be seen, the more the modes are higher, the bigger is the residual stress along the width of the plate.

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Figure 3.34 – Distribution of the longitudinal residual stresses for the different modes of imperfection for a plate with 2 by 0.8 m

The simulation done, with the simplifications considered, presents an appropriate level of resemblance to the reality. This only adds to the conclusion that the simulation reproduces reality fairly well. As it later will be addressed in 3.3 - Plate with 2x0.8 metres and initial imperfections, the modelling of initial imperfections was also taken into account in the simulation of the welding of a stiffener.

3.4 Perfect plate with 200 by 300 mm and 2 mm in thickness

Since that in 3.1.4 one of the conclusions is that the plate can be smaller, in this chapter the geometry was taken to the extreme, where the dimensions were shrunken to the maximum. This model was done with the only intent of showing the limitations of the simplifications made, since the influence of the singularity present on the edges of the welding toe introduce an error to the simulation.

3.4.1 Geometry, BC’s and Loading
For this simulation, the model created has two plates with 200 by 150 millimetres in length and width respectively. Both plates have 2 millimetres in thickness. The $\eta$ was maintained at 1.5 just
for the sake of comparison with the former models presented in 3.1.1 and 3.2.1. The boundary conditions used were the ones used in 3.2.1, where the length edges were constrained in the y-direction and the remaining edges were left unconstrained. As for loading, the same temperature distribution with a peak of 500º Celsius was used.

### 3.4.2 Results

The resulting deformed geometry, as well as the longitudinal residual stress distribution on the deformed shape itself can be seen in Figure 3.35. It is also interesting to consider that this simulation takes about 30 seconds to complete. The deformed shape has, as it can be seen in Figure 3.35, has the overall expected shape.

![Figure 3.35 – Resulting deformed shape of the model with plates with 200 by 300 mm](image)

However, regarding the distribution of longitudinal stresses, it can be seen that the plate is not long enough for the distribution not to be influenced by the singularities present in the edges. The distribution of longitudinal residual stresses can be seen in Figure 3.36. The path chosen for this distribution is the one at mid-length, going from one edge of the plate to the other.
Figure 3.36 – Distribution of longitudinal residual stresses for the plate with 200 by 300 mm at mid-length

It is evident from Figure 3.36 that the distribution is still affected by the singularities present in the edges of the plate. Moreover, the path chosen for this distribution, being at mid-length, is the one farther from the edges, which implies that the paths at quarter and eighth-length are even more affected by the edges of the plate.

It can be concluded that this plate is far too short for this simulation, considering the simplifications considered. Although these types of plates, with these dimensions, are usually the ones considered for simulation, for this simplified model the dimensions are just not big enough.

### 3.5 Welding of Stiffeners on Flat Plates

In shipbuilding, practically all steel structures are made using reinforced panels. These can be produced by welding stiffeners to the flat panels. These stiffeners are composed of either flat bars, bulbous bars, L-shaped bars, or T-shaped bars, and are usually welded with equal spacing between each other. This spacing often varies between 400 and 800 millimetres. The dimensions of the stiffeners may vary from 80 mm to 500 mm in width, with the thickness varying from 6 to 20 mm more often than not.
3.5.1 Geometry, BC’s and Loading

For the creation of the geometry for this simulation, the same plate with 2 by 0.8 metres was used. However, in this case a flat bar with 390 millimetres was added to the middle of the plate, to be welded in the same area where the welding was simulated in 3.2.1. The stiffener, to simplify, was left with the same thickness as the plate. As such, the thicknesses chosen were 6, 10 and 20 millimetres. In the Figure 3.37 can be seen the initial geometry of the model created.

![Initial geometry of the model created](image)

Figure 3.37 – Initial geometry of the simulation of the T-join weld of a stiffener on a plate

A second model with two flat-bar stiffeners was created. The purpose of this second geometry was to attest that the introduction of a second stiffener would not influence the results obtained on the simulation of one single stiffener. This second geometry was obtained by mirroring the first one, with the resulting model being composed by a plate with 2 by 1.6 metres and two stiffeners spaced 800 millimetres between each other. As for loading, the same uniform heating with a time-dependent temperature increase, as seen in 3.1.3, with a peak of 500º Celsius. The Boundary Conditions applied to both models was the impediment of movement in the x-direction of the longer edges of the plate.

Finally, both geometries were also considered to have initial imperfections, modelled in the exact same way as the initial imperfections considered in 3.3. The models were tested with the same modes of initial imperfection.
3.5.2 Results

The results were computed only for the residual stresses in the longitudinal direction, for the middle of the plate, along the width of the same. The results are divided by plates with no initial imperfections, followed by the results for the plates with initial imperfections.

Firstly, the results for both models were considered. The path chosen, as described above, was the one at mid-length. An additional path at mid-length going through the width of the stiffener was also considered for the model with a single stiffener. In the Figure 3.38 can be seen the deformed shape of the model with one stiffener. Also, in the figure can be seen the distribution of residual stresses in the longitudinal direction.

![Figure 3.38 – Deformed shape of the model with one stiffener and no initial imperfections](image)

The resulting deformed shape has the same shrinkage effect present in the unstiffened plates. However, given that the welding only occurs on one of the edges of the stiffener, a curvature is introduced to the stiffener, which is transferred to the plate. There is also bending on the plate. This effect can be explained by the fact that the curvature induced to the plate by the stiffener is more present in the middle of the plate, where plate sustained the most shrinking.

Would the heat been induced only in the top face of the plate, and not at full thickness, a more prominent bending of the plate was to be found, but not seen here in this case. Regarding the distribution of residual stresses present, the shape resembles the one obtained for the simple joining of plates, and the values are in the range predicted by the theory.

The distribution of residual stresses on the paths can be seen in Figure 3.39 and in Figure 3.40. The former represents the distribution at mid-length along the width of the plate, while the latter depicts the distribution of residual stresses at mid-length, along the width of the stiffener.

As it can be seen in both Figure 3.39 and Figure 3.40, the distribution resembles the expected, with the peaks at a value for the peak stress similar to the value of the material’s yield stress. It is important to acknowledge that the distribution of the stiffener, present in Figure 3.40, has a plateau in the area of the heated strip. The absolute value in the negative part of the graph, where the plate is at compression, decreases drastically the bigger the distance from the heated part of the stiffener. This is explained by the fact that the edge of the stiffener is not constrained in any way, which makes room for a bigger deformation.
As it can be seen in both Figure 3.39 and Figure 3.40, the distribution resembles the expected, with the peaks at a stress similar to the yield stress. It is important to acknowledge that the distribution of the stiffener, present in Figure 3.40, has a plateau in the area of the heated strip. The absolute value in the negative part of the graph, where the plate is at compression, decreases.
drastically the more the distance grows further from the heated part of the stiffener. Once more, this is due to a lack of constrains on the edges of the stiffeners.

Regarding the model with two stiffeners, the only path chosen was the one along the width of the full plate at mid-length. In the Figure 3.41 can be seen the distribution of the residual stresses in the longitudinal direction.

![Figure 3.41 – Distribution of the longitudinal residual stresses on the perfect plate with two stiffeners along the width of the plate at mid-length](image)

The distribution is minimally affected by the presence of two stiffeners. The results also show that the graph is mirrored, which is expected given the symmetry of the geometry. As such, it can be concluded that in the presence of two stiffeners, in this perfect case, one does not influence the other. Moreover, for the sake of comparison, on the Table 3.3 can be seen the variation of the values at the path along the width of the plate at mid-length. As both of the distributions are symmetric, only one side was depicted.
Table 3.3 – Percentage of the variation of the residual stresses between the model with one and two stiffeners

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<th>Length [m]</th>
<th>Variation [%]</th>
<th>Length [m]</th>
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<td>-3,80</td>
<td>0,400</td>
<td>0,14</td>
</tr>
</tbody>
</table>

As it can be concluded from the Table 3.3, the variation of the residual stresses is extremely similar. The only value with a significant disparity is the one taken at 0.360 metres. This can be explained by the fact that in that area of the plate, the residual stresses change dramatically. As such, the distribution is slightly wider in that area.

Regarding the model with plates with initial imperfections, the longitudinal residual stresses were computed and compared, and are shown in Figure 3.42. The graph shows that, with the increase in the values of the modes, the distribution in the negative part of the graph also increases slightly. The distributions have the expected values and shape.

Figure 3.42 - Distribution of the longitudinal residual stresses for the different modes of imperfection for a plate with a single stiffener
The Figure 3.43 shows the same distribution, but for the model with two stiffeners. Since the distribution is symmetric, only one side of one of the stiffeners is shown.

As it can be seen in Figure 3.43, the distribution pairs resemblance to the one found in Figure 3.42. That only attests to the conclusion that one stiffener has almost no influence on the one next to it. What can also be seen, as it occurs with the model with one single stiffener, is that the values on the negative side of the graph are slightly higher for the modes with uneven values, especially the ones with $m = 3$.

It can be concluded then that this type of 2-Dimensional simulation, alienated with the usage of a uniform heat source produces reliable results for the input of residual stresses on flat plates and stiffened panels, even with the addition of initial imperfections. These models were then used to compute the cooling process, and the results compared with the simple process with no cooling in 4. Both models with one and two stiffeners were maintained, and are addressed in 4, as to understand if the usage of the model with two stiffeners introduces a reduction on the effectiveness of the cooling process.
Chapter 4

4 FEM Simulation of the Cooling Process

To obtain a successful but also technologically realistic result for the cooling process in reality, this would have to be performed using some sort of liquefied gas at a temperature drastically below 0º Celsius. Liquid nitrogen would probably be the best choice, as it is abundant, relatively cheap and relatively easy to bring to a suitable temperature. Regarding the method of inputting the liquefied gas to the welding toe, an automated device, similar to the machine used to perform automatic welding would be a suitable choice, with a nozzle-type device inputting the liquefied gas directly to the welding toe. Finally, concerning the time window, it is empirically estimated that the liquefied gas would be inputted right after the welding, as not to let the plate cool by itself for much time, in order for the cooling process to have maximum effectiveness.

4.1 Initial Assumptions

In order to retain the level of simplicity of the model, the cooling process was assumed to be performed uniformly along the welding path. As it not the scope of this thesis, the metallurgical aspect of the cooling process was not addressed. Also, since the simulation of the heat input was not designed with the time as a variable of the process, the time of the cooling process was also not bared in mind. Regarding the Boundary Conditions, these were retained from the simulations used to verify the modelling of the residual stresses, in order have a better comparison between the two models with and without the cooling process.

4.2 Loading Conditions

For the modelling of the cooling process, a time-dependent temperature distribution, similar to the one used in 3.1.3 was used here. However, instead using the remaining of the time until the mark of 1200 seconds for the cooling before bringing the plate to 20º C. In the Figure 4.1 can be seen the time-dependant temperature distribution used to emulate the cooling process.
As it can be seen in Figure 4.1, after the 500º C peak the temperature is brought down to a negative temperature before being restored to the chosen reference temperature of 20º Celsius. It is important to acknowledge that the temperature chosen for the negative part seen in Figure 4.1 is equal to -20º Celsius. A second temperature of -50º Celsius was also used, in order to understand how the temperature difference on the negative part of the distribution influences the results of the relaxation of the residual stresses. A third temperature was also considered in some cases, in order to try and reveal a tendency on the results obtained. This third temperature, however, is not technologically feasible.

4.3 Results of the Cooling Process

The results were computed for the models of the plates with 2 metres by 0.8 metres in length and width respectively, for both perfect geometries and with initial imperfections introduced. Results were also computed for the model with one and two stiffeners, also for both perfect and with initial imperfections. The results for both loading cases of cooling for all these models were compared with the distribution without cooling. Finally, the results were displayed using graphs. Each graph displays all three results for each loading, the loading with no cooling and both loadings with cooling integrated.
4.3.1 Perfect Plate with 2 by 0.8 m

Starting with the perfect plate with 2 metres in length by 0.8 metres in width, the results were taken for all three thicknesses, and compared differently. The results can be seen from Figure 4.2 to Figure 4.4, organized by thickness from 6 to 20 mm.

Figure 4.2 – Comparison of the residual stresses on a 6 mm thick plate with and without the added cooling process

Figure 4.3 - Comparison of the residual stresses on a 10 mm thick plate with and without the added cooling process
What can be attested from the graphs is, as it was expected, the cooling process has a significant impact of the relaxation of the residual stresses. Moreover, using a temperature drop to -50º Celsius has a dramatically bigger impact to the distribution than using a temperature drop to -20º Celsius. What is also interesting is that the bigger the thickness of the plate, the less effect the cooling process has, as it can be seen in Table 4.1. An additional temperature decrease to -80º Celsius was also considered, with the sole purpose of finding a tendency on the results.

Table 4.1 – Percentage of drop of the peak value for the longitudinal residual stresses

| Thickness [mm] | Peak drop [%]       |
|               | -20º C | -50º C | -80º C |
| 6             | -22.7  | -40.3  | -58.0  |
| 10            | -21.7  | -38.9  | -56.4  |
| 20            | -20.2  | -35.7  | -51.6  |

Using a temperature drop to -20º Celsius makes the peak stress, in the middle of the welding toe, to drop between 23 and 20%, whereas a decrease in temperature to -50º Celsius makes the value of the peak stress drop from 36 to 40%. It is unanimous that a bigger temperature drop in the cooling process can lead to better effects of residual stress relaxation, regardless of the thickness. However, the process needs to be thoroughly thought through when in use in bigger thickness plates. It is interesting that using a theoretical temperature drop to -80º Celsius only affects the peak residual stresses by 51 to 58%. In order to have a better understanding of the tendency, in
Figure 4.5 can be seen the decrease in residual stresses in comparison to the drop in temperature. The values used are positive for the temperature, only for the graph depicted to have a better presentation.

As it can be seen in Figure 4.5, the decrease shows a dramatic first drop from the value with no cooling added, to using a cooling to a temperature of -20° Celsius. After that, the distribution follows a linear tendency. This tendency shows that using enough temperature drop, the plate would be completely relieved from residual stresses. That value, however, is a bit misleading, as it is not possible to reach such low temperatures. What can be seen here is that the process is successful, and can be recommended to be developed and put into production.

### 4.3.2 Plate with 2 by 0.8 m and initial imperfections

After showing the effect of the cooling process on a perfect plate, the process was used on the models that take into account initial imperfections. The modes used were the same illustrated in 3.3.1. The models were also subjected to both cases of cooling. In this case, and since a comparison between the different thicknesses was performed in 4.3.2, this comparison was performed using only a thickness of 10 mm. Also, a final graph with the evolution of the maximum deformation on the point with higher deformation along the process of heating and cooling was depicted.
As such, the resulting graphs depicting the distribution of longitudinal residual stresses for each mode accounted for can be seen from Figure 4.6 to Figure 4.10. Two additional graphs were computed for the modes with a length of wave of $1.5l$ and $1.5w$.

Figure 4.6 - Comparison of the residual stresses on a plate with modes with $m = 1$ and $n = 1$ of imperfection with and without cooling added

Figure 4.7 - Comparison of the residual stresses on a plate with modes with $m = 2$ and $n = 1$ of imperfection with and without cooling added
Figure 4.8 - Comparison of the residual stresses on a plate with modes with $m = 2$ and $n = 2$ of imperfection with and without cooling added

Figure 4.9 - Comparison of the residual stresses on a plate with modes with $m = 3$ and $n = 2$ of imperfection with and without cooling added
As it can be seen from Figure 4.2 to Figure 4.10, it is unanimous that the cooling process is effective for every plate, even with the increase in the value of the mode of imperfections. Moreover, the distribution is significantly lower when a temperature of -50º Celsius is used, as opposed to the peak temperature of -20º Celsius.

Figure 4.10 - Comparison of the residual stresses on a plate with modes with \( m = 3 \) and \( n = 3 \) of imperfection with and without cooling added

Figure 4.11 - Comparison of the residual stresses on a plate with modes with wave length equal to 1.5l with and without cooling added
Regarding the modes with wave length of $1.5l$ and $1.5w$, the graphs can be seen in Figure 4.11 above and in Figure 4.12 below, respectively. The same conclusion can be taken for the modes in question, where there is a significant drop of the residual stresses.

Figure 4.12 - Comparison of the residual stresses on a plate with modes with wave length equal to $1.5w$ with and without cooling added

Finally, in order to have a better understanding of the value of reduction of residual stresses, in the Table 2.1 can be seen the percentage drop on the peak of the residual stresses for each model of initial imperfection.

<table>
<thead>
<tr>
<th>Mode of imperfection</th>
<th>Peak reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-20° C</td>
</tr>
<tr>
<td>Perfect plate</td>
<td>-21,7</td>
</tr>
<tr>
<td>$m = 1 \ n = 1$</td>
<td>-22,0</td>
</tr>
<tr>
<td>$m = 2 \ n = 1$</td>
<td>-21,9</td>
</tr>
<tr>
<td>$m = 2 \ n = 2$</td>
<td>-21,9</td>
</tr>
<tr>
<td>$m = 3 \ n = 2$</td>
<td>-21,9</td>
</tr>
<tr>
<td>$m = 3 \ n = 3$</td>
<td>-21,5</td>
</tr>
<tr>
<td>$1.5 \times l$</td>
<td>-21,8</td>
</tr>
<tr>
<td>$1.5 \times w$</td>
<td>-22,1</td>
</tr>
</tbody>
</table>
What can be drafted from the Table 4.2 is that the bigger the values of the modes of imperfection, the lower the effect of the cooling process on the plate, regardless of the value obtained for the distribution of residual stresses without the cooling process added. What is also acknowledgeable is that the asymmetric models with a wave length of $1.5l$ and $1.5w$ present no significant change in comparison to the mode with $m = 1$ and $n = 1$.

Regarding the deformation of the plate, the results were computed for the plate with values for the modes of imperfection equal to 1 for both the $m$ and $n$. In Figure 4.13 can be seen the evolution of the amplitude on centre of the plate. The initial value considered was equal to 1 millimetre, which is 10% of the value of the thickness of the plate considered for this analysis. The time-dependent temperature used is the same used throughout the simulations.

At time $t = 0$ seconds, the temperature is at a reference temperature of $20^\circ$ C. At 500 seconds, the temperature is at $500^\circ$ C, its peak temperature. Then it climbs back down to the lowest temperature at 1000 seconds, where it finally reaches a final temperature of $20^\circ$ C for the simulation without cooling, and $-20^\circ$ C and $-50^\circ$ C for the simulations with the added cooling process to $-20^\circ$ C and $-50^\circ$ C respectively. Finally, at 1200 seconds, the temperature gets to the reference $20^\circ$ C.

![Figure 4.13 – Evolution of the amplitude of the wave of the imperfection for a plate with modes $m = 1$ and $n = 1$](image)

As it can be concluded from Figure 4.13, the amplitude of the deformation is mitigated. The initial amplitude is amplified equally for all cases, since all have an initial rise of temperature to $500^\circ$ Celsius. Then, with the drop in temperature, the amplitude also decreases. What is interesting to acknowledge is that, with the welding process performed, the amplitude of the initial imperfection is amplified, which was expected. What is also acknowledgeable is that with the addition of the
cooling process, the amplitude can be mitigated to a value of amplitude 50% smaller, when using a temperature decrease to -50º Celsius.

4.3.3 Welding of Stiffeners on Flat Plates

Finally, the cooling process was implemented on the simulation of welding of stiffeners on flat panels. This is probably where the cooling process would have an easier implementation, as the welding of stiffeners is a repetitive process and usually there is significant number of them to be welded to a single flat panel. For the simulation and comparison of the cooling process on welded stiffeners, the same two cases of thermal loading were used, along with the usage of the case without cooling. This comparison was performed for both the models with one and two stiffeners, as to attest if there is an influence of one stiffener on the one next to it.

As such, from Figure 4.14 to Figure 4.21 is depicted the comparison between both cases of cooling, along with the simulation with no cooling included. The thickness used was of 10 mm. A single thickness was considered in this case, as including both the other thicknesses would be deemed too long of a process on this stage.

![Figure 4.14 - Comparison of the residual stresses on a plate with one stiffener with no imperfections with and without cooling added](Image)
Figure 4.15 - Comparison of the residual stresses on a plate with one stiffener with modes $m = 1$ and $n = 1$ of imperfection with and without cooling added.

Figure 4.16 - Comparison of the residual stresses on a plate with one stiffener with modes $m = 2$ and $n = 1$ of imperfection with and without cooling added.
Figure 4.17 - Comparison of the residual stresses on a plate with one stiffener with modes \( m = 2 \) and \( n = 2 \) of imperfection with and without cooling added

Figure 4.18 – Comparison of the residual stresses on a plate with one stiffener with modes \( m = 3 \) and \( n = 2 \) of imperfection with and without cooling added
Figure 4.19 - Comparison of the residual stresses on a plate with one stiffener with modes \( m = 3 \) and \( n = 3 \) of imperfection with and without cooling added.

Figure 4.20 - Comparison of the residual stresses on a plate with one stiffener with modes with wave length equal to \( 1.5l \) with and without cooling added.
As it can be seen in the graphs depicted from Figure 4.14 to Figure 4.21, the reduction is also very significant, as it would be expected. It is also important to acknowledge that, even if there are modes in which the distribution is slightly lower without the cooling process, the reduction is proportionately smaller. In order to have a better understanding of the percentage of the reduction of the residual stresses, in the Table 4.3 is illustrated the percentage of reduction of the peak residual stress, which occurs in the middle of the plate.

Table 4.3 - Percentage of reduction of the peak value for the longitudinal residual stresses for the different modes of initial imperfections for a plate with one stiffener

<table>
<thead>
<tr>
<th>Mode of imperfection</th>
<th>20°C</th>
<th>50°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfect plate</td>
<td>-21.8</td>
<td>-38.9</td>
</tr>
<tr>
<td>( m = 1 \ n = 1 )</td>
<td>-22.4</td>
<td>-39.9</td>
</tr>
<tr>
<td>( m = 2 \ n = 1 )</td>
<td>-21.7</td>
<td>-38.8</td>
</tr>
<tr>
<td>( m = 2 \ n = 2 )</td>
<td>-21.6</td>
<td>-38.6</td>
</tr>
<tr>
<td>( m = 3 \ n = 2 )</td>
<td>-21.8</td>
<td>-39.0</td>
</tr>
<tr>
<td>( m = 3 \ n = 3 )</td>
<td>-22.4</td>
<td>-39.9</td>
</tr>
<tr>
<td>( 1.5 \times l )</td>
<td>-22.3</td>
<td>-39.8</td>
</tr>
<tr>
<td>( 1.5 \times w )</td>
<td>-22.3</td>
<td>-39.7</td>
</tr>
</tbody>
</table>
As it can be retrieved from the Table 4.3, the reduction is very similar to the one resulting from cooling a flat plate. The values are also similar to the ones retrieved for the flat plate. However, the distribution follows no significant tendency as the mode values increase, as opposed to the tendency of the results found for the flat panel in 4.3.2. The only tendency that can be encountered is the fact that the modes with an odd number for the value of \( n \) produce better results. This can be explained by the fact that in these cases, the maximum amplitude of the wave is where the stiffener is welded to the plate, which means that, due to the geometry of the stiffener, it also has geometric imperfections, which amplify the results obtained.

There is a general consensus in the results that a cooling process performed to a temperature of -20\(^\circ\) Celsius affects the distribution of residual stresses by reducing them in 22\%, while a usage of a temperature of -50\(^\circ\) Celsius produces a reduction of around 39\%.

Regarding the reduction of the overall initial imperfections, it can be seen in Figure 4.22 that the same effect can be found for this geometry, with one stiffener. There is a significant reduction in the amplitude of the initial imperfections. However, the effect of the cooling process to a temperature of -20\(^\circ\) Celsius is almost the same as the effect for a bigger decrease in temperature, to -50\(^\circ\) Celsius.

![Figure 4.22 – Evolution of the amplitude of the wave of the imperfection for a plate with one stiffener with modes m=1 and n=1](image)

A second comparison for the usage of the cooling process was performed, but instead of using the model with one stiffener, the model with two stiffeners was considered. This comparison also took into account the same loading cases present for the simulation with one stiffener, and the same modes used in the model with one stiffener. As such, from Figure 4.23 to Figure 4.30 are depicted the graphs comparing the results of the residual stresses with and without cooling. The
first set of graphs depicts the results for the modes of imperfection with a value for the longitudinal and transversal wave lengths equal to $l$ and $w$, respectively, while the last two have a wave length of $1.5l$ and $1.5w$ respectively.

Figure 4.23 - Comparison of the residual stresses on a plate with two stiffeners with no imperfections with and without cooling added

Figure 4.24 - Comparison of the residual stresses on a plate with two stiffeners with modes $m = 1$ and $n = 1$ of imperfection with and without cooling added
Figure 4.25 - Comparison of the residual stresses on a plate with two stiffeners with modes $m = 2$ and $n = 1$ of imperfection with and without cooling added

Figure 4.26 - Comparison of the residual stresses on a plate with two stiffeners with modes $m = 2$ and $n = 2$ of imperfection with and without cooling added
Figure 4.27 - Comparison of the residual stresses on a plate with two stiffeners with modes $m = 3$ and $n = 2$ of imperfection with and without cooling added.

Figure 4.28 - Comparison of the residual stresses on a plate with two stiffeners with modes $m = 3$ and $n = 3$ of imperfection with and without cooling added.
Figure 4.29 - Comparison of the residual stresses on a plate with two stiffeners with modes with wave length equal to $1.5l$ with and without cooling added

Figure 4.30 - Comparison of the residual stresses on a plate with two stiffeners with modes with wave length equal to $1.5w$ with and without cooling added
As it can be assessed from the graphs presented from Figure 4.23 to Figure 4.30, the behaviour of the model is exactly the same found in the model with one stiffener. This only adds to the conclusion that the model with one stiffener is completely capable of depicting the behaviour of the structure during the heating and cooling processes. As such, the graphs show a tendency of decreasing the overall value of residual stresses in each point. In order to have a better grasp of the percentage of reduction of the value of residual stresses, in Table 4.4 is illustrated the reduction of the value of residual stresses in the area subjected to traction.

Table 4.4 - Percentage of reduction of the peak value for the longitudinal residual stresses for the different modes of initial imperfections for a plate with two stiffeners

<table>
<thead>
<tr>
<th>Mode of imperfection</th>
<th>Peak reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-20º C</td>
</tr>
<tr>
<td>Perfect plate</td>
<td>-21,6</td>
</tr>
<tr>
<td>(m = 1 ) (n = 1)</td>
<td>-22,2</td>
</tr>
<tr>
<td>(m = 2 ) (n = 1)</td>
<td>-21,7</td>
</tr>
<tr>
<td>(m = 2 ) (n = 2)</td>
<td>-21,6</td>
</tr>
<tr>
<td>(m = 3 ) (n = 2)</td>
<td>-21,9</td>
</tr>
<tr>
<td>(m = 3 ) (n = 3)</td>
<td>-22,4</td>
</tr>
<tr>
<td>(1.5 \times l)</td>
<td>-22,3</td>
</tr>
<tr>
<td>(1.5 \times w)</td>
<td>-22,4</td>
</tr>
</tbody>
</table>

The results confirm what was attested for the model with one stiffener, in which the value have a tendency of favouring the modes of imperfection in which the stiffener itself is also affected by the geometric imperfection, causing a slight amplification of the results. Should the stiffeners be depicted without the geometric imperfections, and this tendency would disappear.

In conclusion, the results obtained for all of the models used in the comparison of the effect of the cooling process show that with a drop in temperature to -20º results in a reduction of the peak longitudinal residual stresses in around 20 to 22%, while a drop in temperature to -50º results in a reduction of around 38 to 40%. The process is a success, even for the stiffened plates. This is important, as it is for stiffened plates that the cooling process has more possibility of being developed.

Finally, the reduction of amplitude of the initial imperfections using the cooling was also considered. This can be seen in the graph depicted in Figure 4.31, where it is shown the evolution of the amplitude of the wave of imperfection, measured in the centre of the plate, for a plate with a mode with \(m = 1\) and \(n = 1\).
As it can be seen in Figure 4.31, and as it can be seen in the model with one stiffener, the usage of a bigger temperature does not affect the overall result for the reduction of the amplitude of the imperfections. Both temperatures, however, produce a significant reduction of the amplitude of the initial imperfections, in comparison to the simulation without a cooling process. As such, when it regards reduction of initial imperfections, a simple cooling to -20°C Celsius is more than enough.
Chapter 5

5 Conclusion

Firstly, starting with the modelling of the geometry, the initial geometry employed resulted to be far too big in order to find significant results that proved that the method used was effective. Still the dimensions of geometry were important to assess the validity of the model used. The model with 2 metres in length by 0.8 metres in width proved to be a realistic compromise between being big enough so that the singularities would not influence the results obtained it the middle of the plate, and being sufficiently fine in mesh for the distribution to be illustrated correctly. The model with 300 by 200 millimetres proved to be too small for the method employed to be effective, as the singularities present in the edges of the plate were not distant enough.

Regarding the uniform heat input, it was proven to achieve adequate results for the validation in question to be performed. The stepped heat input shown, although more complex in its employment, introduced additional errors to the resulting distributions of residual stresses, more importantly in the distribution of transversal residual stresses along the welding toe and near it. The model with smaller 100 by 100 millimetre plates also added no significance to the results obtained.

In concern to the modelling of initial geometric imperfections, the method employed proved to be effective in showing that the plate suffers a reduction in strength. The results concerning the deformed shape also proved to be sufficiently realistic, regardless of the usage of a 2-Dimensional geometry.

Moving to the simulation of the T-joint welding of stiffeners on flat plates, the method created proved to be acceptable to depict the resulting deformed geometry. Moreover, the deformation obtained depicts the flection and curvature expected for a more complex model, which only adds to the validity of the model employed. Also, the addition of another stiffener does not influence significantly the first one. As such, the simulations could be performed for one stiffener only.

Secondly, regarding the cooling process, this was proven to be a success. More concretely, it was possible to have a significant reduction of the distribution of the residual stresses for all of the models used. Regarding the cooling process of the flat plate with imperfections, the results showed that the bigger the mode of imperfection, the less effective was the cooling process. Still, it was possible to achieve a reduction of the stresses in the area subjected to traction of up to 22% using a drop in temperature to -20º Celsius, and a reduction of up to 40% using a drop in temperature to -50º Celsius.

Regarding the cooling process employed on stiffened plates, once more the usage of a model with one stiffener proved to be sufficiently accurate, as the usage of a second stiffener has no
significant influence on the first one. The results of the cooling process are also extremely
effective, as the reduction of the peak values of the longitudinal residual stresses is similar to the
values obtained for the cooling process of the flat panel.

As a final concluding remark, the cooling process, although proven to be very effective, requires
advanced technology that is probably very costly to be employed in a shipyard. The cooling
process would require the input of a liquefied gas directly to the welding path, by a machine
capable of doing the process automatically. This process would be financially more sustainable
for the cooling of stiffeners, as the process of welding the stiffeners are more systematic, as there
is a significant number of stiffeners to be welded to a single flat panel.

5.1 Achievements

This dissertation firstly concluded that the implementation of a FEM model in 2D is capable of
producing reasonable results for the distribution of residual stresses. With the model created it is
easier to perform simulations faster and have significant results using different geometries at
choice. The implementation of simple geometries and heat inputs allowed for a significant amount
of runs to be made, for different thicknesses and modes of initial imperfection. More simulations
for several other thicknesses could be made, but were left out given the limited size of this
dissertation. The successful implementation of a simple yet effective model of inducing residual
stresses along several geometries was definitely one of the major achievements.

However, the biggest achievement of this dissertation is without any doubt the success of the
effectiveness of the cooling process devised. With this new set of results, a new method of
relaxation of residual stresses can be developed in order to help mitigate several problems
inherent to the production of welded structures. With the correct real implementation of this
method, a major part of the time spent unmaking the deformations caused by the welding of
structures can be saved, reducing the construction time and therefore reducing the construction
costs.

5.2 Future Work

Although this dissertation covers two different aspects related to residual stress induction and
subsequent mitigation, several modifications could be made in order to have better results.
Regarding the modelling itself, a modification to the value of \( \eta \) could be done in order to achieve
a better distribution of values along the negative part of the distribution. Other modifications to the
model could be made in the definition of the material and its elasto-plastic behaviour. The
implementation used is by far one of the simplest, and a refinement would not imply a much
greater simulation run time. Other materials, such as Aluminium of Stainless Steel could be used,
and a comparison between the two could be made.
Regarding the simulation of the cooling process, a much more refined, 3-Dimensional analysis could be performed. The distribution of the input of the cooling charge after the input of heat, along with the simulation of its movement, could be implemented. With the simulation of a moving cooling charge source, an analysis of the effectiveness of the method with the variation of the speed of input would also be of interest.

Several real life experiments could be performed, in a controlled environment, to attest the veracity of the results obtained in the simulations performed in this dissertation. For that, a system able to input the cooling charge necessary would have to be devised and produced. Several studies could be performed to identify the best choice of liquefied gas to serve as a mean to input the cooling temperatures. Also, and finally, since this dissertation does not touch the metallurgical side of the method employed, experiments of that matter could be of interest.
6 References


