

Finite Element Analysis for the Design of Cold Roll Forming Lines

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To my family...

“It always seems impossible until it is done”

Nelson Mandela

Abstract

Cold Roll forming is a continuous process whereby flat metal strips are gradually bent by successive rotating rolls until the final section of the desired profile is obtained. This process is widely used in the automotive industry because it allows the mass production of profiles with different levels of complexity and with high productivity.

This dissertation aims to simulate, study and optimize one of the roll forming processes present in the facilities of the company Coproget S.r.l., intended for the production of beams for rear bumpers of a commercial van. The simulation software used during this project was COPRA® FEA RF and the beams under study correspond to a C-profile made of a high strength steel (Docol®1400M). The goal of this project is to improve the quality of the parts produced through the study of solutions capable of reducing the springback effect on the profile and capable of reducing the magnitude of common defects in profiles produced by the roll forming process, namely end flare and twist, while respecting the dimensional and geometric tolerances and the mechanical behaviour of the profile.

Initially, the simulation model of Coproget's roll forming line was designed using the COPRA® RF software, based on the roll design made in Autocad software. Subsequently, the model of the company's roll forming process was developed and simulated using the COPRA®FEA RF software. Based on these simulations, a comparative analysis was performed between the behaviour of the profile along the simulated line and the behaviour of the profile along the experimental line in order to understand what adjustments needed to be made to obtain an accurate simulation of the C-profile and to reduce the defects present on it.

Subsequently, a parametric study consisting of 11 simulations considering the first ten stations of the roll forming process was performed. This study arose from the need to analyse the influence of different parameters on the behaviour and final geometry of the formed profile, as well as the need to understand which parameters were most appropriate for the design of an accurate and optimized simulation of the C-profile. The parameters analysed in this study included the number of stations, the radius-to-thickness ratio of the profile, the roll diameter, the use of driven (friction) rolls, the part cut type (pre-cut or final cut) and the use of deformable shafts. Special attention was given to the analysis of the longitudinal and transverse residual stresses through the thickness and width of the sheet, the CPU time of the simulations, the three-dimensional defects observed in the profiles obtained, as well as their final geometry.

Based on the literature review and the parameters analysed in the parametric study, improvements were made to both the process design and the accuracy of the simulations in order to obtain a C-profile with better quality than the C-profile currently produced.

Finally, the optimized process developed was validated through a comparison between the defect measurements observed in the simulated C-profile and the defect measurements observed in the experimental C-profile. With these measurements it was verified a reduction of the profile final angles for three of the four profile bends (minimum reduction of 17.7% and maximum of 74.1%), a reduction of the end flare for all bends except for one bend of the lead end and one bend of the tail end of the profile (minimum reduction of 5.1% and maximum of 56%) and also a reduction of the twist angle by 3°.

Keywords: Cold roll forming, Bending, High strength material, Residual stresses, Three-dimensional defects, Rear bumper, C-profile, Roll design.

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Resumo

A perfilagem é um processo contínuo através do qual chapas metálicas planas são dobradas gradualmente por sucessivos rolos rotativos até a secção final do perfil pretendido ser obtida. Este processo é amplamente utilizado na indústria automóvel porque permite a produção em massa de perfis com diferentes níveis de complexidade e com elevada produtividade.

A presente dissertação visa simular, estudar e otimizar um dos processos de perfilagem presente nas instalações da empresa Coproget S.r.l., destinado à produção de vigas para pára-choques traseiros de uma carrinha comercial. O software de simulação utilizado durante este projeto foi o COPRA® FEA RF e as vigas em estudo correspondem a um perfil em C constituído por um aço de alta resistência (Docol®1400M). O objetivo deste projeto é melhorar a qualidade das peças produzidas através do estudo de soluções capazes de reduzir o efeito do *springback* no perfil e capazes de reduzir a magnitude de defeitos comuns nos perfis produzidos pelo processo de perfilagem, nomeadamente, o *end flare* e o *twist*, respeitando as tolerâncias dimensionais e geométricas e o comportamento mecânico do perfil.

Inicialmente foi concebido o modelo de simulação da linha de perfilagem da Coproget através do software COPRA® RF, com base no *design* dos rolos efetuado no *software* Autocad. Posteriormente, o modelo do processo de perfilagem da empresa foi desenvolvido e simulado utilizando o software COPRA®FEA RF. Com base nestas simulações, foi realizada uma análise comparativa entre o comportamento do perfil ao longo da linha simulada e o comportamento do perfil ao longo da linha experimental, a fim de se compreender quais os ajustes necessários a realizar para a obtenção de uma simulação precisa do perfil em C e para a redução dos defeitos nele presentes.

Posteriormente, foi efetuado um estudo paramétrico composto por 11 simulações considerando as primeiras dez estações do processo de perfilagem. Este estudo surgiu da necessidade de se analisar a influência de diferentes parâmetros no comportamento e geometria final do perfil conformado, bem como da necessidade de se compreender quais os parâmetros mais apropriados para a conceção de uma simulação precisa e otimizada do perfil em C. Os parâmetros analisados neste estudo incluíram o número de estações, o rácio raio/espessura do perfil, o diâmetro dos rolos, a utilização de rolos acionados (fricção), o tipo de corte da peça (pre-cut ou final cut) e a utilização de veios deformáveis. Foi dada especial atenção à análise das tensões residuais longitudinais e transversais através da espessura e da largura da chapa, ao tempo de CPU das simulações, aos defeitos tridimensionais observados nos perfis obtidos, bem como à geometria final dos mesmos.

Com base na revisão bibliográfica e nos parâmetros analisados no estudo paramétrico, foram efetuadas melhorias quer ao nível do *design* do processo quer ao nível da precisão das simulações, a fim de obter um perfil em C com melhor qualidade do que o perfil em C atualmente produzido.

Finalmente, o processo otimizado desenvolvido foi validado através de uma comparação entre as medições dos defeitos observados no perfil em C simulado e a medição dos defeitos observados no perfil em C experimental. Com estas medições verificou-se uma redução dos ângulos finais do perfil para três das quatro dobras do perfil (redução mínima de 17.7% e máxima de 74.1%), uma redução do *end flare* para todas as dobras exceto para uma das dobras da extremidade da frente e outra na extremidade de trás do perfil (redução mínima de 5.1% e máxima de 56%) e ainda uma redução do ângulo de *twist* em 3°.

Palavras-Chave: Perfilagem a frio, Flexão, Material de alta resistência, Tensões residuais, Defeitos tridimensionais, Pára-choques traseiro, Perfil em C, Design de rolos.

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List of Symbols

E – Young's modulus

K – Strength coefficient

n – Strain hardening exponent

ε_0 – Material parameters for Swift's hardening law

ε_p – Equivalent plastic strain

μ – Friction coefficient

ν – Poisson's ratio

σ_p – Equivalent Stress

List of Abbreviations

AHSS – Advanced High Strength Steel

CAD – Computer-Aided Design

CNC – Computer Numerical Control

CPU – Central Processing Unit

CRF – Circle-to-Rectangular Forming

DEMEC – Department of Mechanical Engineering

S.R.L – Società a Responsabilità limitata

FE – Finite Element

FEA – Finite Element Analysis

FEM – Finite Element Method

FEUP – Faculty of Engineering of the University of Porto

FP7 – Seventh Framework Programme

FRF – Flexible Roll Forming

H2020 – Horizon 2020

HSS – High Strength Steels

NURBS – Non-uniform rational B-spline

PoliTO – Polytechnic of Turin

RF – Roll Forming

SRF – Strip to Rectangular Forming

UHSS – Ultra High Strength Steel

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1 Introduction

The present dissertation was developed during an internship of 6 months at Coproget's S.R.L facilities, Italy, in a partnership with the Department of Mechanical and Aerospace Engineering (DIMEAS) of the Polytechnic of Turin (PoliTO), Italy, and with the Department of Mechanical Engineering (DEMec) of the Faculty of Engineering of the University of Porto (FEUP), Portugal. Furthermore, this dissertation is part of the specialization of Materials and Technological Processes of the Master's in Mechanical Engineering. This chapter presents the company where the internship took place, the Polytechnic of Turin, context of the project, the background and the current challenges of the project, the objectives of the project, the planning and methodology used and also the structure of the dissertation.

1.1 Partners

This subsection provides a brief presentation of the company as well as the university where the internship took place, for a better understanding of the internship context.

1.1.1 Coproget S.R.L.

Coproget S.r.l is a company based in Turin, specialized in the design and manufacture of tooling, special purpose machinery and automated production lines for the cold processing of sheet metal and profiles. Currently, Coproget S.r.l leads a group of several companies (the Coproget Group) focused on machine building.

Coproget S.r.l started in 1974 initially as a toolmaker, but quickly expanded in terms of type of production, quality, and service. Currently, Coproget S.r.l supplies production lines all over the world. As a machine builder Coproget S.r.l covers a wide range of basic technologies in the sheet metal industry, such as: cutting, forming, bending (stretch bending) and assembly. In addition, Coproget S.r.l is able to produce everything from stamping tools to complete key turn production lines. However, its core business focuses on parts based on roll formed or extruded profiles. The parts produced in Coproget S.r.l are applied in various sectors such as aerospace, logistics, energy, construction, furniture, motorcycles/bicycles and agriculture, being its main application in the automotive industry (private and commercial vehicles).

Given the experience acquired in roll forming and stretch bending processes, Coproget S.r.l. has also opened a new division dedicated to customer service. Furthermore, the constant search for continuous improvement through research and innovation has enabled the company to collect 9 patents. Coproget's mission is primarily to help its customers build their cars more accurately, cheaply and quickly, i.e. better (Coproget S.R.L 2014; Coproget Group 2018).

As represented in Figure 1, the internship conducted during this dissertation, took place in two of Coproget's facilities, Coproget I and Coproget II. Coproget I is where the administrative department, the mechanical design department and the automation department are located. The mechanical design department is the section of Coproget I where the simulations that will be presented later in this dissertation were performed. In turn, the Coproget II, is the place where the roll forming line that serves as base to the study performed in this dissertation is located, and it is there that most of the production stages of the beams for car bumpers are performed.



Figure 1– Illustration of Coproget's logo and the two Coproget facilities where the internship took place:
(a)Coproget I, (b) Coproget II.

1.1.2 Regio Politecnico di Torino

Regio Politecnico di Torino (Royal Polytechnic of Turin) is an Italian state university, located in Turin (Piedmont region), specialized in engineering, architecture, design and urban planning studies (Figure 2). It was founded as institution in 1906, but its origins are older. Politecnico was preceded by the Scuola di Applicazione per gli Ingegneri (Technical School for Engineers) founded in 1859 after the Casati Law, and by the Museo Industriale Italiano (Italian Industry Museum) founded in 1862, under the aegis of the Italian ministry of agriculture, trade and industry. Every year, Politecnico di Torino draws up around 800 contracts with industries, government-funded institutions and local organisations. In addition, its participation in many national and international projects has allowed it to accrue a great experience. For example, in the FP7, it had more than 230 projects approved and in H2020 programme it already has 167 approved projects. During its existence, it has been one of the most prestigious Italian and international universities in training, research, technology transfer and services in all sectors of architecture and engineering. Moreover, it is a reference point for training and research in Italy and Europe, presenting around 35500 students from more than 100 countries and employing around 900 people among professors and tenured researchers (Politecnico di Torino n.d.).



Figure 2 – Politecnico di Torino Logo (Politecnico di Torino n.d.).

1.2 Research and project context

The present thesis arises from the need to redesign and optimize a cold roll forming line at Coproget S.R.L.'s facilities, which is used for the production of C section beams. These beams obtained from Coproget's roll forming process compose the rear bumpers of a commercial van model produced by the multinational automobile production company Stellantis.

The material of the beams produced by this roll forming line is Docol1400M steel. This steel is considered an AHSS (Advanced High Strength Steel) and is therefore an extremely difficult steel to form properly, since it has high springback angles as a consequence of its high strength.

Due to the high difficulty in forming profiles with this type of material, the beams produced by Coproget's roll forming line present significant defects such as springback, end flare and twist. The magnitude of these defects must be reduced to obtain a part with higher quality. Therefore, the goal of this project is first to create a model of Coproget's roll forming line using Copra RF software that is able to accurately simulate the C-profile produced by the company. This model is obtained through a process of trial and error in which the simulated profile is validated or rejected based on comparisons made with the geometry of the experimental profile in each of the forming stages. Based on these comparisons, it is intended to make design and positioning adjustments to the simulated line in terms in order to bring the simulation closer to reality. The experimental line provides a direct view of the process and allows the validation of the models developed for Coproget's roll forming process.

For the optimization and improvement of the process it is also fundamental to perform a parametric study for the C-profile under study in order to understand the influence that different parameters have on the final geometry of the part produced and thus understand which parameters best fit the profile under study, that is, which parameters allow a more accurate simulation of the profile. Based on the simulations performed by the COPRA FEA RF software and taking into account the most appropriate parameters for the C-profile, the intention is to analyse the behaviour of the profile in the various forming stages in order to verify which stations present problems such as inadequate forming (cross-section of the profile at the station under analysis is far from the desired cross-section of the flower) or strong contact between the profile outer flanges and therefore need to be improved. These improvements focus mainly on the roll design level and must take into account the steel properties, the dimensional tolerance requirements, the profile cross sections, possible roll wear problems and the surface quality of the produced part.

After obtaining a simulated process where the forming is adequate at each of the stations and where the contact between the outer flanges is minimal, it is also intended to study the implementation of solutions and alternatives on the simulated roll forming line based on the literature and the conclusions drawn from the parametric study in order to reduce the defects present in the profile. Simulation softwares such as COPRA FEA RF are therefore fundamental to test new concepts and ideas in a cost-effective way.

1.3 Background and Current Challenges

Cold roll forming is a continuous process that enables the production of profiles with the desired cross-section by progressively bending metal strips along several stations with rotating rolls. This process has applications in a wide range of industries, since it not only allows a wide variety of cross-sections to be obtained, but also high production rates.

The cold rolling process started to be used in the 14th century for gold and silver applications and the first rolling mills were designed in 1480 by Leonardo da Vinci. In turn, at the end of the 18th century the process of cold rolling of steel appeared, being widely used only in the 19th century. This process enabled a wide variety of metals such as aluminium, copper, titanium and special alloys to be formed and made commercially available (Halmos 2006). At an early stage, little importance was given to the behaviour of the material during the process and so the design of the rolls and the process was mainly based on the experience of the designers. Only in the 20th century, cold roll forming became an established industrial process (Martins 2018). After World War II, the demand for formed metal parts has increased and so roll forming has become more popular. Due to the high productivity of roll forming lines and the increase in labour costs more and more sheet metal products designed for brake forming have started to be roll formed. In turn, in 1950 other operations began to be incorporated into roll-forming lines, such as pneumatic press applications, in-line welding and the use of pre-punching and pre-painting metals. In the late 1970s and early 1980s computer aided roll design systems were introduced and in the 1990s programmable controllers and computers started to be used to

control the lines (Halmos 2006). Over the years, increased competitiveness has led to the need to reduce the number of operators and to improve the quality of the products. As such, the products began to be manufactured at higher production rates, at lower cost and with increasingly tighter material tolerances. In the present century, the roll forming industry is still showing high growth (Halmos 2006). Nowadays, there is a wide variety of CAD and FEA programs suitable for the design and simulation of roll forming processes, including forming rolls, roll pass sequences and flower design. Developments in numerical techniques have led to a reduction in the time required to design the process, allowing new products to be introduced to the market sooner. Finite element analysis has thus become fundamental to predict and avoid defects in the parts, as well as to reduce strains (Martins 2018). In the present thesis COPRA® RF design software and COPRA® FEA RF simulation software are used. The use of these software allows the production of reliable and efficient models. Since COPRA® FEA RF is usually used in an industrial context, simulation time is one of the most relevant parameters because it has a direct impact on productivity and efficiency.

1.4 Goals

The main purpose of the present thesis is to study a solution to minimize the springback effect and some defects like end flare and twist that are visible on the beams for van bumpers produced by the Coproget's cold roll forming process. In order to achieve this goal, several other objectives must be fulfilled:

- Understand the fundamental principles of cold roll forming as a manufacturing process, which means understanding the types of variables, the types of deformations, the type of defects common in this process, as well understanding the influence of geometrical and process parameters and material properties on residual stresses and on three-dimensional effects;
- Make predictions of the material's behaviour using Copra RF and Copra FEA software. Therefore, it is fundamental to develop the FEA model of the roll forming process currently existing at Coproget. To do this, a comparison should be made between the behaviour of the simulated profile and the behaviour of the experimental profile for each of the forming stages and based on the observations made, make the respective adjustments to the model. With this it is intended to obtain a model capable of reproducing results similar for the simulated profile, to those observed in the parts produced by this process, in order to allow a better perception of the defects, parameters and residual stresses existing in these same parts;
- Perform a parametric study for the C-profile under study, in order to get a better understanding of the influence of the various parameters on the residual stresses, on the three-dimensional defects present in the part and on the final part geometry obtained. The distribution and magnitude of residual stresses should be evaluated especially in the corner regions, since these areas tend to present the highest residual stress values and the critical areas should be identified. Furthermore, in this study, conclusions should also be drawn about the parameters that allow simulating the C-profile under study in a more accurate and optimized way, in order for the simulations of process improvement to be reliable and efficient;
- Develop and improve the current Coproget's roll forming process in order to obtain a reduction in the magnitude of the defects observed in the parts produced by this process. This improvement must be done based on the results obtained in the parametric study previously done for the profile under study and based on the literature review and on already existing solutions and methods for reducing the defects present in the parts. Furthermore, the process improvement should be done through changes in the geometric and process parameters of the simulation, as well as in the design of the rolls.

- Perform experimental tests on Coproget's roll forming line in order to validate the results obtained from the simulations;
- Compare the magnitude of the observed and measured defects for the experimental profile obtained from the current process, with the magnitude of the observed and measured defects for the simulated profile obtained from the simulated line with the improvement modifications.

Through the analysis of the simulations performed and the experimental results taken from Coproget's roll forming, it is intended to obtain a process with lower duration, with lower associated costs and capable of producing parts with better mechanical performance and better dimensional and geometric precision, being therefore very useful for the company.

1.5 Planning and Scientific Methodology

The present research arises from Coproget's need to improve the mechanical performance and dimensional and geometric accuracy of the beams currently produced, by reducing the springback effect and the defects observed in them, such as end flare and twist. The research plan to be achieved is divided into 8 tasks with defined deadlines as shown in Table 1.

- Task 1: State of art review;
- Task 2: Software learning;
- Task 3: Analysis and measurement of the various components that compose the roll forming line under study, as well as the measurement of defects present in a part obtained from it;
- Task 4: Design of all rolls and side bars present in Coproget's roll forming line using Autocad software;
- Task 5: Development of the simulation model of Coproget's current roll forming line for the production of beams for van bumpers and analysis of the respective model simulations;
- Task 6: Parametric study up to station 9 of Coproget's roll forming process.
- Task 7: Process improvement simulations with the aim of reducing the defects present in the parts produced by Coproget's roll forming process;
- Task 8: Reports (MSc dissertation writing and presentations preparations).

Table 1–Timeline for execution of tasks.

	March	April	May	June	July	August	September
Task 1							
Task 2							
Task 3							
Task 4							
Task 5							
Task 6							
Task 7							
Task 8							

1.6 Dissertation Structure

The present dissertation is divided into 7 chapters and is structured as follows:

- **Chapter 2 – Literature Review** introduces the roll forming process, as well as its variables, the traditional and the flexible one. In this chapter, the main types of deformation are also discussed, as well as the most common three-dimensional defects derived from the roll forming process. In addition, the typical residual stresses in a final product obtained by the roll forming process are presented. Subsequently, the importance of numerical simulation particularly in the cold rolling process is clarified and the software used for modelling, numerical analysis and simulation during this project is explained. Finally, the various steps required for the design, modelling and simulation of a roll forming line are presented;
- **Chapter 3 – Dissertation Context and Methodology** provides a description of the part to be studied during this dissertation, the beam for car bumpers. Its function, the characterization of the materials that constitute it and the entire manufacturing process until it is obtained, are described in this chapter. Furthermore, the measurements of springback and of the end-flare and twist defects present in the final part obtained from the process are presented, as well as a description of the methodology used for these measurements;
- **Chapter 4 – Numerical Simulation of Coproget's current C-profile** presents the stages in the development of the simulation model of the old Coproget roll forming line as well as the model of the current line, in order to clarify the modifications implemented by the company in the line over the years. In addition, a comparison was made between the behaviour of the current simulated profile and the behaviour of the current experimental profile for the various forming stages, in order to identify the differences between them and thus make the necessary adjustments to the model in order to obtain an adequate simulation of the profile under study. The simulation models were created using Copra RF software and the simulations were run on Copra FEA software;
- **Chapter 5 – Parametric Study of Coproget's current C-profile** provides a parametric study for the first 10 stations of Coproget's roll forming process, where several parameters are studied, such as material properties, number of stations, profile radius/thickness ratio, roll diameter, use of driven rolls, type of sheet cutting and use of deformable shafts, in order to understand their influence on the geometry, three-dimensional defects and residual stresses of the final profile obtained;
- **Chapter 6 – Improvement of Coproget's current C-profile** presents an analysis through numerical simulations of some modifications implemented in the simulated Coproget's roll forming line in order to reduce springback and defects such as end flare and twist visible in the beams currently produced by Coproget. These modifications were made based on the results obtained from the parametric study, on some defect reduction methodologies present in the literature review and also on some advice provided by a Turkish company with experience in numerical simulation of roll forming processes named Linde Opsan ;
- **Chapter 7 – Conclusions** is divided into two parts. The first part presents the most relevant conclusions of this research, and the second part proposes recommendations and future research in order to improve the project developed so far.

2 Literature Review

This chapter analyses the available literature regarding the most relevant topics related to this dissertation project. Initially, an introduction to the roll forming process is presented. This is the main topic of this project, since all the simulations performed, as well as all the results obtained from them, are intended to be applied in the improvement of this process. Within this topic, the two variants of the roll forming process are also described, the conventional roll forming and the flexible roll forming. Furthermore, an analysis is performed on the deformation modes of the sheet, as well as on the most common defects and residual stresses, in order to facilitate the understanding of the effects of the manufacturing process parameters on the material and to elucidate which are the most relevant process criteria to take into consideration during the simulations. Finally, an introduction to the finite element method analysis is presented in order to facilitate the understanding of the advantages of numerical simulations, as well as to clarify the capabilities of the software used in this research.

2.1 Traditional Roll Forming

Roll forming is a continuous sheet forming process in which a flat semi-finished product (workpiece), such as sheet or strip is bent incrementally into the desired shape by sets of rotating rolls (Buddhika Abeyrathna et al. 2017). Therefore, during the roll forming process the workpiece is continuously fed through a rolling mill consisting of a series of rolls stands. Each stand includes at least two "shaped" work rolls whose complexity intensifies as the workpiece advances in the rolling mill. Consequently, the complexity of the bending radius applied to the part also increases (Halmos 2006; Taylor 2016).

The friction involved in the contact between the sheet and the rotating rolls enables the longitudinal movement of the sheet. The rotation speed of the rolls can vary from 0.5m/min to 250m/min and is adjusted to obtain a constant flow of material. The most commonly used speed range for rolls is between 25 and 30 m/min(Y. Wang et al. 2022). Therefore, these rolls impose bending stresses, which plastically deform the workpiece gradually to the desired final geometry (Halmos 2006).

Since this is a pure forming process that applies bending rather than compression, the thickness of the sheet remains constant at room temperature, except at the bending lines where it usually decreases. Subsequently, when the workpiece leaves the rolling mill, it is sectioned into final pieces of the desired length, although it can also be cut before or during the process (Halmos 2006; Taylor 2016).

The traditional Roll forming process only allows to produce profiles with constant cross-sections(Kasaei et al. 2014). However, as represented in Figure 3, bending (or sweeping) stations can be added to the end of the roll forming line to produce curved profiles (Ferreira 2016).



Figure 3 – Examples of bending stations added at the end of the roll forming line: (a) change of shape in one direction; (b) change of shape in two directions;(c) change of shape in three directions. Adapted from(World Auto Steel 2020).

Figure 4, illustrates a traditional roll forming line, where a sheet is gradually bent at each pass in order to obtain the final cross-section of the desired profile.

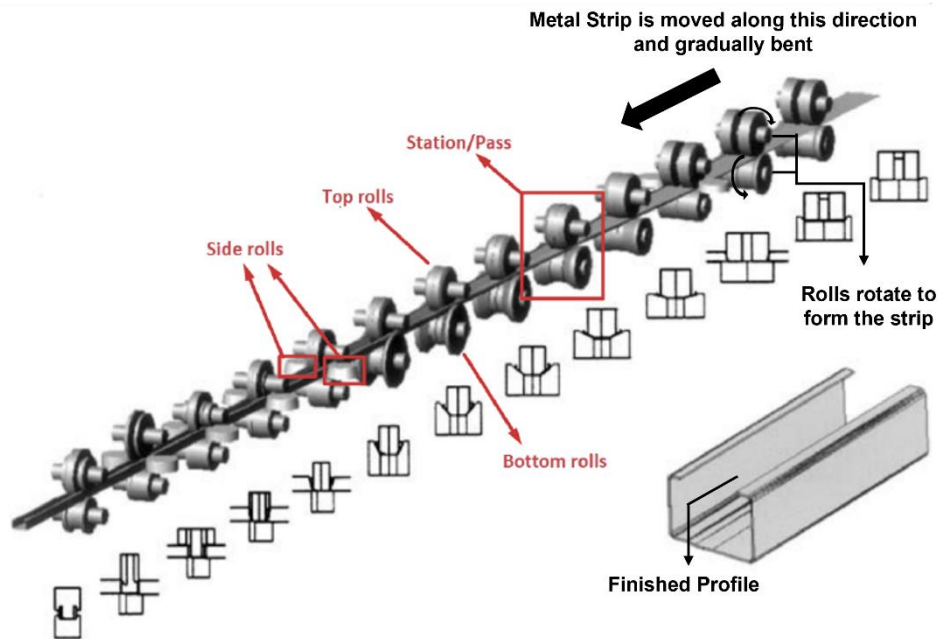


Figure 4 – Schematic representation of a traditional roll forming line where a strip is gradually bent until a finished profile is obtained. Adapted from (Halmos 2006).

A roll forming line can also perform secondary operations such as punching, cutting, flanging, stamping and welding, avoiding additional labour and inventory costs, reducing the space occupied and turning the profile leaving the machine into a completely finished product (Figure 5). In addition, pre-heating or localised in-line heating can also be used (Forte 2021). However, these operations not only increase production time by delaying the continuous feeding of the sheet, but also add value to the product (Halmos 2006).

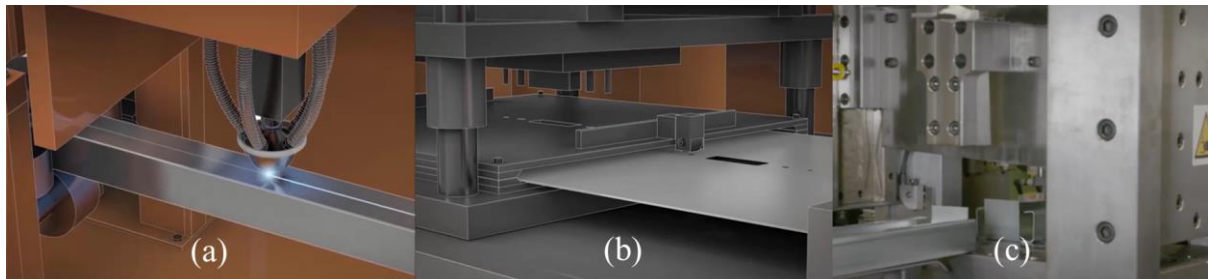


Figure 5 – Examples of secondary processes that can be incorporated into a roll forming line: (a) welding, (b) punching, (c) cutting. Adapted from (World Auto Steel 2020).

The roll forming process can be performed "hot" or "cold" (defined by above or below the recrystallization temperature, respectively). However, cold roll forming is characterised by lower cost and higher production efficiency, as it allows eliminating the equipment, floor space, energy and time needed for heating (Taylor 2016). In the present dissertation only the cold roll forming process will be investigated and therefore, whenever the term "roll forming" is mentioned from now on in this thesis, it will refer to the cold roll forming process.

The RF process brings a wide range of advantages to the sheet metal industry, such as:

- Offers very high cost-effectiveness due to its relatively low tool costs and due to its high production capacity, usually 1500-1800 m per working hour (Groche et al. 2008; GÜNER 2007);
- Allows the application of tight bending radius without crack formation and the production of complex cross-sections (Bui et al. 2006);
- Provides the possibility to process materials that combine high strength with limited ductility at tight radius and with less springback than normally found in bending operations (Buddhika Abeyrathna et al. 2017);
- Produces sections with a higher strength to weight ratio than those that are hot rolled or extruded (GÜNER 2007);
- Does not damage the fine surface finish of the raw material and allows the forming of painted and electroplated material without damage to the coating (GÜNER 2007);
- It exhibits low noise emissions and provides efficient use of material (Groche et al. 2008).

The conventional roll forming has been used for several decades for the manufacture of construction products, where the requirements for dimensional accuracy are not particularly stringent. Conventional roll-formed products are thus mainly structural members for buildings, gutters, roofing, window and door frames, tracks, trailers and containers. However, the roll forming process is also widely applied in the automotive industry, architecture, transportation, and so on (Buddhika Abeyrathna et al. 2017; Bui et al. 2006).

Therefore, CRF process enables the manufacture of a wide range of products with different section geometries, such as quadrate, hat type, corrugated, and non-symmetrical sections (Yan et al. 2014). Figure 6 shows the variety and complexity of profiles manufactured by roll forming.



Figure 6 – Different profiles manufactured by the roll forming process. Adapted from (Nu-Tech Roll Forming 2010).

There is a wide variety of materials that can be used in the roll forming process, from metals to composites and multi-materials. Aluminium, steel, stainless steel and copper are the most commonly used materials and can be pre-painted or precoated before being submitted to this process (Lindgren 2009). In turn, yield strength, tensile strength and elongation are the most important mechanical properties of materials to ensure good results (Forte 2021).

The speed at which a profile can be produced varies between 15 m/min and 185 m/min, depending on the cross-section tolerance, the material and how quickly the machine can be fed with raw material or how quickly the finished product can be taken off the run-out table. In turn, the thickness of the material that can be rolled varies from 0.15 mm to 19 mm (Lindgren 2009).

Another important factor is that in the conventional roll forming, the strips are gradually bent in the transverse direction, occurring longitudinal tension and compression when the sheet enters and leaves the rolls, as shown in Figure 7. This happens, because when the central part normally travels in a straight line, the edge portions often rise vertically and elongate. This type of longitudinal tension depends on the working conditions, such as the number of rolls, roll profiles, and horizontal distance between stands (Yan et al. 2014).

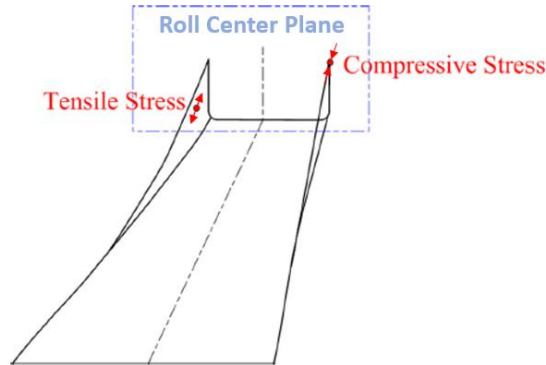


Figure 7 – Tensile and compressive stress in conventional roll forming. Adapted from (Yan et al. 2014).

2.2 Flexible 3D Roll Forming

As previously mentioned, roll forming sections have a constant longitudinal cross-section when produced by the conventional method. However, flexible or 3D roll forming is a manufacturing process developed by Ortic AB approximately 20 years ago, which can produce parts with variable cross-sections by controlling the roll stands with a CNC (Yan et al. 2014; Sedlmaier and Dietl 2018; Lindgren 2009). This process is widely used in the automotive industry to produce profiles with variable cross-sections and to meet the demand for weight reduction (Yan et al. 2014). Therefore, automotive components made from Ultra High Strength Steel (UHSS) and Advanced High Strength Steel (AHSS) that have limited tensile elongation are usually manufactured by this process (B Abeyrathna et al. 2016).

In the flexible roll forming process, the rolls move back and forth in a direction perpendicular to the sheet feeding direction (Sheu et al. 2018). In addition, some rolls remain stationary with an axial rotation, while others have both axial rotation and translational movement to generate the variable width or depth of the parts (B Abeyrathna et al. 2016). Furthermore, as represented in Figure 8, some rolls rotate around their central horizontal axis and around their vertical axis, while others rotate only around their central horizontal axis.

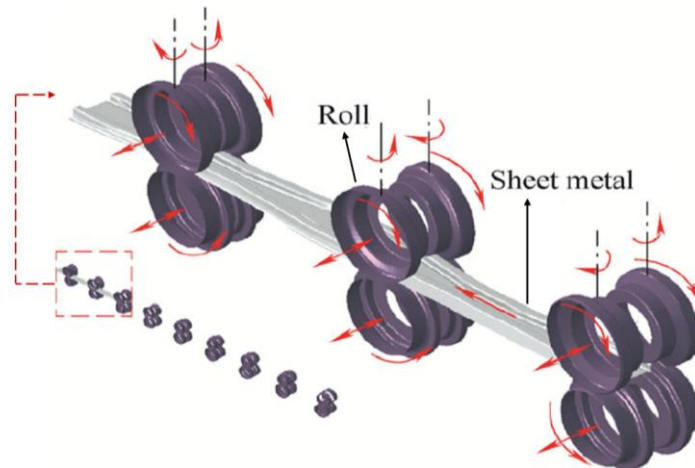


Figure 8 – Schematic illustration of 3D flexible roll forming process. Adapted from (Yan et al. 2016).

The forming rolls position must be such that they always are tangent to the deformed flange to avoid its further deformation. As represented in Figure 9 (a), this is achieved by superposition of a translational and rotational movement of the rolls (Kasaei et al. 2014). Figure 9 (b) shows different profiles with variable cross sections that can be obtained by the flexible roll forming process.

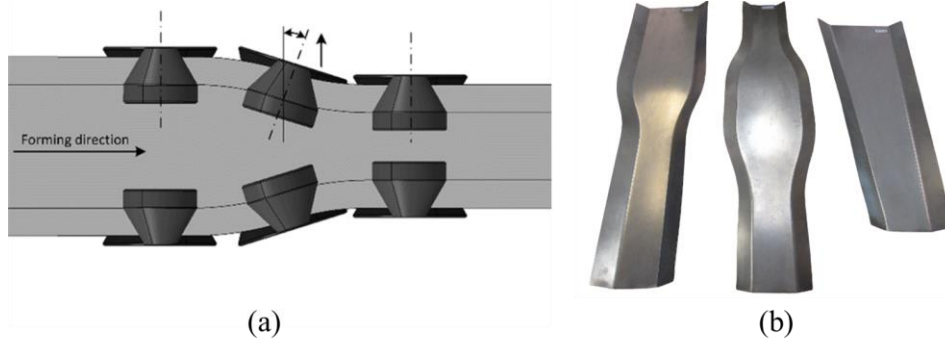


Figure 9 – (a) Schematic representation of the tangency of the forming rolls in relation to the deformed flange; (b) Different profiles with variable cross section produced by 3D flexible roll forming. Adapted from (Kasaei et al. 2021).

The stress and strain state of the flexible roll forming process is also more complex than the conventional one, since the bending lines are not always parallel to the longitudinal axis. The non-uniformity of deformation in this process drastically affects the dimensional accuracy of the product and therefore forming defects such as twist often occur. The main deformation in flexible roll forming is bending, with almost all the plastic deformation produced occurring only in the bending corners. Therefore, the outer layer of the material is subjected to tension and the inner layer is subjected to compression (Yan et al. 2014).

Furthermore, in the flexible roll forming process, the original blank sheet presents some redundant material in the convex arc, while in the concave arc the material is insufficient, which can cause compression or tension on the formed part (Figure 10). Furthermore, too much compression can cause the edge waves at the convex arc, while too much tension in the concave arc can lead to damage or even fracture at the concave arc. As with conventional roll forming, the tensile and compressive stresses at the edge of the flange are greater than those at the bottom. Therefore, the larger the flange and the faster the change in cross-section width, the higher the tensile and compressive stresses (Yan et al. 2014).

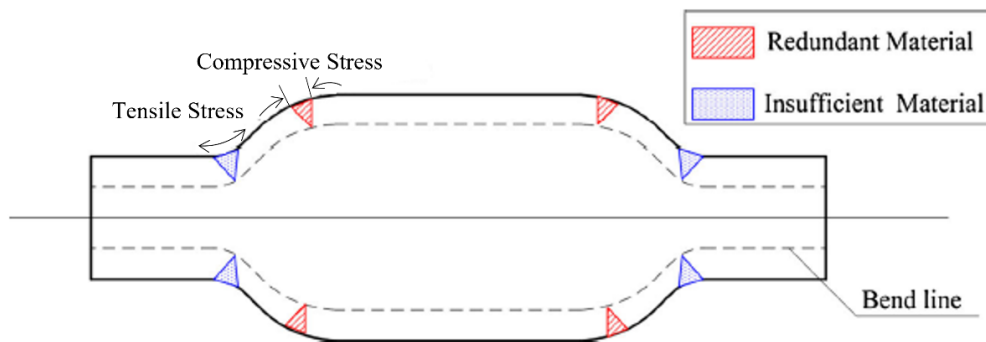


Figure 10 – Representation of the redundant and insufficient material as well as the compressive and tension stresses in flexible roll forming. Adapted from (Yan et al. 2014).

The shear stress in flexible roll forming is also larger than in the conventional roll forming process. During the formation of the variable cross-sections, the rolls move back and forth in the width direction, strongly pushing or pulling the flange material. Thus, this movement gives rise to tension or compressive stresses that are perpendicular to the bending line. In addition,

the existing bending moment also causes stress or compression in the perpendicular direction to the bending line. In turn, these normal stresses (tension and compression) in different directions originate shear stresses, as represented in Figure 11. Furthermore, shear stress at the bending corner is the main cause of fracture in the flexible roll forming process and has an important influence on the springback deformation of the cut-off end (Yan et al. 2014).

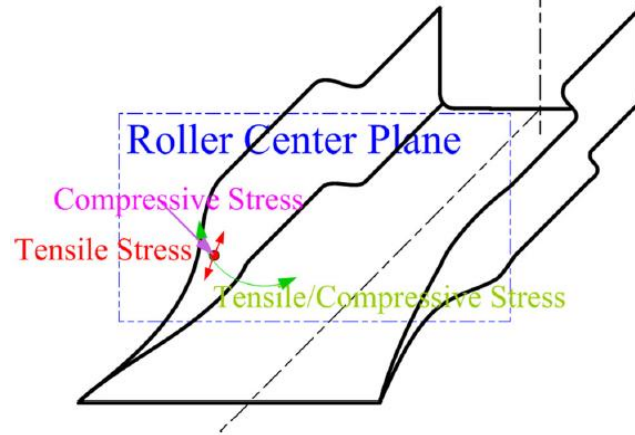


Figure 11– Normal Stresses (Compressive and Tensile stresses) in flexible roll forming (Yan et al. 2014).

The main failure modes associated with flexible roll formed profiles are flange wrinkling and bow (web warping). Wrinkling is an unstable deformation due to excessive longitudinal compression at the strip edge (Kasaei et al. 2014). In turn, bow is the variation from a straight line in the vertical plane (Halmos 2006). Wrinkling and bow, appear due to geometric deviations in the transition zones of the profile between the initial metal strip and the roll formed profile, such as the concave zone and the convex zone, as shown in Figure 12 (J. C. Park et al. 2014).

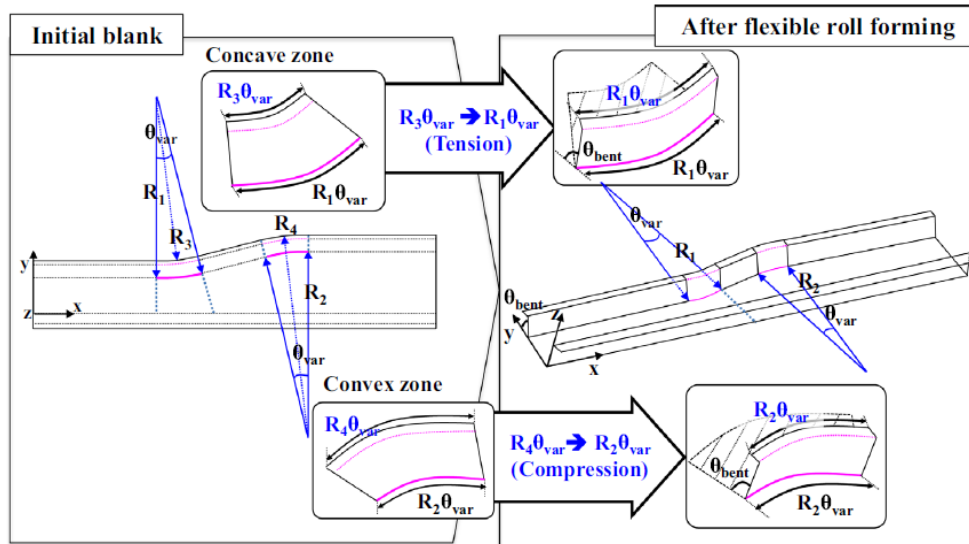


Figure 12 –Illustration of the geometric deviations in the transitional zone of a profile with variable cross sections between the initial strip and the profile obtained from the flexible roll forming process (J. C. Park et al. 2014).

Therefore, in order to compensate for the geometric deviations between the initial metal strip and the roll formed profile, the transitional zones of the profile with variable cross sections must be stretched in the concave zone and compressed in the convex zone along the longitudinal direction (J. C. Park et al. 2014).

2.3 Types of Deformation During Roll Forming - Metal Strip Behaviour

As previously mentioned, during the RF process the sheet metal, undergoes different types of deformations that influence the quality of the final product. A characteristic of the RF process is the creation of a three-dimensional forming zone when the sheet is bent in the transverse direction while moving in the longitudinal direction (M Moneke and Groche 2021).

Therefore, in the RF process, the main types of deformation are elongation and bending in the transverse and longitudinal directions, as well as shear along the strip and through the strip thickness. However, only transverse bending is the desirable type of deformation, while the others are usually redundant deformations that lead to the appearance of shape defects (Akbar Abvabi 2014). Therefore, in this subsection the different forming mechanisms involved in the RF process are described.

2.3.1 Transversal Bending

The most common of all sheet forming processes is the bending process along a straight line (Marciniak et al. 2002). In the roll forming process, the desired shape of the product is obtained mainly by applying progressive transverse bending using a series of contoured rolls.

Therefore, transverse bending is the most important and indispensable deformation for metal strips, since it is this deformation that allows to originate each of the cross-sections required for the final product (Figure 13) (Halmos 2006).

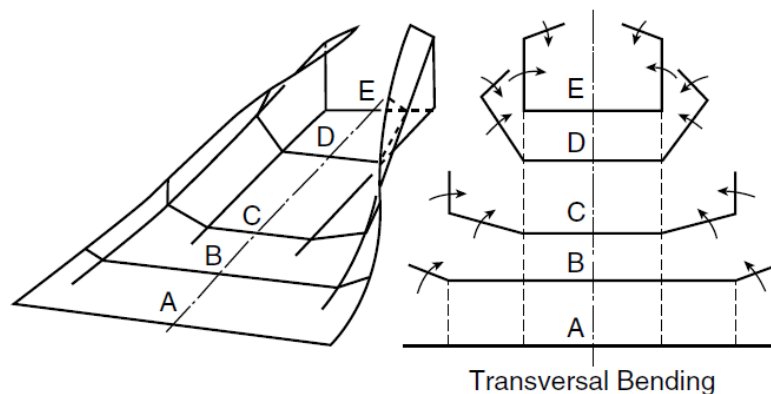


Figure 13 – Transversal bending of metal strip during the roll forming process (Halmos 2006).

However, during the roll forming process, the metal strips are subject to many other redundant deformations that are superimposed on the transversal bending, significantly influencing the formation of the cross-section and shape of the product and causing problems during the process (Halmos 2006). These redundant deformations are described in the following subsections.

2.3.2 Transversal Elongation and Shear in Strip's Plane

Products with wide cross-sections are roll formed from wide metal coils. In these cases the force required to pull the edge and intermediate portions towards the centre of the semi-formed cross-section is quite large, since a considerable amount of shear deformation in the plane of the coil is required to shift the flat portions in the transverse direction. This transverse shifting is usually induced by transverse bending of the central portions of the coils (Figure 14 (a)) (Halmos 2006).

Futhermore, considerable transverse elongation can occur at the bending lines if the convex roll is pushed against the coil surface with such a force that it causes a local reduction in metal thickness. The transverse tensile force created by transverse bending has a strong effect on

transverse elongation. In addition, when the top of the convex rolls exerts an excessive force on the inner surface of the bending corner, a sort of bulging deformation occurs, and there is both longitudinal and transverse elongation (Figure 14(b)) (Halmos 2006).

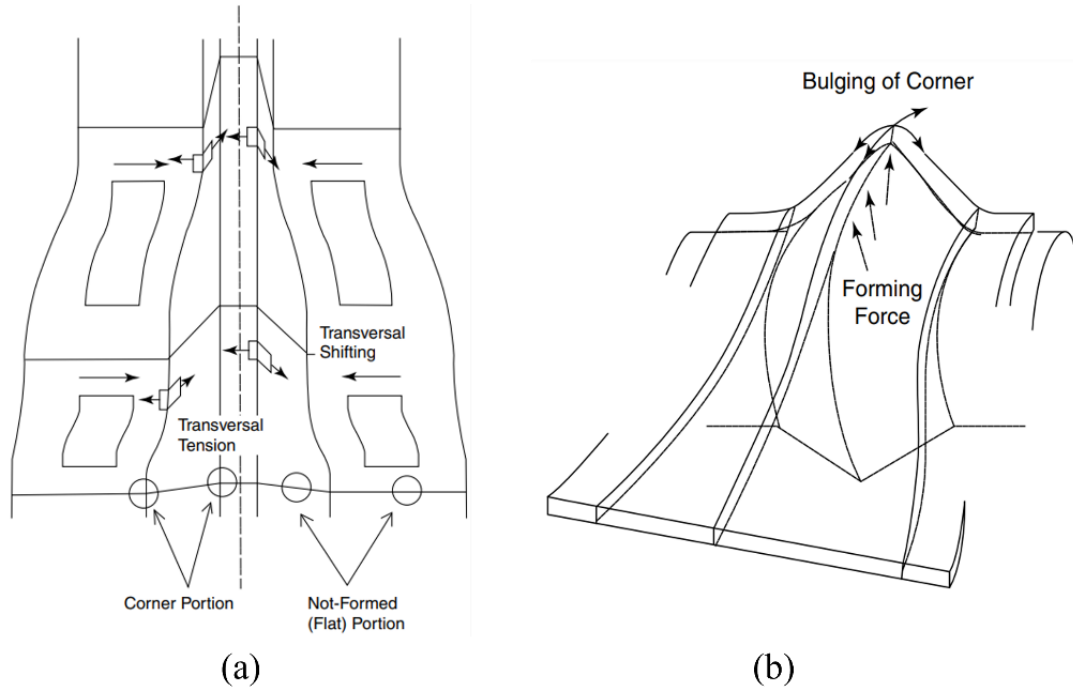


Figure 14 – a) Transverse shifting induced by transverse bending of the central portions of the coils, b) Bulging deformation on the inner surface of the bending corner. Adapted from (Halmos 2006).

Furthermore, when the metal strip is driven into the roll gap, the flange of the profile is bent upwards and its elements are sheared. In turn, when the metal strip exits the gap between the forming rolls, the flange elements are sheared back and residual shear stresses remain in the flange (Matthias Moneke and Groche 2018).

Therefore, Figure 15 shows the shear deformation of elements and the corresponding shear stresses within the flange during roll forming.

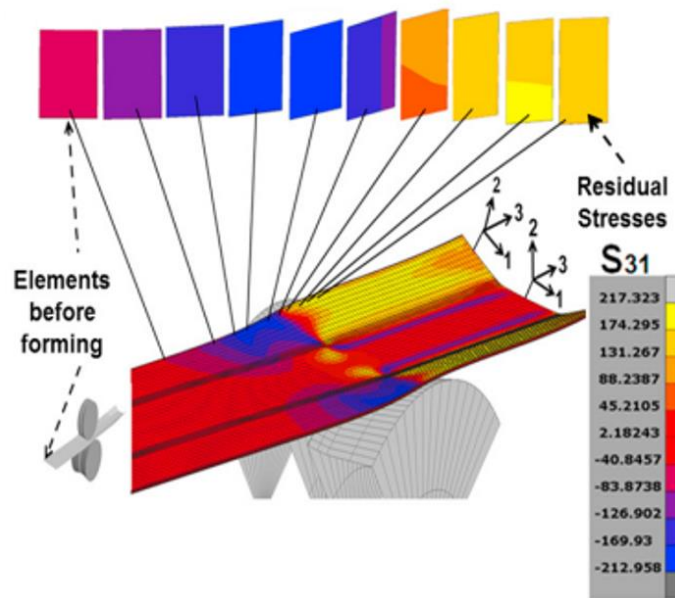


Figure 15 – Representation of the shear deformation of the strip elements, as well as the corresponding shear stresses, during the roll forming process. Adapted from (Matthias Moneke and Groche 2018).

2.3.3 Longitudinal Elongation

In the RF process, each portion of the strip shifts, moves and deforms in both vertical and horizontal directions. Furthermore, the transverse edges and adjacent areas of the strip usually move along flow lines which are longer than those for the center and intermediate portions in the bending zone ((Figure 16(a)) (Halmos 2006). This phenomenon is due to the fact that in the roll forming process, forming takes place not only on the forming tools, but also between each forming stand (Lindgren 2009). Therefore, the center part of the strip generally moves in a straight line, whereas the edge portions usually move vertically and at the same time horizontally toward the centre of the cross-section (Figure 16(b)) (Halmos 2006).

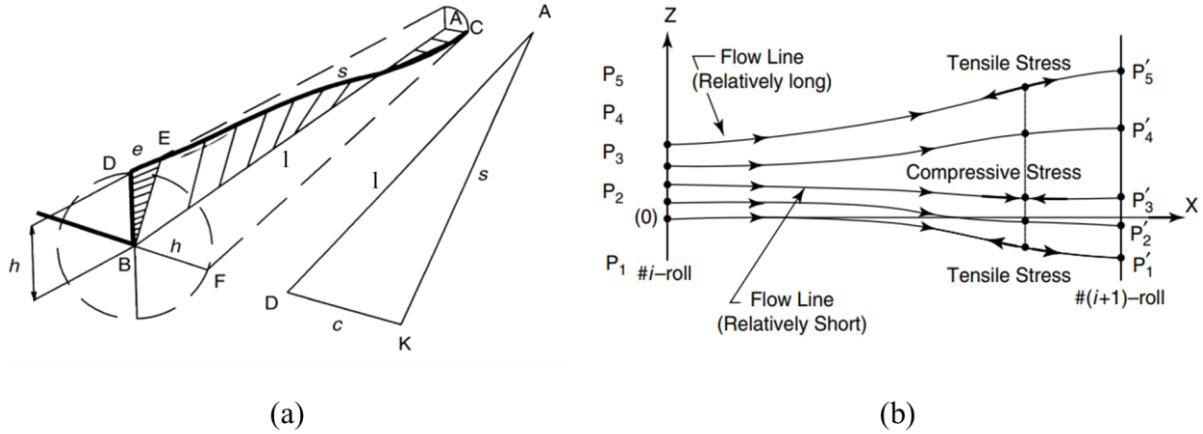


Figure 16 – (a) Schematic representation of the theoretical edge travel of a strip formed into a “U” channel (l: length of the bend line, h: height of the leg, s: helicoidal path travelled by the edge from point C to D, c: length of arc from point F to D, e: elongation) (Lindgren 2009), (b) Representation of the flow lines for different strip portions (P_i) (Halmos 2006).

Due to this vertical rising and horizontal shifting, the edge portions generally undergo an elongation, while the center and intermediate portions undergo a shrinkage in the longitudinal direction (Halmos 2006). The theoretical elongation (difference in length between “l” and “s”) can be expressed in percentage as represented in equation 2.1:

$$e = \frac{s-l}{l} \times 100\% \quad (2.1)$$

Therefore, the flange is subjected to homogeneous longitudinal strains (constant over the sheet thickness) in addition to transverse bending strains, which implies a longer path for the forming curve of the band edge than for the forming curve of the nondeformed profile web (M Moneke and Groche 2021). These generated strains should not be plastic, in order to avoid large longitudinal residual stresses in the finished profile (Lindgren 2009). The level and distribution of longitudinal edge strain are prominent factors in common roll forming defects such as longitudinal bowing, twisting and camber. The peak longitudinal strain depends, among other things, on the flange length, the sheet thickness, the web width, the material yield strength, the roll diameter, the station distance, the calibration method and the bending angle (M Moneke and Groche 2021). Furthermore, the tension or compression caused by the rolls, also influences the longitudinal forces between stands (Buddhika Abeyrathna et al. 2017).

In turn, the relative length of the flow line along which each portion of the strip moves along the several roll stands, depends upon the working conditions, such as the number of rolls, roll profiles, roll positions, horizontal distance between supports, product cross-section geometry and forming angle (Buddhika Abeyrathna et al. 2017).

The deformation length is an important parameter to take into account when determining the peak longitudinal strain as well as the minimum distance between stations (Figure 17) (Buddhika Abeyrathna et al. 2014b).

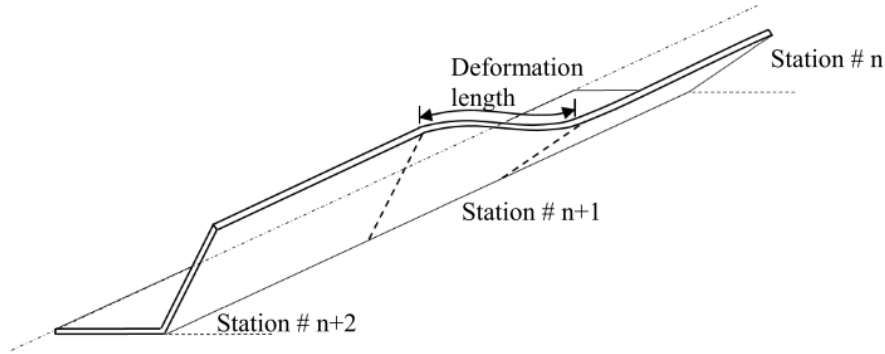


Figure 17 – Deformation length(Buddhika Abeyrathna et al. 2014b).

One of the main goals for process designers is to try to maintain the peak longitudinal edge strain under the elastic limit of the material in order to provide a reduction in geometric defects and residual stresses (Buddhika Abeyrathna et al. 2014b).

As illustrated in Figure 18, during the RF process, the sheet follows a real path that is not the same as the theoretical path, due to the springback (Ferreira 2016). Therefore, the real elongation is usually higher than the theoretical elongation (calculated by Equation 2.1). In turn, if this elongation exceeds the elastic limit, then the permanently strained edges of the final product will be wavy or the product will exhibit a bow, camber or twisting. Therefore, materials with higher yield strength and lower elastic modulus are less likely to be wavy (Halmos 2006).

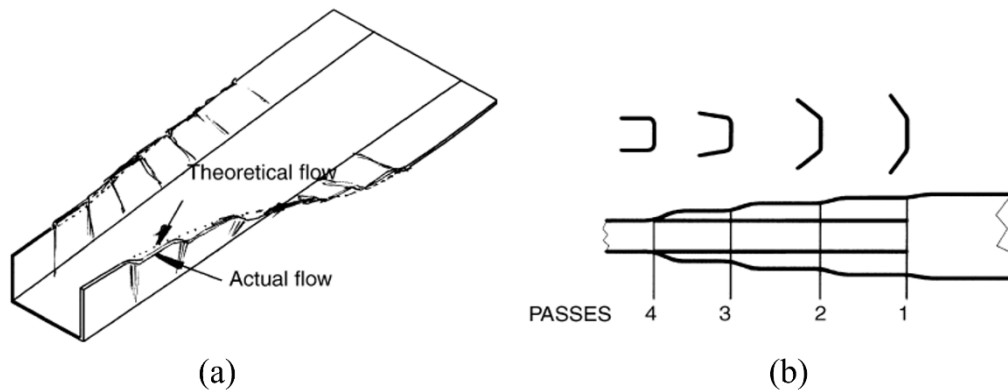


Figure 18 – (a) Real and theoretical flow of the sheet, (b) Representation of the cross-section deformation along the number of passes. Adapted from (Halmos 2006).

2.3.4 Longitudinal bending and bending back

At the beginning of the forming process, the metal strip is lifted upwards in longitudinal direction by the lower rolls, before being directed into the roll gap through contact with the upper roll (M Moneke and Groche 2021).

As the strip enters the roll gap, the several strip portions move along individual spatial flow lines. Thus, a longitudinal inclination is induced in each of these portions. These flow lines have different inclinations, since some are close to the periphery of the convex roll and others are close to that of the concave roll (Halmos 2006).

Thereby, as represented in Figure 19, the flange moves first along a concave forming curve where it is concavely bent around axis b-a in longitudinal direction and then along a convex forming curve where it is convexly bent around axis b-c following the shape of the lower roll(Matthias Moneke and Groche 2018). The contact line between the flange and bottom roll then starts at the web edge and extends towards the bending zone (M Moneke and Groche

2021). Another factor to take into account, is that during convex bending, significant plastic shear and longitudinal strains occur in the a-b-c area (M Moneke and Groche 2021).

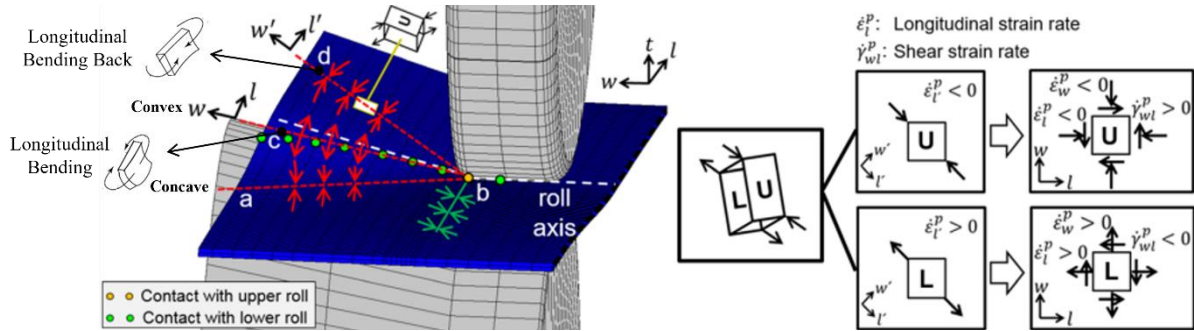


Figure 19 – Longitudinal bending of metal strip during roll forming process (U:Upper side, L:Lower side).Adapted from (M Moneke and Groche 2021)

After the initial bending of each strip portion occurs, the strip is bent back (around the axis b-d) to a longitudinal straight shape at the centre or exit side of the roll gap, so that the band edge and the undeformed profile web move again parallel to each other (Halmos 2006; M Moneke and Groche 2021). During reverse bending (b-d axis), the material is subjected to a bending and torsional moment. As such, on the upper side of the flange (U), compressive residual stresses in the longitudinal direction and positive residual shear stresses (in the plane of the sheet) remain, while on the lower side (L) tensile residual stresses in the longitudinal direction and negative residual shear stresses remain (M Moneke and Groche 2021). This repeated longitudinal bending and bending back under the longitudinal tensile stress is especially high in the web edge portion, thus contributing to the longitudinal elongation (Halmos 2006).

2.3.5 Through-thickness compression

In roll forming, the metal thickness is not significantly altered, except for the bend radius where it is slightly reduced. However, during the roll forming process, compression may occur in the direction of the metal strip thickness through contact of the strip with the upper and lower rolls, especially when the roller gaps are close to the metal strip thickness (Forte 2021).

The metal strip may also suffer thickness compression when subjected to additional processes implemented in the roll forming line, such as the grooving (Figure 20(a)) and coining (Figure 20(b)). In these two cases, the material thickness is reduced locally (Halmos 2006).

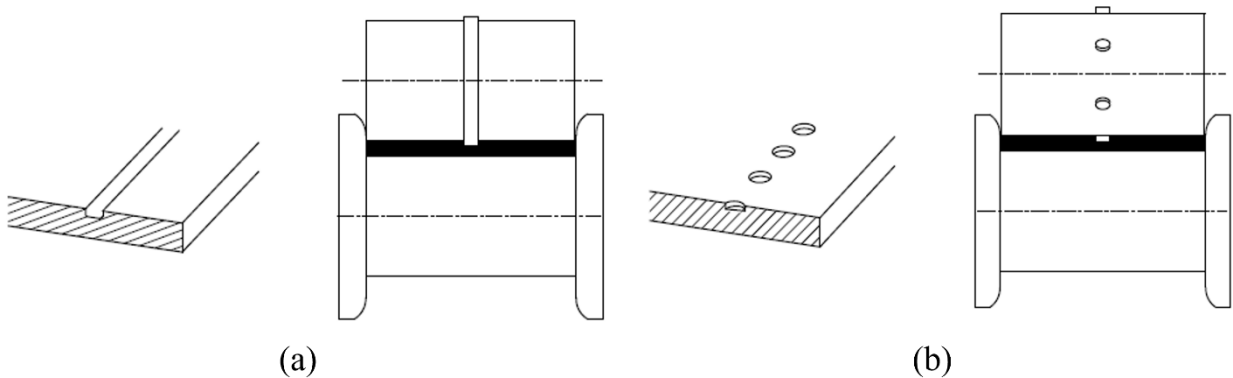


Figure 20 – (a) Rotary grooving, (b) Rotary coining. Adapted from (Halmos 2006).

2.4 Typical shape defects In Roll Forming

The RF process is a very robust process if set up correctly, showing small variations in the geometry of the profiles produced. However, if the RF process is not well designed, the profile

may contain defects such as bow, twist, end flare and spring back. Many of these defects depend on the number of forming steps. If this number is too small, residual stresses are generated in the profile which cause unwanted deformation (Lindgren 2009).

Furthermore, when HSS and UHSS materials are used in the RF process it becomes even more difficult to achieve the desired dimensional accuracy (Akbar Abvabi 2014). Some of the most common shape defects in the cold roll forming of HSS and UHSS materials are illustrated in Figure 21. All these shape defects are often not visible until the strip is fully unloaded (Akbar Abvabi 2014).

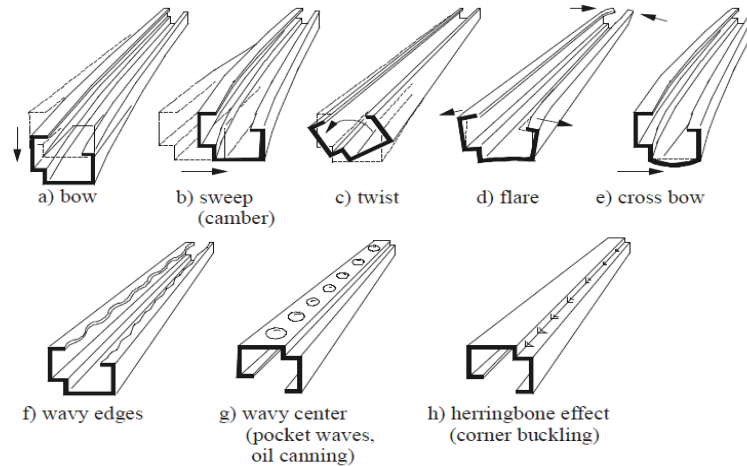


Figure 21 – Common shape defects of cold roll formed profiles (Galakhar et al. 2006).

As previously mentioned, the main shape defects that arise in the RF process are due to redundant deformations. Therefore, predicting changes in material properties by performing material tests and adjusting roll configurations is fundamental to reduce defects in the part and, consequently, to reduce the high losses associated with product rejection (Akbar Abvabi 2014).

In the following subsections, some of the most common defects in the RF process are presented, with special focus on end flare, springback and twist which are the most common defects in the beams for van bumpers produced by Coproget.

2.4.1 Springback

Springback represents the elastic recovery that the material exhibits due to the release of residual stresses after bending. This material behaviour often occurs in the RF process after the part is released from the rolls, producing changes in the final cross-section geometry of the profile (Akbar Abvabi 2014). Furthermore, springback is common and unavoidable in all phases of the production process where the material undergoes geometric changes and is therefore one of the most difficult problems in the applying high-strength steel sheet to automotive body parts (Chikalthankar et al. 2014; Groche et al. 2008).

As represented in Figure 22, springback generally refers to the change of bending angle and bending radius when unloading the part. Thus, the green colour illustrates the geometry of the bends under load while the blue colour represents the unloaded configuration of the bends.

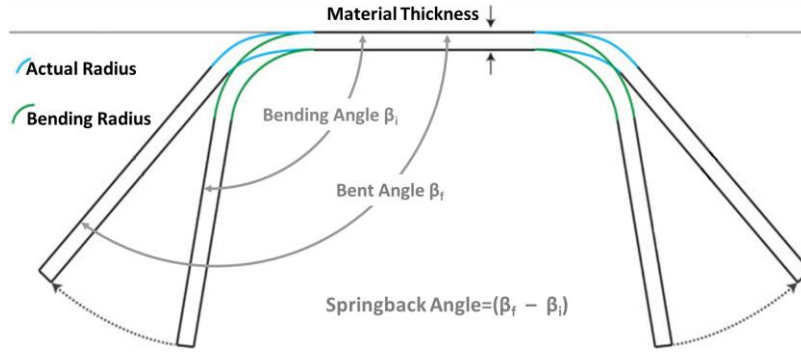


Figure 22 – Springback effect. Adapted from (DAHLSTROM 2020).

The springback angle can be considered as the angle difference between the bent angle β_f after release and the bending angle β_i , as represented by equation 2.2:

$$\text{Springback} = \beta_f - \beta_i \quad (2.2)$$

Therefore, the complete springback angle is given by this difference multiplied by two due to symmetry. A common measurement procedure is to take springback angle measurements on the part at 5 or 6 locations (cross-sections) at equal distances from each other and 300 mm away from the lead and tail end of the formed profile, to exclude the end flare effect (Akbar Abvabi 2014).

The springback is dependent on several material and process parameters, increasing with:

- Increasing yield and tensile strength of the material (Buddhika Abeyrathna et al. 2014b; Akbar Abvabi 2014);
- Increasing bend radius to thickness ratio (Radius to Thickness). Therefore, an increase in the inner bend radius leads to a higher springback angle and an increase in the sheet metal thickness leads to a decrease in this value (Groche et al. 2008; Xiaoli Liu et al. 2017);
- Increasing roll gap (Buddhika Abeyrathna et al. 2014b; Akbar Abvabi 2014);
- Increasing strain hardening (H. S. Park and Anh 2010);
- Increasing rotational velocity of the rolls (H. S. Park and Anh 2010);
- Increasing flange width and sidewall height (Xiaoli Liu et al. 2017);
- Decreasing web width (Groche et al. 2008; Xiaoli Liu et al. 2017);
- Decreasing Young's modulus (Buddhika Abeyrathna et al. 2014b; Akbar Abvabi 2014);
- Decreasing elastic modulus (Halmos 2006) (Buddhika Abeyrathna et al. 2014b; Akbar Abvabi 2014; Halmos 2006);
- Decreasing distance between roll stands (H. S. Park and Anh 2010). However, a study conducted by Buddhika Abeyrathna et al. (2017) demonstrated the opposite, i.e. that springback increases with inter-station distance, since increasing this distance makes bending more progressive, reducing redundant deformation and consequently increasing springback;
- Decreasing level of redundant deformation in the part, since residual stresses restrict elastic recovery in the transverse direction (Halmos 2006).

Furthermore, according to Buddhika Abeyrathna et al. (2017), springback decreases in most cases with increasing flange length. When the flange length increases, the deformation in the bending region remains the same, but the length of the flange outside the bend undergoes an increase (Figure 23). This factor demonstrates that both the deformation in the bending area

and the amount of material outside the bend, influence the springback in the roll forming process.

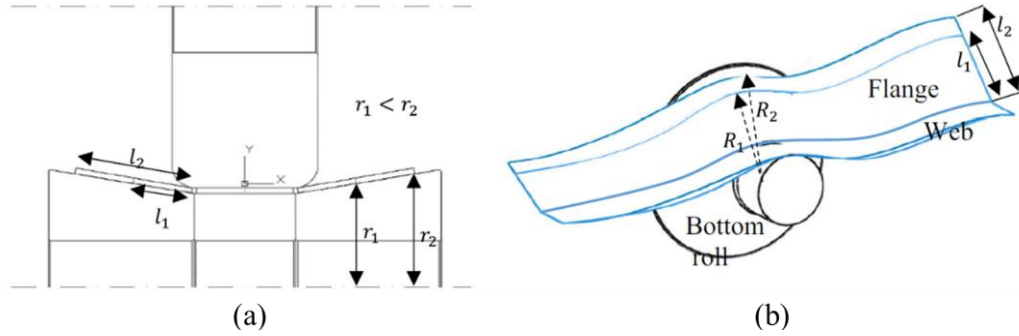


Figure 23 – a) Schematic representation of the effective tool radius (r , where $r_2 > r_1$), as well as the corresponding flange length (l , where $l_2 > l_1$), when the strip passes the roll station; b) Schematic representation of the radius of curvature of the strip edge (R , where $R_2 > R_1$), as well as the corresponding flange length (l , where $l_2 > l_1$) (Buddhika Abeyrathna et al. 2017).

To compensate the springback effects, the sheet is usually overbent so that the bend angles obtained after the elastic recovery are as close as possible to the desired angles (Forte 2021). According to Halmos (2006), when using the overbending method, the section must be bent to about the same degree as the springback to achieve the angle (α), as specified in Figure 24.

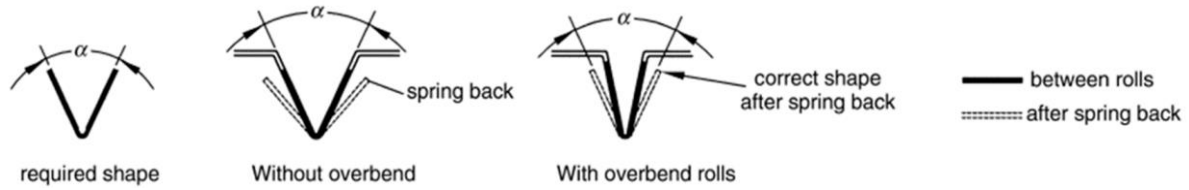


Figure 24 – Illustration of the importance of overbending to achieve the required bending angle (Halmos 2006).

Groche et al. (2008), also presented an inline closed-loop calibration system to be used during the CRF process of ultra-high strength steels, without considering material parameters or process parameters. This system was based on the feedback signal through the use of laser sensors and cameras (Figure 25).

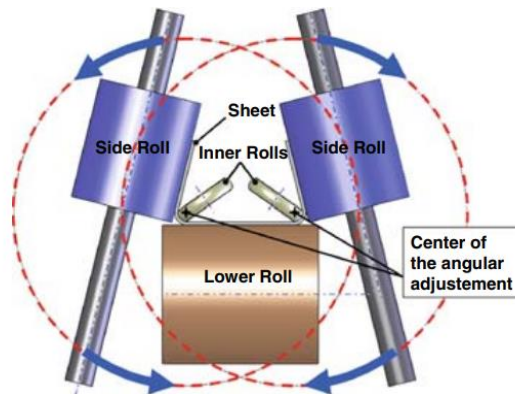


Figure 25 – Kinematics of the calibration stand (Groche et al. 2008).

Buddhika Abeyrathna et al. (2014b) have also introduced an inline compensation system dependent on an adjustable roll torque by a forming stand introduced to eliminate springback in the CRF process.

Halmos (2006) also suggests applying a straightening unit to eliminate springback defects. However, this involves changing the adjusting tool to compensate for the continuous variation of parameters in forming different shape products.

In Jiao-Jiao et al. (2020), an angle compensation method based on an angle adjusting method was also developed to reduce springback in a Hat-channel made of high-strength steel in the roll forming process through FEA simulation. In this method, the inner and outer flanges are bent simultaneously, whereby the bending angle of the outer flange is always higher than the bending angle of the inner flange. The proposed method allowed to achieve high precision springback control by the FEA simulation, strictly meeting the market requirements of less than 0.5° .

In Xiao-li Liu et al. (2020), is proposed a new method for springback calculation and compensation called "USTB Durable Integration of Springback Control (UDI)" that takes into account angle overbending compensation (AOC), small radius compensation (SRC), and revere-bending compensation (RBC) based on roll shape design. This method has higher precision, especially for the springback compensation of ultra-high-strength complex section in CRF.

The springback measurement by experimental process is costly and time consuming. In this regard, in recent years, there has been increasing use of finite element software for springback prediction (Yoshida et al. 2013). Another factor that has raised interest in the use of finite elements software to predict springback is the increasing use of high and ultra-high strength steels in the lightweight construction and automotive industries, since these steel grades show a higher springback than that of mild steels and consequently lead to lower dimensional accuracy (Groche et al. 2008). Furthermore, according to Groche et al. (2008) the Biswas formula provides the most accurate results for springback prediction in CRF process.

2.4.2 End Flare

End flare is a defect that corresponds to the change in cross-section geometry at the ends (lead and tail ends) of a roll formed part compared to any other sections along its length (Figure 26) (Akbar Abvabi 2014).

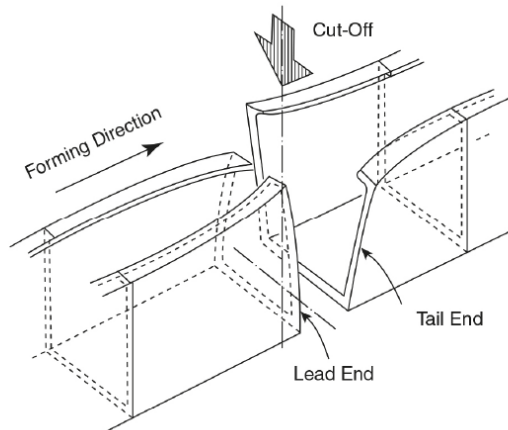


Figure 26 – Flare of cut-off ends (Halmos 2006) .

When a profile “flares out”, deformation occurs against the bending direction and conversely when a profile “flares in”, deformation occurs in the bending direction. Therefore, a positive end flare always corresponds to a “flaring out” and a negative one always corresponds to a “flaring in”(Matthias Moneke and Groche 2018).

As represented in Figure 27, end flare is determined as the difference between the bending angle of the flanges in the stationary zone (α_{sz}), at the middle of the strip, and the bending angle in the cut-off (α_{co}) (Matthias Moneke and Groche 2017).

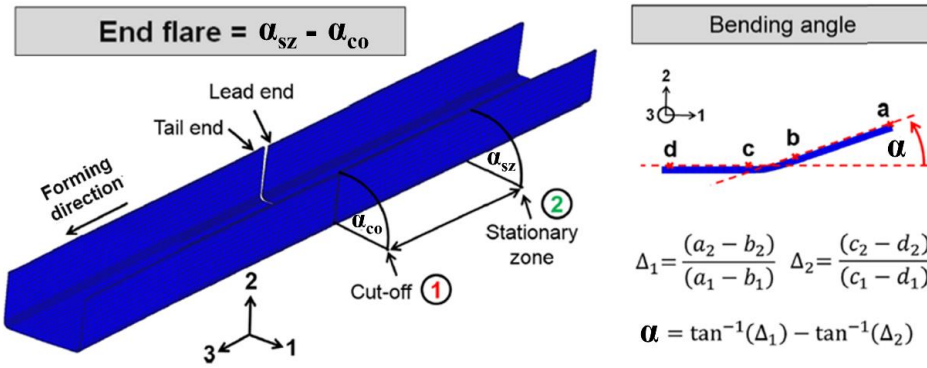


Figure 27– Measurement of end flare angle. Adapted from (M Moneke and Groche 2021).

End flare should be determined at the end of the RF process when the strip is fully unloaded. Furthermore, the cut-off angle should be measured 10 mm inwards from the ends of the strip. As the sheet typically exhibits greater distortion at the lead end due to initial contact with the rolls during the process, the end flare measurement at the tail end is generally more reliable (Akbar Abvabi 2014).

During the RF process, residual longitudinal stresses and residual shear stresses are induced into the sheet profile (Matthias Moneke and Groche 2018). Therefore, when the roll formed products are cut off into parts after forming, the entry and exit cross-sections of each part are frequently flared due to springback deformation, as well as due to the release of process-inherent residual stresses (Halmos 2006). When these residual stresses are released, a bending moment due to residual longitudinal stresses and a torsional moment due to shear stresses are generated (Figure 28). As such, the torsional moment causes a “flaring in” at the lead end and a “flaring out” at the tail end, while the bending moment causes a “flaring out” at both profile ends. The final profile deformation results from the superposition of both deformations, where the bending moment reduces “the flaring in” caused by the torsional moment at the lead end and increases “the flaring out” at the tail end. This superposition of opposite deformations at the lead end forms a turning point, where the flange end “flares in” as a whole, but the tip of the flange is turned outwards (M Moneke and Groche 2021).

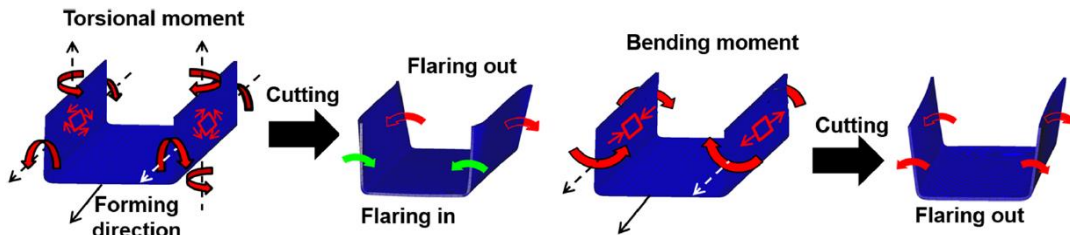


Figure 28 – Moments and profile deformations originated by the release of residual stresses (M Moneke and Groche 2021).

The changes in width and angle caused by end flare can lead to problems in joining parts as well as problems in the application and appearance of the product. In many cases, the distortion of both ends may even exceed the tolerance set for the product (Halmos 2006).

As represented in Figure 29, in roll forming of not very deep sections of lower strength materials and especially with pre-cut blanks, the lead end generally exhibits "flared-in" and the tail end "flared-out", i.e., the lead end is slightly bent inwards and the tail end is bent outwards but in a slightly sharper way (type A). However, if deep or high strength materials are used in roll forming, there is usually "flared-out" at both ends, with one end slightly less bent than the other (type B) (Akbar Abvabi 2014; Johnson Bros 2016).

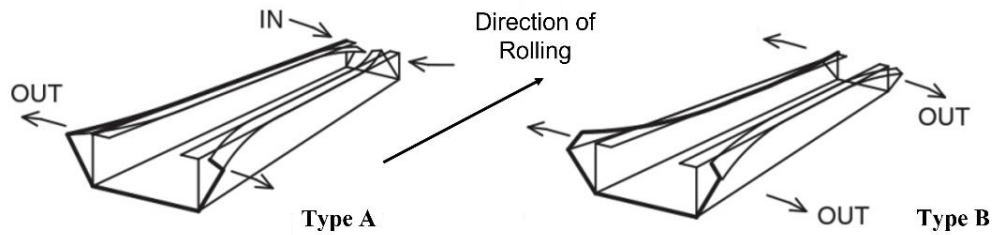


Figure 29 – Schematic illustration of two types of flare. Adapted from (Akbar Abvabi 2014).

The higher the strength of the material and the more abrupt the forming (fewer passes, shorter horizontal distances), the larger the flare will be (Akbar Abvabi 2014). Furthermore, the flare value also tends to increase if the side passes, placed between the main passes, used for forming the edges or overbending, are at reduced horizontal distances from each other. Also, if the entry path of the edges is extended in the last passes and changes suddenly in the flow direction after the last pass, the flare also tends to increase (Figure 30).

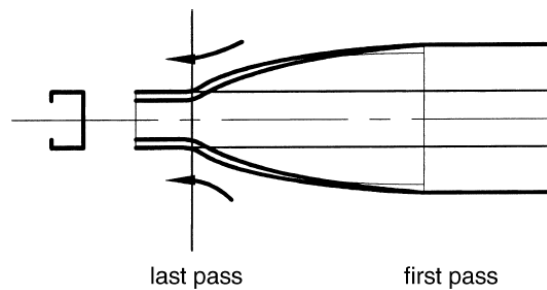


Figure 30 – Sudden change of the flow direction after the last pass (Halmos 2006).

Another important factor to consider, is that when pre-cut strips are roll formed, the flare is usually higher. However, flare does not depend on the cutting method (Halmos 2006).

Experiments and numerical analyses carried out by A. Abvabi et al.(2015) for the roll forming of a V-section have shown that thickness reduction rolling increases the end flare in the component. Also, in this study it was demonstrated that an increase in the strength of the material due to plastic deformation reduces end flare. In turn, the higher the increase in the level of longitudinal residual stress at the front of the strip the higher the end flare (A. Abvabi et al. 2015).

The direction and magnitude of the end flare also varies according to the profile and the process parameters implemented, which in turn can change throughout the forming steps. However, there are characteristic profile deformations of the inner and outer flanges for the U, Hat and C profiles as depicted in Figure 31 (M Moneke and Groche 2021).

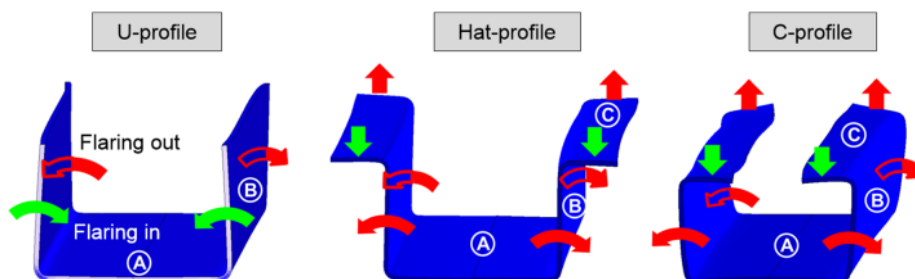


Figure 31 – Typical end flare for U, Hat and C profiles (M Moneke and Groche 2021).

Profiles with multiple bending zones, such as Hat or C-profiles tend to vary in direction and amount of flaring for every bent section and therefore every flange deforms differently. As shown in Figure 32, for the case of Hat or C-profiles the end flare is determined by the

superposition of the torsional and bending moments that act on the inner flange B and on the outer flange C.

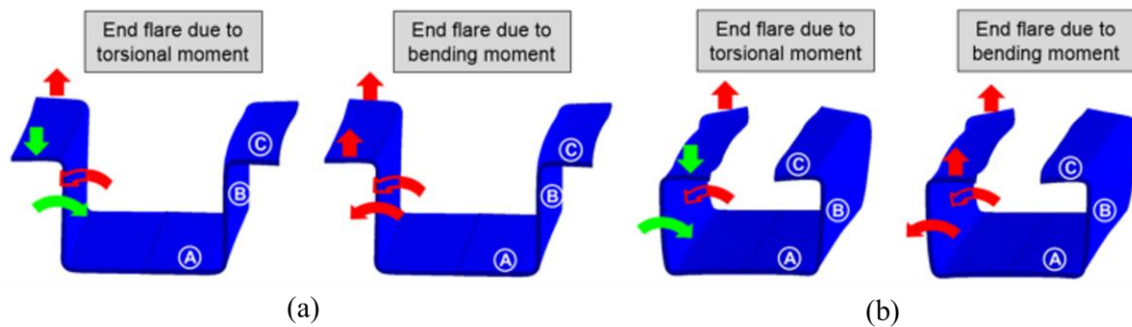


Figure 32 – End flare direction due to the release of shear and longitudinal stresses: (a) Hat-profile, (b) C-profile (M Moneke and Groche 2021).

According to Halmos (2006), there are some recommended and proven techniques for reducing flare namely:

- Use more passes, particularly to form the edges;
- Use a mill with larger horizontal centres, mainly when forming deeper sections;
- Overbend before the last pass and bending out at the last pass so as to induce an opposite "bending moment" to the edges;
- Use the "gentle" forming at the last few passes;
- Apply two identical "last passes";
- Use three roll straighteners designed for the edges only;
- Apply force to squeeze (crash) the outside legs and bend lines;
- Preform bends with a radius slightly larger than the desired final radius and then reduce the radius in the last forming passes.

In a study performed by Matthias Moneke and Groche (2021), a countermeasure to reduce end flare by a targeted adaptation of the roll gap was presented. In this study it was shown that the reduction of the roll gap strengthens convex bending and reverse convex bending during the forming process, allowing a targeted reduction of the residual twisting moment, whereas the residual bending moment remains in the flange.

According to M Moneke and Groche (2021), two types of countermeasures are usually applied to prevent or minimise end flare during the roll forming process. A first type of countermeasure suggested, consists in the use of an additional plastic deformation in order to allow the change in the distribution of residual stress. For example, in Ona et al. (1988) plastic deformations were induced by compressing flanges of thick-walled U-profiles using a punch. In addition, a die was used to prevent the flanges from buckling. In turn, the second type of countermeasures proposed consists in inducing opposite directed plastic strains during the forming process in order to allow a counterbalance between the distribution of residual stresses along the cross-section. This counterbalance is achieved by "overbending and bending back" or by "lowering and elevating" the profile (M Moneke and Groche 2021). In Halmos (2006), a third method is also suggested which falls within type of countermeasure, the "inverse bending by inner rollers".

Accordingly, by the "overbending and bending back" method, the excessive transverse bending (overbending) is applied to the corners (bend lines) of the cross-section just before the final forming stage. Subsequently, those corners are bent back to the required shape or angle Figure 33(a) (Halmos 2006). As such, the residual shear stress accumulated in the corner portions in the previous forming stages is cancelled by the sufficiently large inverse shear deformation given at the bending back stage (Figure 33(b)) (Halmos 2006).

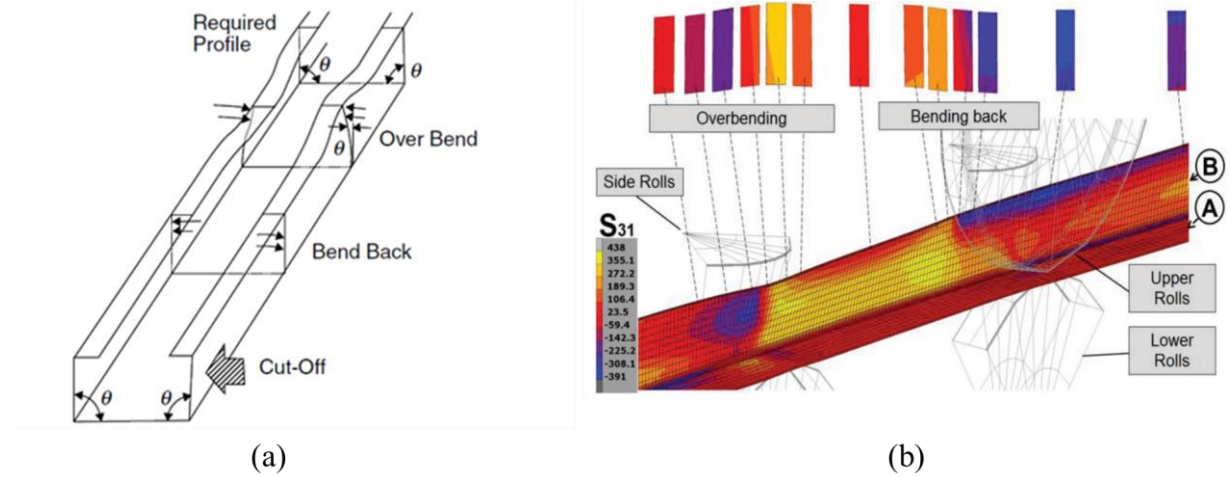


Figure 33 – (a) Overbending and bending back method for a C-profile (Matthias Moneke and Groche 2017), (b) representation of the residual shear stresses for a U-profile during the implementation of the overbending and bending back method (Halmos 2006).

In turn, the "lowering and elevating" method allows a reduction in longitudinal residual stresses by using two additional roll stations after the forming has been carried out and the final profile geometry has been obtained (Figure 34). As such, the profile is moved downwards in the vertical direction at the first additional roll station and it is elevated back to its original height at the second station. This movement thus reduces the residual longitudinal stresses in all areas A, B and C and consequently the end flare, as it induces longitudinal stresses in the opposite direction to the roll forming. This countermeasure is only suitable for profiles, which have high longitudinal residual stresses and flare out at both ends of the profile (Matthias Moneke and Groche 2017).

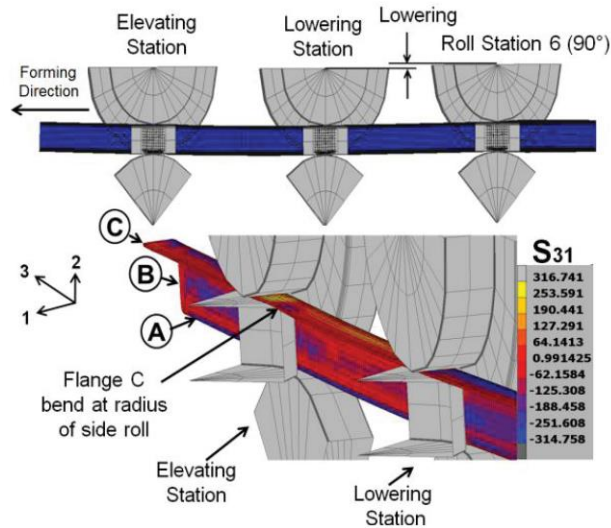


Figure 34 – Profile deformation in the "lowering and elevating" method (Matthias Moneke and Groche 2017).

Finally, by "the inverse bending" method (Figure 35), the semiformed sheet is bent transversely to the inverse direction by side inner rolls installed at the appropriate stage of the forming process. The use of these rolls allows an effective and sufficiently large inverse shear deformation in the sheet metal, cancelling the effects of the residual shear stress accumulated in the previous forming stages and eliminating the causes of springback distortion of the cut-off edge (Halmos 2006).

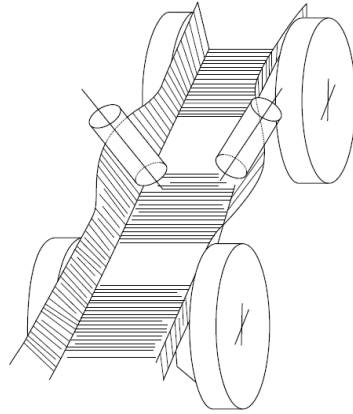


Figure 35 – "Bending back by side (inner) roll" method (Halmos 2006).

In a study conducted by B. Abeyrathna et al. (2020) at a 3D flexible roll forming facility at Deakin University, allowed improved accuracy of critical forming angles by implementing a flexible "overbending" approach to overcome springback and flare defects observed in an automotive component of variable width, through the use of Copra FEA software. The orientation of the tool used for regular overbending is shown in Figure 36 (a). However, in order to produce more overbending at the ends and less at the center, the tool path used was deviated from the part contour towards the component center, as shown in Figure 36 (b).

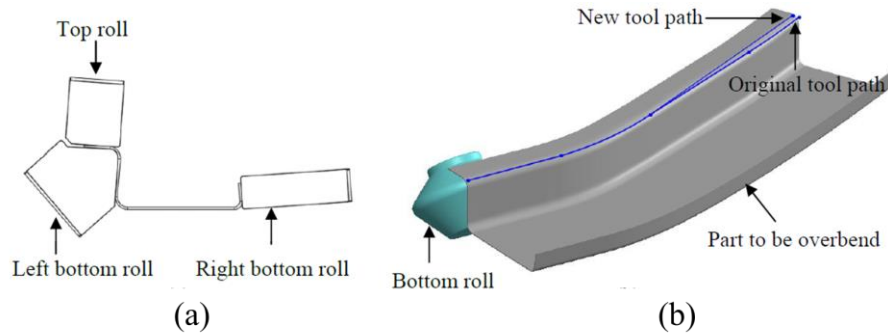


Figure 36 – (a) Tool orientation for regular overbending; (b) Flexible overbending approach (B. Abeyrathna et al. 2020).

Despite the countermeasures presented here, the flare defect cannot be completely eliminated except by subjecting the metal to stretch forming or to stress-relieving anneal. The latter improves ductility, reduces brittleness and relieves stresses absorbed by the metal during RF (DAHLSTROM 2020).

2.4.3 Longitudinal Bow and Twist

Longitudinal Bow and twist are caused by nonuniform transverse distribution of the longitudinal membrane strain and are the most common defects in narrow roll formed products (Halmos 2006). Longitudinal bow can be defined as the vertical height deviation of the web over the length of the part compared with the target shape (Buddhika Abeyrathna et al. 2017). According to Buddhika Abeyrathna et al. (2014a), the longitudinal bow depends not only on the material strength, but also on the profile geometry used. An investigation by Buddhika Abeyrathna et al. (2017) concluded that the longitudinal bow increases with the forming angle for all the materials studied. Furthermore, it was verified that the longitudinal bow decreases with increasing inter-station distance, as increasing the distance between stations leads to a smoother progression of bending, resulting in lower residual stresses through the profile cross-section.

In turn, twist is a common defect when asymmetrical-channel sections are roll-formed (Tajik et al. 2018). In these cases the finished product shows twist after leaving the last pass, even if the starting material is flat (Halmos 2006). The main reason for twist is the existence of uneven plastic deformation on each side of the strip. Consequently, this results in the uneven distribution of the longitudinal membrane strain along the transverse direction of the final part. Therefore, edge strain may be used as a tool to determine the occurrence of twist in a part. The twist depends on the imbalances in roll load, symmetry of the tooling and alignment of the rolls and can be considered as the angle between the channel web at the strip's leading edge and the horizontal as shown in Figure 37 (Buddhika Abeyrathna et al. 2014b).

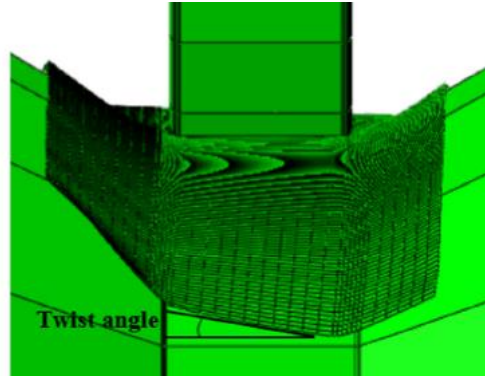


Figure 37 – Twist angle (Tajik et al. 2018).

The magnitude and direction of the bow and twist follow the variation in the distribution pattern of the membrane strain, as represented in Figure 38.

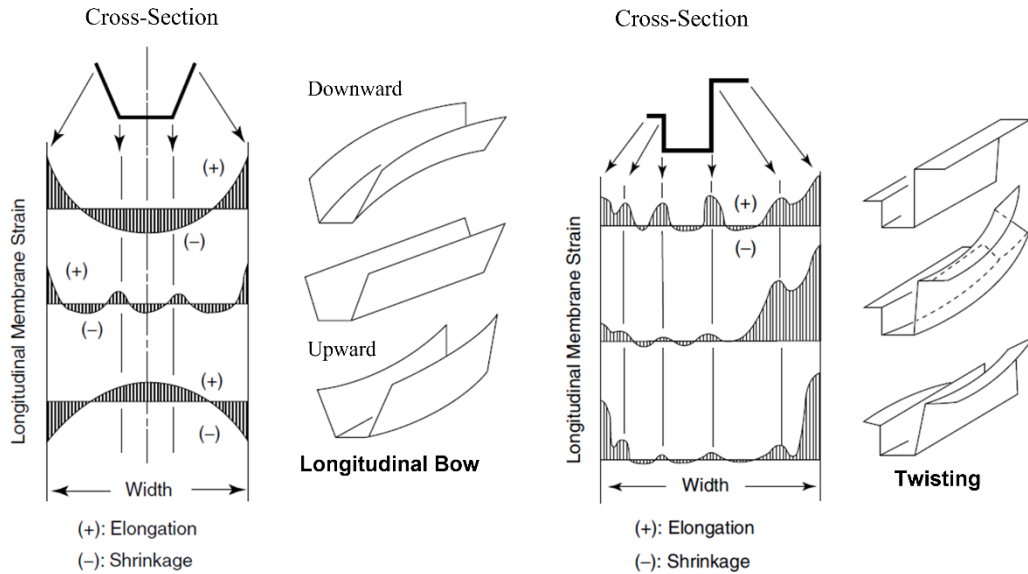


Figure 38 – Relationship between transversal distribution of longitudinal membrane strain and longitudinal bow or twist of product: (a) longitudinal bow; (b) Non uniform longitudinal membrane strain distribution due to twisting. Adapted from (Halmos 2006).

When flat metal strips are roll formed into products with cross-sections having different heights and widths from those of flat metal strips, the transverse non-uniformity of the longitudinal membrane strain is inevitable. Nevertheless, the magnitude of longitudinal strain and its transversal distribution can be reduced by choosing an appropriate number of passes during the design of the roll forming process. The use of too few number of passes lead to an excessive amount of transverse bending deformation caused by each pair of rolls. In such cases, some portions of the strip, such as the flange portion and edge portion are forced to rise sharply as the strip is bent too much in the transverse direction. This abrupt bending in the transverse direction, generates a greater difference between the spatial length of the flow lines of the flange

and the edge portion compared to other flow lines, which consequently leads to an increase in the nonuniformity of the longitudinal membrane strain that is distributed in the transverse direction. On the other hand, the use of too many number of passes leads to a significantly increase in the cost of the forming mill, the tooling and the setup time (Akbar Abvabi 2014). In addition to the number of passes, the roll profiles, the roll positions and the use of entry and intermediate guides should also be taken into account, since their correct use and positioning makes the flow of each sheet strip portion smoother and allows height and width variations to be minimised. Consequently, the magnitude of the longitudinal membrane strain is reduced and the undesirable effects of transversal non-uniformity are minimised or eliminated (Halmos 2006; Forte 2021).

2.4.4 Waviness

Strip waviness is the most common shape deviation in CRF and it is caused by elastic or elastoplastic buckling. This type of defect is generated when there is an excessively high longitudinal membrane strain and usually appears locally at the edge portion of the strip. At the initial forming stage, longitudinal elongation always occurs at edge portion of the strip, as it has to move both vertically and transversely. Subsequently, when the edge portion enters the roll gap it undergoes additional elongation. At a later stage, when the edge portion exits the roll gap, it undergoes a shrinkage, since the longitudinal length of each portion of the semi-formed strip must be equal to keep the product straight. However, if the local edge elongates excessively, it is very difficult for this shrinkage to occur smoothly and therefore if the compressive stress acting on the edge portion exceeds the critical value, buckling (edge wave) is generated (Figure 39) (Halmos 2006; Akbar Abvabi 2014).

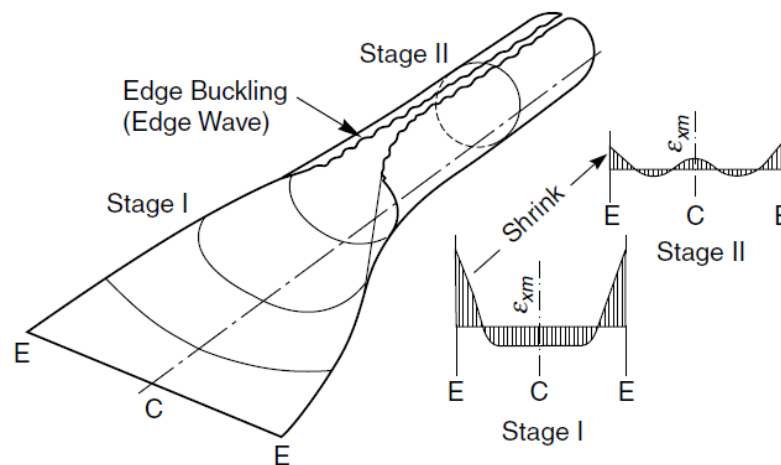


Figure 39 – Edge buckling during roll forming of ERW pipes (Halmos 2006).

Therefore, the appearance of edge waves can be prevented by reducing the longitudinal elongation of the edge part below the critical value, using a sufficient number of rolls, roll profiles, roll positions, guides and a correct pass line. In addition, there are other countermeasures that can be implemented, such as the "local heating method", the "pre-forming method" and the "smoothing flow line method" (Halmos 2006). The "local heating method" allows to prevent edge waves by reducing the contribution of plastic deformation, using the effect of thermal deformation induced by local heating of the strip. This heating provides a reduction in the magnitude of the plastic longitudinal shrinkage of the edge portion occurred at the exit of the roll gap. Consequently, with the drop in temperature, the shrinkage of the edge portion occurs in a smooth way, preventing the occurrence of edge waves. In turn, in the "pre-forming method", the metal coils are preformed either by a "roll preformer" or by a special leveler called a "shape correcting". The roll preformer or leveler consists of several crowned rolls or roll bending systems that allow adjustment of the longitudinal elongation at the

preforming stage to compensate for non-uniform longitudinal elongation that occurs at the forming stage. Consequently, when the longitudinal elongation due to forming is superposed upon the longitudinal elongation caused by the preforming, the elongation of the sheet metal becomes practically uniform in the transverse direction, thus preventing the occurrence of edge wave. Finally, the "smoothing flow line method" use guide rolls in order to make the flow line of the edge portion as smooth and short as possible, thereby reducing edge elongation and consequently edge waviness (Halmos 2006; Forte 2021).

In addition to the edge waviness, a pocket or center wave caused by slight elastic buckling can also occur and may be located at webs, flanges, and other nonbent portions of the cross-section. This central wave is widely observed on products that have a wide cross-section and a low thickness, such as roofing, siding, deck, panels, automotive components, garage, and other doors, as well as other wide products. In addition, their webs and flanges usually exhibit low stiffness against longitudinal buckling (Figure 40).

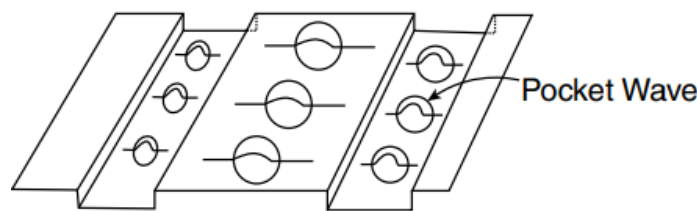


Figure 40 – Pocket or center waviness(Halmos 2006).

Some countermeasures can be used to minimize center waviness namely:

- Reduce the transverse tensile stress and transversal elongation affecting the bend lines by reducing the transverse shifting of each strip portion, making the roll gap as large as possible.
- Bend the corners of the center portion before the corners of the intermediate and edge portions.
- Use guide rolls in order to promote transverse shifting of the edge and intermediate portions of the coil.
- Decrease the radius of the convex corners of the rolls gradually.

2.5 Roll Design

The design of a roll forming line is an iterative optimization process that involves several steps and depends on the experience and knowledge of the designer about the process. The great challenge of the roll design is to obtain a final product that presents the required shape, within the imposed tolerances and with the least number of incremental steps possible, i.e., that is produced as quickly as possible (Halmos 2006) .

The first step of the RF design process is to define the orientation and position that the part will exhibit at the exit of the last pass (Halmos 2006). In turn, the orientation of the workpiece influences the positioning of the rolls, the tool design and other additional operations, such as welding and punching (Forte 2021). Subsequently, the designer defines the number of passes suitable to form each bend, so that the final product does not present significant defects. As can be seen in Figure 41, the selection of the number of passes is a critical step because, while a very small number of passes distorts the product due to the high stresses applied in the metal, a very high number of passes makes the tooling and the process very expensive. The use of an adequate number of passes is fundamental for a gradual sheet forming and for the reduction of the longitudinal membrane strain. Therefore, there must be a good compromise between quality and cost of the finished product (Halmos 2006; Akbar Abvabi 2014).

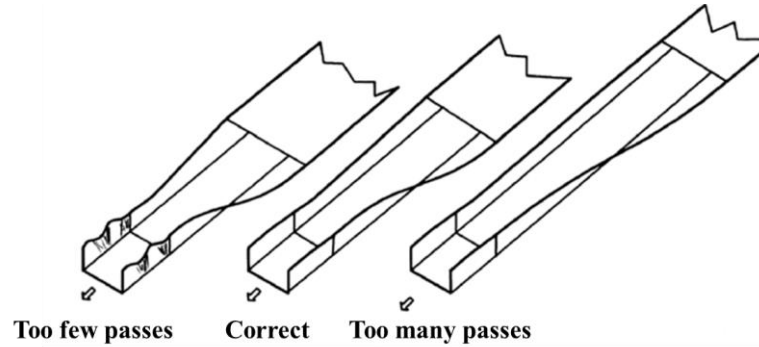


Figure 41 – Effect of the number of passes on the final product (Halmos 2006).

Although some computer-aided roll design systems are able to recommend the number of passes and calculate the stresses created by forming, this step is still very dependent on the designer who is responsible for accepting or modifying the computer's calculations and setting the correct number of passes based on their experience (Halmos 2006).

After the numbers of passes are established, the material flow is defined, and the forming may begin in the centre with a bead (Figure 42 (a)) or at the edges with the short lip (Figure 42(b)) with the bead formed at later passes (Halmos 2006) .

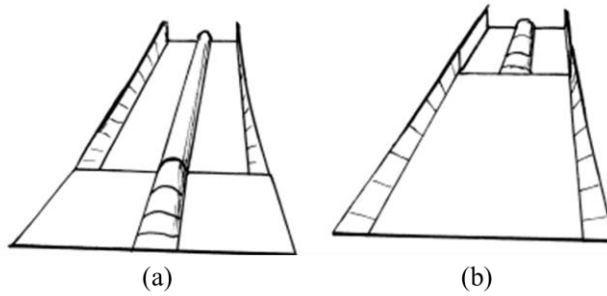


Figure 42 – (a) Centre bead, (b) Outside lip (Halmos 2006).

Once these steps are finished, the most important step in the design of roll forming processes follows, which is the design of a flower pattern. As can be seen in Figure 43, the flower pattern allows a good identification of the bending sequence, since it illustrates the several successive stations.

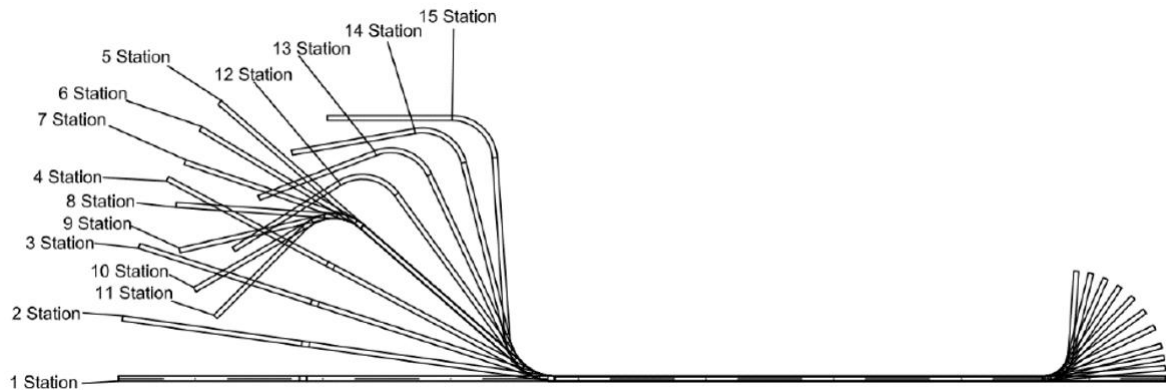


Figure 43 – Flower Pattern (B Abeyrathna et al. 2016).

With the use of an optimised flower pattern, it is possible to achieve the dimensional and geometric precision desired for the products and with a minimum number of forming stands. However, the realisation of this step is currently still largely dependent on the trial-and-error method and the experience of the designer (Tajik et al. 2018).

2.6 Residual Stresses in Roll Forming

Residual stresses are stresses that remain in the material after the part has been removed from the constraints of the manufacturing process, that is, when the part is no longer subjected to any outside stresses. The residual stresses present in the material can be due to several factors such as: phase transformation, differences in cooling rate or change in plastic flow in the material (Akbar Abvabi 2014; Martins 2018).

All manufacturing processes introduce residual stresses in the materials. Products obtained by CRF go through a series of manufacturing steps until their final shape is achieved. Usually, at an early stage, thin cold-formed steel members start out as a sheet of the material that have to be melted, hot-rolled, cold-reduced and annealed. This material in sheet form is then coiled and shipped to the producers of roll formed products to be cold roll formed into the final shape. This entire complex process generates plastic stresses and residual stresses through the sheet thickness that influence the load displacement response and ultimate strength of cold-formed steel members (Moen et al. 2008).

The residual stresses can be classified into three groups (Akbar Abvabi 2014):

- Macro residual stresses (type I): stresses that exist in the material on the scale larger than the grain size of the material. These stresses are particularly important for the sheet material properties;
- Micro residual stresses (type II): stresses that vary on the scale of an individual grain;
- Micro residual stresses (type III): stresses that exist within a grain, especially due to the presence of dislocations or other crystalline defects.

Residual stresses result from misfits between different phases within a material or different regions of a material that influence the fatigue behaviour, fracture strength and even corrosion resistance of mechanical parts, and can be one of the most influential parameters on service behaviour, especially for high-strength material states (Akbar Abvabi 2014).

Residual stresses can be divided into two different parts: flexural and membrane (Figure 44). For cold-formed steel profiles, the residual stresses across the thickness are mainly flexural (bending). In turn, membrane residual stresses are present mostly in the corner regions. These membrane residual stresses cause a direct loss in compressive strength and are more common in roll-formed profiles than in pressed-braked profiles. However, to counteract this effect, yield stress is elevated in the corner regions as a result of the significant cold work of forming (Schafer and Peköz 1998). Early yielding at the surfaces of cold-rolled steel members is due to dominant flexural residual stresses through thickness (Akbar Abvabi 2014).

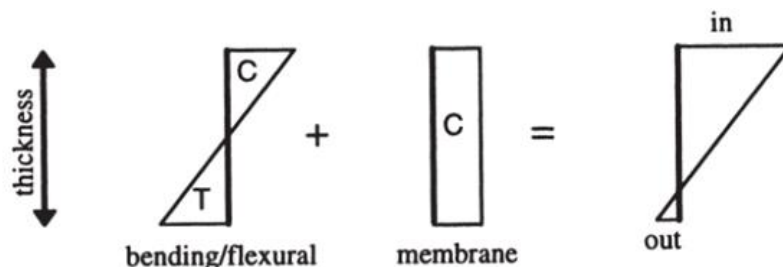


Figure 44 – Flexural and Membrane Residual Stresses (Schafer and Peköz 1998).

CRF process originate residual stresses and strains across the sheet thickness, which influence the load-displacement response and ultimate strength of cold-formed steel profiles. Figure 45 illustrates the distribution of nonlinear residual stresses through the thickness (in the bending direction) caused by plastic bending followed by elasticity springback (Moen, Igusa, and Schafer 2008).

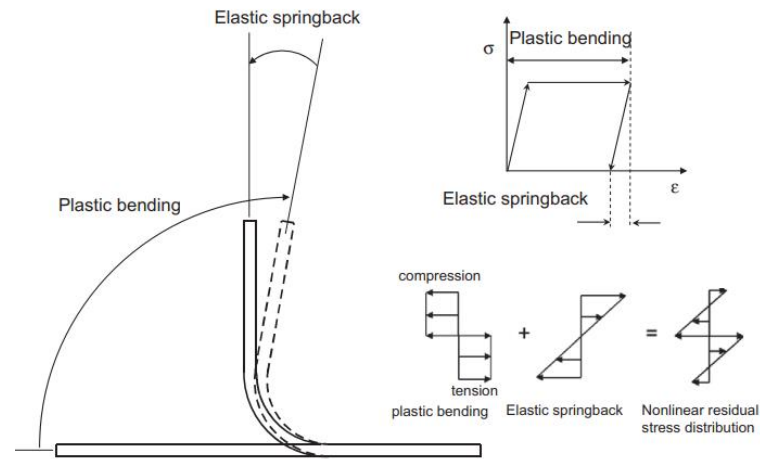


Figure 45 –Forming a bend: Nonlinear through-thickness residual stress distribution (Moen et al. 2008).

In a study conducted by Moen et al. (2008), a prediction method was developed to determine the initial residual stresses and effective plastic strains in cold-formed steel members. The authors assumed that the residual stresses only existed at the location of the formed corners, between the roller die reactions (Figure 46).

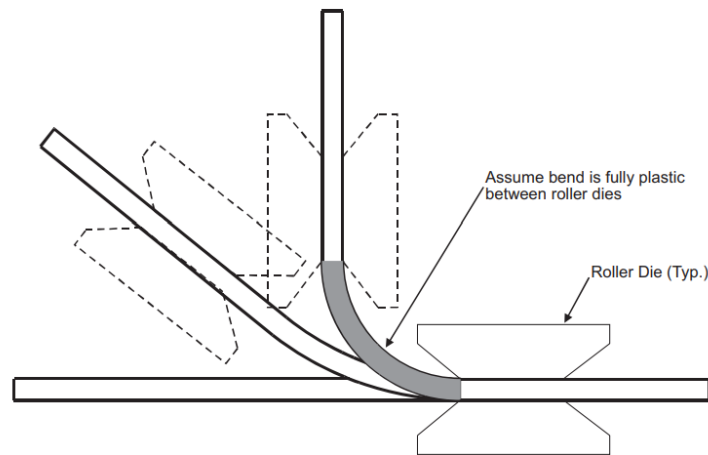


Figure 46 –Cold forming of a steel sheet(Moen et al. 2008)

During the RF process, the steel sheet yields through its thickness to small bend radius common in the cold forming industry. As depicted in Figure 46, the sheet will reach the fully plastic stress state as the corner approaches its final radius. In turn, after the sheet becomes fully plastic through its thickness, the engineering strain continues to increase as the radius decreases. Subsequently, an elastic springback occurs, provided that the final bend radius is reached and the imposed radial displacement is removed. This elastic rebound promotes a change in through thickness stress (Figure 47) (Moen et al. 2008).

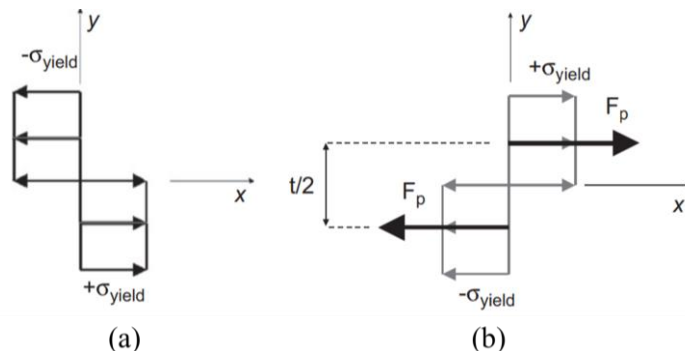


Figure 47 – Fully plastic transverse stress state from cold-forming; (b) Force couple applied to simulate the elastic springback of the steel sheet after the imposed radial deformation is removed (Moen et al. 2008) .

The final transverse stress state results in the sum of the fully plastic stress distribution through the thickness and the unloading stress of the elastic springback of the corner (Figure 48) (Moen et al. 2008).

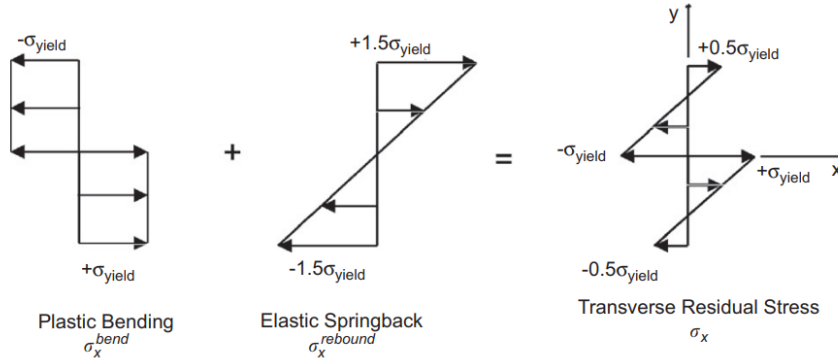


Figure 48 – Cold-forming of a steel sheet occurs as plastic bending and elastic springback which in turn results in a self-equilibrating transverse residual stress(Moen et al. 2008).

In turn, in a study conducted by Amouzegar et al. (2016), a comprehensive incremental numerical method was developed to calculate residual stresses and strains in cold-formed members both in the flat parts and in corner regions. This method was developed in order to simulate the cold working process, including coiling, uncoiling, flattening, and cold forming (either by press breaking or roll forming). This algorithm was obtained by the authors considering that the steel sheet is free of residual stresses before coiling. In addition, strains perpendicular to the bending direction were ignored assuming that strain hardening is isotropic. The main conclusions drawn from this study were:

- Residual stresses in corner regions are marginally affected by the specifications of the cold-formed steel member;
- In the flat regions, the residual stresses can be significant depending on the coil radius, yield stress and sheet thickness;
- In flat regions, strain hardening has a negligible contribution to the variability of residual stresses;
- The corner radius greatly affects the equivalent plastic strain and variations of section thinning in corner regions.

2.7 Finite Element Method Analysis

Finite element method (FEM) is a numerical method that aims to transform mathematical expressions into a set of algebraic equations dependent on a finite set of parameters. FEM can be used in a variety of applications such as steady and transient thermal analysis in solids and fluids, stress analysis in solids, crash car analysis, fluid flow analysis, manufacturing process analysis, among others (Martins 2018; Rao et al. 2012). In turn, finite element analysis (FEA) is considered an essential tool in the early design and optimization stages and has been increasingly applied in the roll forming industry, enabling the improvement of part quality and the reduction of process costs (Jiao-Jiao et al. 2020). The introduction of finite element simulation in RF has made it possible to check and change all design decisions, such as the number of passes and bending strategy, before any manufacturing takes place(Ferreira 2016).

The software used for the simulations developed during this dissertation were COPRA® RF and COPRA® FEA RF. The COPRA® FEA RF software is the world's leading software solution for the simulation of the roll forming process and enables predictions with high accuracy even for the most complex production processes. As such, this software is able to calculate the entire process including pre and post operations through the so called non-linear elastoplastic calculation method. In addition, the coupling of RF design software COPRA® RF with COPRA® FEA RF software allows simple and fast changes to be applied to the simulation

model, reducing simulation setup time. In turn, the COPRA® FEA RF software is able to import the necessary data directly from the design module COPRA® RF (Data M 2014). Since the COPRA®FEA RF software allows the configuration of virtual RF lines, various forming strategies and new roll designs can be tested before the actual process is performed. This avoids iterative trial and error approaches that require costly equipment replacement (Data M 2014; Ferreira 2016). In addition, COPRA® FEA RF is able to simulate material changes that occur during manufacturing processes reliably and quickly. Thus, common RF defects can be prevented through design verification (Data M 2014). The visualization of some important information such as applied forces, torsional moments, pressure and tension values is also possible with this software (Data M 2014).

The FEA performed during this thesis involve three stages: pre-processing, analysis and post-processing. The pre-processing stage is carried out using COPRA®RF design software (based on Autocad and HP-UX ME10) and Copra®FEA RF simulation software. In this stage, the stations of the machine, the distance between stations, the profile geometry, the flower and the the rolls design, the contact interactions between the strip and the rolls and the necessary load cases are established. In addition, the material properties, the mesh, the element type and the boundary conditions to be used are also defined. With this information, COPRA® then creates a Marc® model of the roll forming machine as well as the metal strip to be roll formed. The Marc® software uses the FEM to numerically simulate the CRF process. In Marc®, the user can further specify the isotropic or kinematic material hardening rules, the element type to be used, extra load cases, solver options, etc. The analysis stage and is performed exclusively by the MSC Marc software. In this stage, the job is carried out, the program is run and the results are calculated. Finally, the post-processing stage follows. This stage is performed using the simulation software Copra FEA RF, which is based on MSC Marc/Mentat software. The results obtained are analysed and studied, station by station, and their validation is performed.

Therefore, FEA can be used to find out the reasons for problems in the manufacturing process in terms of tolerances, surface quality, or roll wear issues, for example. This without ever underestimating the importance of the experience and knowledge of the design engineers in detecting these same defects (Ferreira 2016).

Figure 49 summarizes the different steps of the design process of a RF line.

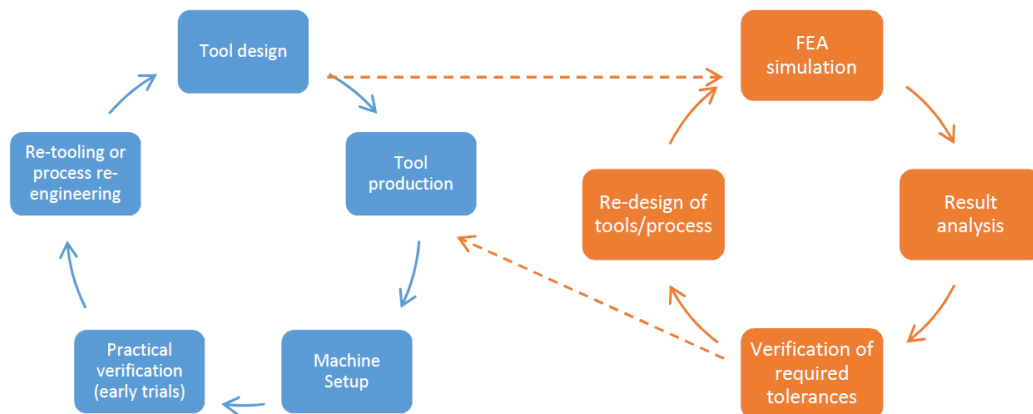


Figure 49 – Design process of a roll forming line: The blue colour represents the traditional trial and error process; The orange colour represents the upgraded process with virtual testing; The dashed lines represent the connection between the cycles(Ferreira 2016).

3 Analysis of Coproget`s roll forming line and the respective C-profile produced

Nowadays, the traditional RF process as well as the flexible RF process are used for the production of a large amount of components for the automotive industry due to their ability to form a wide variety of materials and due to their high productivity (Figure 50). For the case of this dissertation, it will be studied a C-profile corresponding to a beam that constitutes a rear bumper of a commercial van produced by the Stellantis group. Therefore, this chapter will present the beam under study, the material from which it is made, the manufacturing process, the measurements of the defects present in it and the process issues.

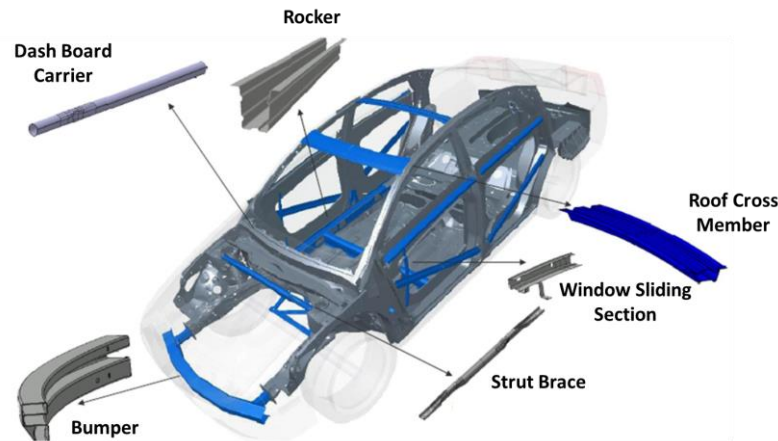


Figure 50 – Examples of automobile components produced by the roll forming process. Adapted from World Auto Steel (2020).

3.1 Automotive bumper beam

In the automotive industry, bumpers are used as safety parts that absorb energy in the event of a collision. These structures are attached to the front and rear ends of motor vehicles by means of brackets, which act as shock boxes by taking the loads mainly in the axial direction (Hosseinzadeh et al. 2005; Tanlak et al. 2015). The automotive bumper is the first component that absorbs the impact energy during the crashing and that undergoes deformation, mainly bending deformation (Rambhad et al. 2020).

The fundamental mechanical properties of the automotive bumper are strength and toughness. Another important property is ductility, as the beam is expected withstand high level of deformation before fracture (Osokoya 2017). Therefore, its design and manufacture must be performed carefully in order to achieve good impact behaviour and a consequent reduction in damage to the vehicle and risk of injury to the occupants (Hosseinzadeh et al. 2005).

To sum up, car bumpers have four main functions, namely (Rambhad et al. 2020):

- Absorb energy and minimise vehicle damage in low and medium speed collisions;
- Guide the crash forces into the body structure at high-speed crashes to reduce passenger component intrusion;
- Dampen the effect load and energy to the left and right of the crash containers and longitudinal rails as uniformly as possible, reducing the deformation of the bumper beam.

Coproget is responsible for the production of two types of beams which constitute the rear bumpers of a van model of automaker Stellantis. The model of this van cannot be revealed for confidentiality reasons. These two types of beams are identical, differing only in the location

of the respective holes. Figure 51, shows the two types of beams produced by Coproget, which are subsequently welded together by Proma Group to form the bumper.

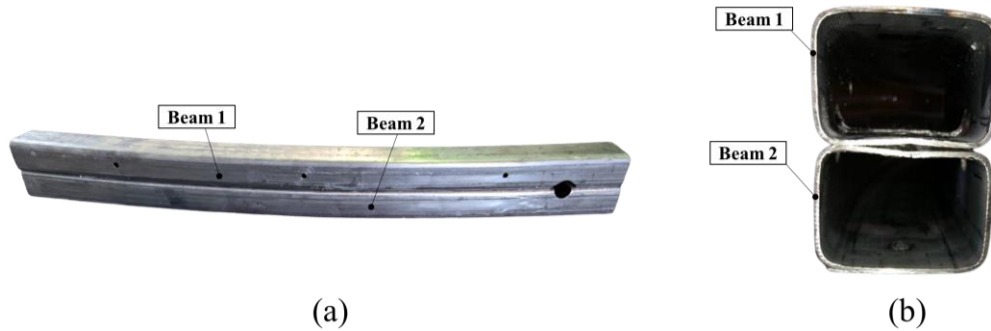


Figure 51 – Illustration of the two types of beams produced at Coproget: (a) Front View; (b) Left view.

Once produced, these beams are packaged and sent to the Proma Group, which is responsible for all operations and additional parts that result in the assembly of the rear bumper shown in Figure 52.

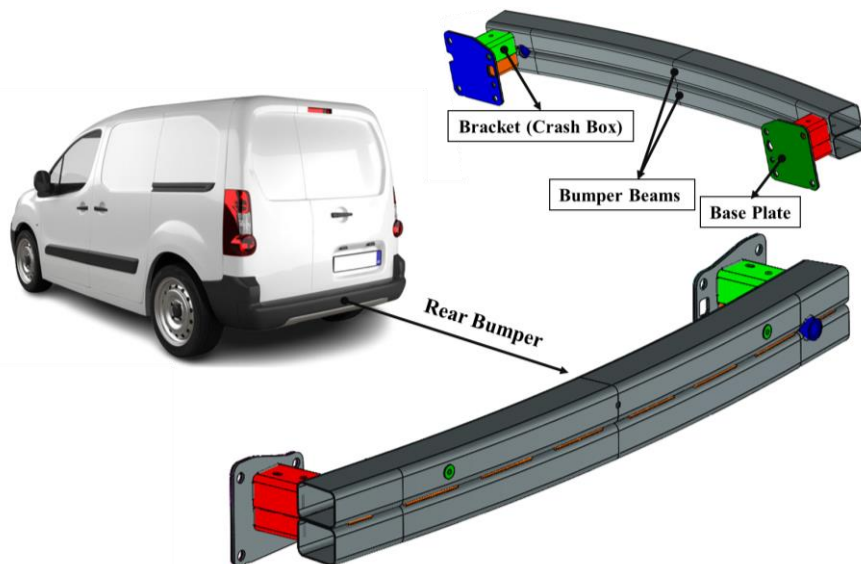


Figure 52 – Rear bumper assembly for a van.

3.2 Materials

The roll forming process has been used traditionally in the construction and housing industry for the production of longitudinal components. However, nowadays, this process is being increasingly used by the automotive industry for the manufacture of structural and crash components from advanced high-strength steel (AHSS) and ultra-high-strength steel (UHSS) (Buddhika Abeyrathna et al. 2017). One of these components are the beams for car bumpers, as is the case of the beams produced by Coproget.

The use of advanced and ultra-high strength steels (AHSS/UHSS) is aimed at reducing body weight and consequent CO₂ emissions, as well as increasing safety in the event of a collision (Yoshida et al. 2013). Compared with other light-weight materials, high-strength steels are advantageous in terms of costs, ability to ensure high forming forces and availability of production facilities (Lindgren 2009). However, these materials exhibit higher fluctuations in their properties than conventional steel grades (Groche et al. 2008). Furthermore, their high strength causes higher levels of residual stress and elastic recovery when compared to conventional low strength steels (Buddhika Abeyrathna et al. 2017). Consequently, a greater amount of springback and dimensional defects are generated. In addition, the risk of sheet

breakage during sheet forming becomes higher due to the low elongation resulting from the higher strength of these materials (Yoshida et al. 2013).

As the dimensional tolerances imposed on automotive components are tighter than those applied in the housing and construction industry, the quality of AHSS/UHSS products can be unacceptable. Therefore, appropriate measures must be taken to deal with the increased elastic recovery of the high-strength sheets. (Yoshida et al. 2013).

Studies performed by Lundberg and Melander (2008) revealed that, in terms of finite element simulation of sheet metal forming processes, high-strength steels present a better forming behaviour in roll forming than in air bending. Furthermore, the roll forming process has been shown to be able to form tighter radius without failure, since the damage factor in this process is lower than in air bending (Ferreira 2016). However, when the RF process is performed with high strength steel, its defects must be viewed more carefully, since with the use of this type of material, the difficulty to control the deformation behaviour, namely longitudinal elongation, longitudinal bending, transverse bending, and shear is higher (Joo et al. 2011).

In Coproget's RF process, essentially two types of high strength materials are used to produce beams for car bumpers, Docol®1400M and Ancelor MartINSite®1500.

Docol 1400M is one of the strongest cold rolled advanced high-strength steels on the market. This material is mainly applied in the automotive industry, in components such as side impact beams, bumpers and structural components, thus enabling high crashworthiness, lightweight design and a more cost-efficient production (SSAB 2022). Table 2 presents its main mechanical properties and Table 3 its chemical composition.

Table 2 – Mechanical properties of Docol® 1400M (SSAB 2022).

Steel Grade	Coating	Test Direction	Yield strength $R_{p0.2}$ (MPa)	Tensile strength R_m (MPa)	Elongation A_{80mm} Min (%)	Min. inner bending radius for 90°
Docol CR1150Y 1400T- MS	UC, EG	T	1150-	1400-1600	3	4.0 x t

Where:

- A_{80mm} % is the percentage of elongation after fracture using a specimen with gauge length $L_0 = 80$ mm (ISO 6892-1 type 2 (EN20x80))(Arcelor Mittal n.d.);
- Uncoated (UC) is available as oiled;
- Electrogalvanized (EG) is available as oiled and/or chemically passivated or phosphate.

Table 3 – Chemical composition of Docol® 1400M (SSAB 2022).

Steel Grade	C Max (%)	Si Max (%)	Mn Max (%)	P Max (%)	S Max (%)	Al Min (%)	Nb+Ti Max (%)
Docol CR1150Y 1400T-MS	0.20	0.40	1.60	0.020	0.010	0.015	0.10

The MartINSite® steel family is an addition to ArcelorMittal's range of advanced high strength steels. This family of steels follows the VDA 239-100 standard and allows the creation of lightweight structural elements through a forming process such as RF. Furthermore, these steels have excellent mechanical properties, good roll forming, bending and hole expansion behaviour, good fatigue properties and are not difficult to weld. MartINSite® steels are therefore suitable for automotive safety parts for shock resistance such as front and rear bumper

beams, door beams, side sill reinforcements and roof crossmembers (ArcelorMittal n.d.). Table 4 presents its main mechanical properties and Table 5 its chemical composition.

Table 4 – Mechanical properties of MartINsite®1500(ArcelorMittal n.d.).

Steel Grade	Test Direction	Yield Stress $R_{p0.2}$ (MPa)	Tensile Strength R_m (MPa)	Type 1 A_{50mm} (min %)	Type 2 A_{80mm} (min %)	Type 3 A_{50mm} (min %)
MartINsite® 1500	L	1220-1520	1500-1750	3	3	3

Where:

- A_{80mm} % is the percentage elongation after fracture using a specimen with gauge length $L_0 = 80$ mm (ISO 6892-1 type 2 (EN20x80));
- A_{50mm} % is the percentage of elongation after fracture using a specimen with gauge length $L_0 = 50$ mm (ISO 6892-1 type 1 (ASTM12.5x50) or type 3 (JIS25x50));
- $A\%$ is the percentage of elongation after fracture using a proportional specimen with $L_0 = 5.65$ (So)^{1/2}(Akbar Abvabi 2014)(Arcelor Mittal n.d.).

Table 5 – Chemical composition of MartINsite®1500(ArcelorMittal n.d.). .

Steel Grade	C Max (%)	Si Max (%)	Mn Max (%)	P Max (%)	S Max (%)	Al Min (%)	Cu Max (%)	B Max (%)	Ti + Nb Max (%)	Cr + Mo Max (%)
MartINsite ® 1500	0.28	1	2	0.02	0.025	≥0,010	0.2	0.01	0.15	1

3.3 Manufacturing Process

Currently, the beams produced by Coproget are intended for rear van bumpers for the automaker Stellantis. The manufacturing process of this beams starts in Coproget II. Initially the raw material in coil form is checked by the production manager. If the raw material does not meet the necessary quality requirements it is sent to the raw material rejection area, to be later returned to the supplier. In turn, if the raw material is approved, it is then submitted to Coproget's roll forming process (Figure 53(a)) by which the parts (beams) shown in Figure 53(b) are obtained.

Coproget's current roll forming process is defined by the following parameters:

- Number of stations: 25 (starting the countdown at 0 and ending at 24);
 - 19 stations with top and bottom rolls;
 - 4 stations with two side bars each;
 - 2 stations with two side rolls each;
- Distance between main stations: 600 mm;
- Distance between main stations and secondary stations (side bars/side rolls): 300 mm.



Figure 53 – Roll forming line of Coproget II.

In Coproget's roll forming process, the sheet metal is initially unwound from the coil (Figure 54) as it moves forward into the gap between the rolls. The coil is supplied by SSAB EMEA AB has 2.10 x 232.50 mm with a tolerance of ± 0.5 mm for the width.



Figure 54 – Coil.

The first stations of the line (station 0 and station 1) are used as a guide for the strip to enter the following stations and therefore the sheet remains flat during the travel between these stations. Subsequently, between the first and second stations the sheet is subjected to the cutting process in order to produce blanks of 2345mm (Figure 55).



Figure 55 – Cutting operation between stations 1 and 2.

Then, the sheet is incrementally bent by successive rolls along the line until it acquires the desired cross-section shape. Between the main stations 11 and 13, 13 and 15, 15 and 17 and 18 and 20 the process has intermediate stations where there are no rolls, but two sidebars (Figure 56 (a)). These intermediate stations composed by sidebars are used to guide the sheet to the rolls' entrance with no plastic deformation and to prevent the part from opening during its travel between the main stations due to the springback effect. These side bars are unusual components in a RF machine and are only used in the Coproget RF process due to the high difficulty in forming the high strength materials. There are also intermediate stations between the main stations 20 and 22 and between stations 23 and 24. However, these intermediate stations are constituted by side rolls and not by side bars as represented in Figure 56(b).

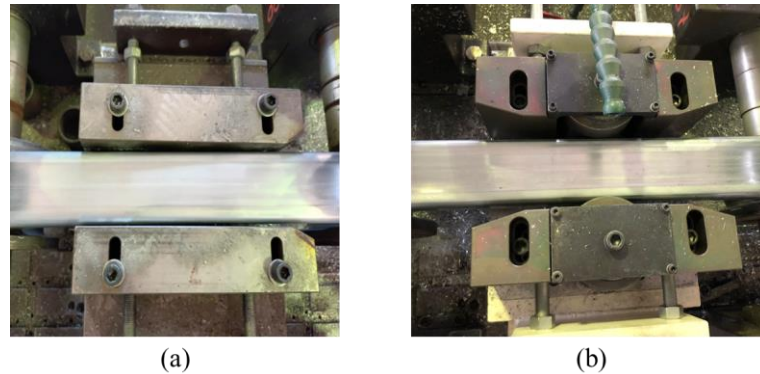


Figure 56 – (a) Side bars; (b) Side rolls.

After every 100 parts produced, the alignment of the outer flanges of the part is controlled, which is crucial for the welding operation (Figure 57).



Figure 57 – Control of the alignment of the outer flanges.

Once the roll forming process is complete, the parts are subjected to some additional secondary processes. First, they are submitted to a TIG welding process (Figure 58(a)), originating the parts represented in Figure 58 (b). This process is particularly difficult because of the defects present in the part when it is removed from the roll forming process.

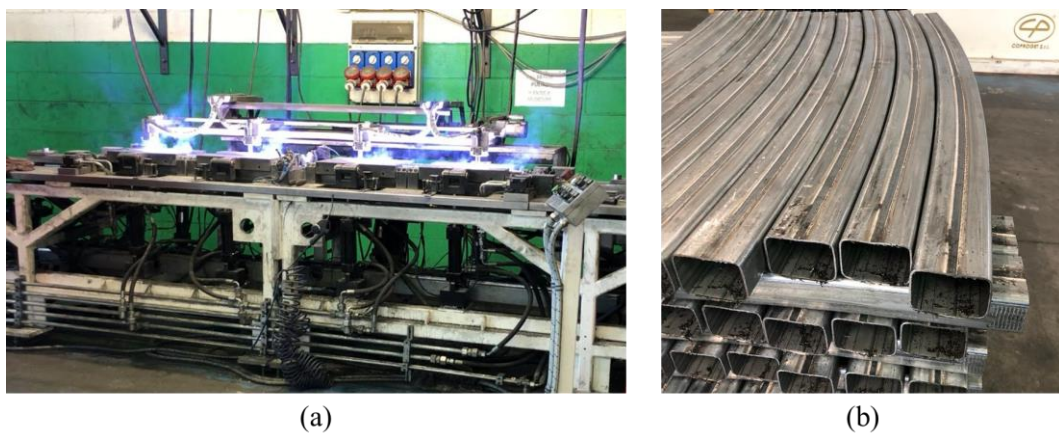


Figure 58 – (a)Welding machine; (b)Welded part.

Subsequently, the parts are bent by the stretch bending process, in order to acquire the desired curvature for the final product (Figure 59(a)). In (Figure 59(b)), it is possible to observe a set of parts obtained after this process. Afterwards, a curvature control method is performed using a calibrator to check the quality of the part.



Figure 59 – (a) Stretch bending machine; (b) Stretch bent part.

After being subjected to the stretch bending process, the parts are cut into two parts of equal size and then drilled on the top surface. The cutting machine is represented in Figure 60 (a) and the parts obtained from it are shown in Figure 60(b).



Figure 60 – (a) Cutting machine; (b) Cut parts.

After this stage, the parts are submitted to various control methods namely: hole presence control, hole size control with dedicated plug gauge and control with cutting square. If the part does not meet the dimensional and quality requirements intended by the customer, the part is sent to the rejection area. On the other hand, the conforming semi-finished parts are subjected to the stamping process in Coproget II or can be transported to Coproget I to be submitted to this process there. In the stamping machine, the part is moved along six different stations (Figure 61(a)) to form the holes of the part surrounded in red in Figure 61(b). The movement of the part from station to station is done manually by the operator.

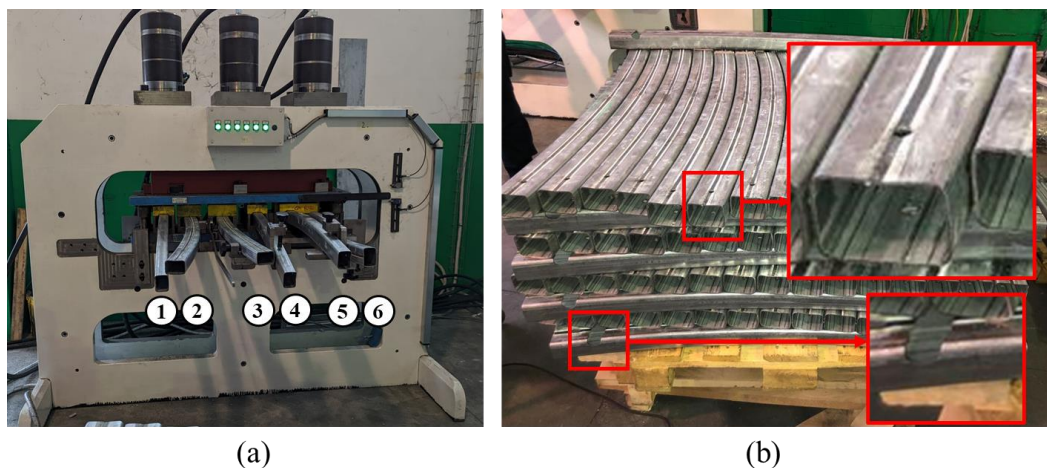


Figure 61 – (a) Stamping machine; (b) Stamped parts.

At the end of the stamping process the parts are subjected to a control through a calibrator, in order to verify if the stamping and the holes have been properly made (Figure 62).



Figure 62 – Stamping and punching control with a calibrator.

Subsequently, the beams are also subjected to a visual control and a 100% revision and the compliant ones are stored on special platforms and are sent to the customers. Figure 63 shows an example of a final beam produced at Coproget.



Figure 63 – Final car bumper beam produced at Coproget.

3.4 Beam Defects Measurements

The beams for car bumpers produced by Coproget's RF process present springback and defects such as end flare and twist which are common defects when AHSS are used (Figure 64).

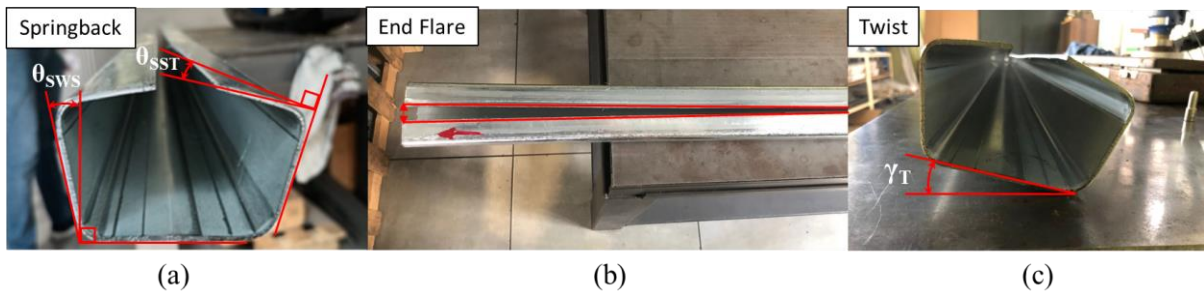


Figure 64 – (a) Springback, where θ_{SWS} is the springback angle between the web and the side flange and where θ_{SST} is the springback angle between the side flange and the top flange; (b) End flare; (c) Twist, where γ_T is the twist angle.

These defects need to be improved in order to obtain a high-quality part that ensures greater safety for vehicle passengers in the event of a collision. Furthermore, minimizing these defects is intended to facilitate the welding process that is performed after the roll forming operation, since under the current conditions the beam needs to be clamped to be welded properly. In order to quantify the mentioned defects, measurements were made on a beam obtained from Coproget's RF process. Figure 65(a) shows the profile final angles that were calculated for the four bends of the profile cross-section. To obtain these profile final angles, the angle that the side flange made with the web (β_2) and the angle that the side flange made with the top flange (β_1) were measured, as represented in Figure 65(b) and Figure 65(c), respectively. For a better understanding only the angles measured for the left side of the part are shown in these figures, however, these measurements were performed in the same way for the right side of the part, obtaining the angles β_3 and β_4 in bend 3 and bend 4, respectively.

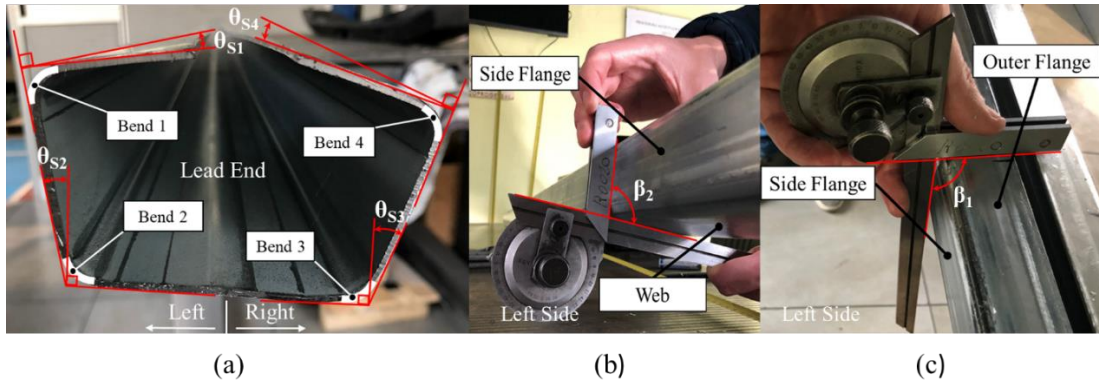


Figure 65 – Profile final angles measurement: (a) bends used in the measurements and respective profile final angles (θ_s) to be calculated; (b) bending angle measurement on the left side between side flange and web (β_2); (c) bending angle measurement on the left side between side flange and outer flange (β_1).

As suggested by Akbar Abvabi (2014), the β angle measurements were taken in six distinct planes (cross-sections), distanced 300 mm from the ends (to exclude the end flare effect) and spaced 349 mm apart, as shown in Figure 66. The results of these measurements are shown in Appendix A, Table A1.

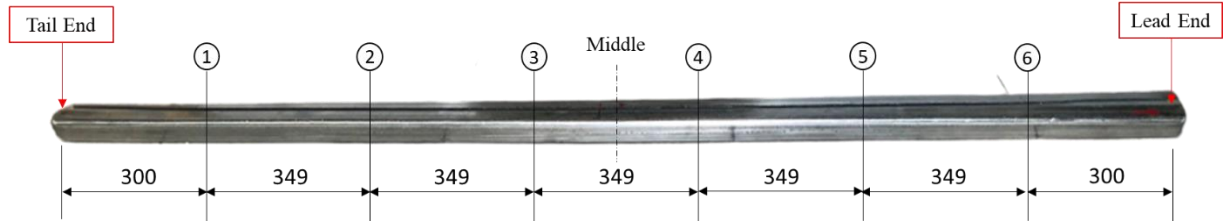


Figure 66 – Distance between measuring sections (mm).

Finally, the profile final angles illustrated in Figure 65 were calculated according to Figure 22 in section 2.4.1 using equation 3.1 for each of the bends of the six cross sections under study. These values are shown in Table 6.

$$\text{Profile final angle } (\theta_s) = \beta_f - \beta_i(90^\circ) \quad (3.1)$$

Where:

- θ_s , is the profile final angle for each profile bends and for all cross-sections under study;
- $\beta_i(90^\circ)$, is the theoretical bending angle (90°), that is, it is the angle that the bends of the profile cross-section theoretically present at the exit of the last station of Coproget's roll forming process;
- β_f , is the bent angle after release measured for each of the profile bends and for all cross-sections under study.

Table 6 – Profile final angles (θ_s) in degrees obtained for the four bends of the six cross-sections of the beam under study[°].

Cross-Section	Left		Right	
	Bend 1 (θ_{s1})	Bend 2(θ_{s2})	Bend 3(θ_{s3})	Bend 4 (θ_{s4})
1	-1.0	6.0	6.0	-1.0
2	-2.0	5.5	4.5	-2.0
3	-2.0	4.0	4.0	-2.5
4	-2.0	4.5	4.5	-1.5
5	-2.0	5.5	4.0	0.5
6	-2.0	7.0	5.0	3.0
Average	-1.8	5.4	4.7	-0.6

Analysing Table 6, it is possible to verify that the highest absolute average value for the profile final angle is 5.4° and occurs in bend 2 of the sections under study, i.e., in the lower left corner. Furthermore, the highest absolute value (7.0°) also occurs in the bend 2, for the measurement performed 300 mm from the lead end (cross-section 6). Therefore, it can be concluded that bend 2 presents the worst values regarding the profile final angle. On the other hand, the best profile final angle values occur in bend 4 corresponding to the upper right corner of the sections, since the absolute average value is closest to 0° , that is, closest to the ideal value. The best value of the profile final angle (0.5°) also occurs in this bend, for cross-section 5. Therefore, it can be concluded that the bends between the side flanges and the web (bends 2 and 3) have bent less than intended and therefore require a profile final angle compensation. In turn, bend 1 and 4 bent more than intended with more prominence for bend 1. Another aspect to note in the table, is the fact that the profile final angle for bend 1 remains the same for all cross-sections but the first one, which may indicate that the existence of defects such as waviness in the top flange is almost nil. For bend 4, the profile final angle values already show a greater variation, indicating the existence of waviness in the outer right flange although it is not significant.

Regarding the end flare, the calculation of the angles was based on a study conducted by M Moneke and Groche (2021) where the following equation is considered (see section 2.4.2):

$$\text{End flare angle}(\alpha_{EF}) = \beta_{lead/tail} - \beta_{sz} = \alpha_{sz} - \alpha_{lead/tail} \quad (3.2)$$

Where:

- α_{EF} , is the end flare angle for each profile bends and for all cross-sections under study;
- β_{sz} , is the bending angle between the web and the side flange or between the side flange and the outer flange measured in the stationary zone (at the middle of the part length);
- $\beta_{lead/tail}$, is the bending angle between web and side flange or between side flange and outer flange measured in the planes at 10 mm from the lead and tail end;
- $\alpha_{lead/tail}$, is the supplementary angle of $\beta_{lead/tail}$ calculated for each of the 4 bends of the planes at 10 mm from the tail and lead end ($\alpha_{lead/tail} = 180^\circ - \beta_{lead/tail}$);
- α_{sz} , is the supplementary angle of β_{sz} calculated for each of the 4 bends of the plane located at half of the part length (stationary zone) ($\alpha_{sz} = 180^\circ - \beta_{sz}$).

The measurement of the angles β for each bend of the planes under study was carried out in the same way as explained previously for the profile final angle (Figure 64 (b) and (c)). However, for end flare case, the measurements of the angles that the side flanges make with the web (β_2 and β_3) and the angles that the side flanges make with the top flange (β_1 and β_4) were performed only for three different cross-sections, two of them at 10 mm from the ends and another one located in the middle of the part (stationary zone), as suggested by Akbar Abvabi (2014) and as represented in Figure 67. The choice of these cross-sections was made in order to make it possible to evaluate the effect of the end flare at the lead and tail end. These measured angles for the four bends of the three cross-sections under study are presented in Appendix A, Table A2.

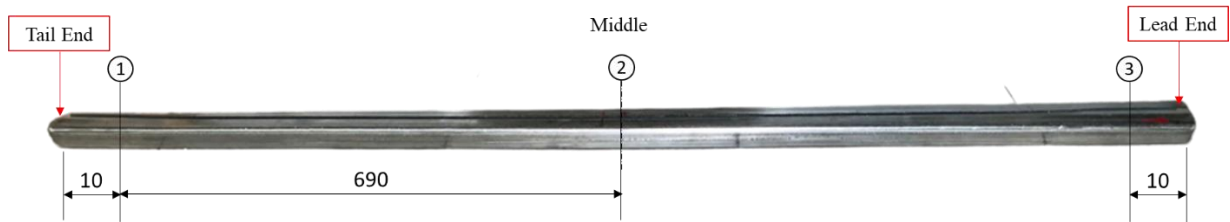


Figure 67 – Location of measuring sections and their distance from ends (mm).

However, as performed by the literature (see section 2.4.2), the β angles were not considered for the end flare calculation but rather their supplementary angles (α) as represented in Figure Figure 68. The values of the angles α obtained are shown in Appendix A, Table A3.

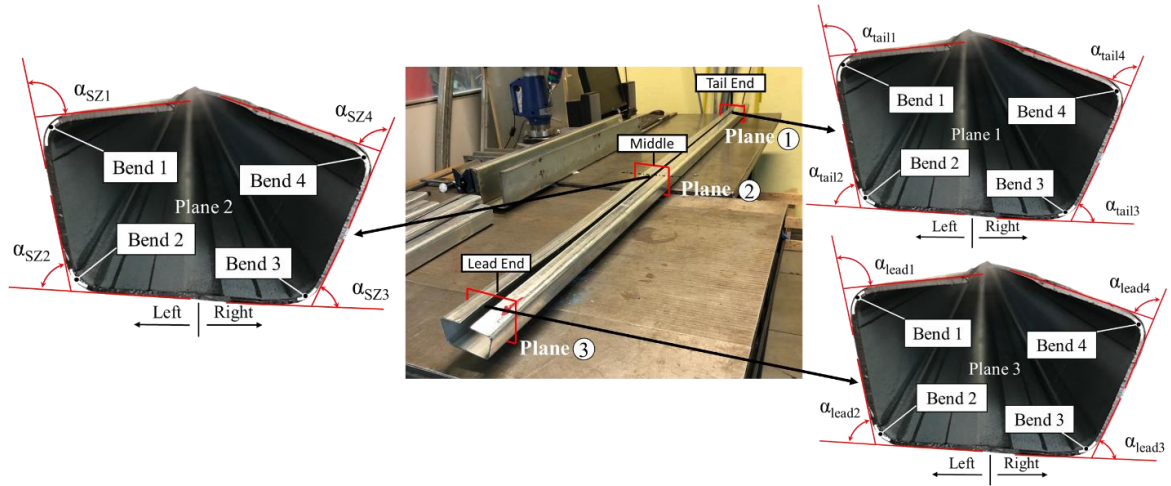


Figure 68 – Representation of the bending angles in the stationary zone (α_{sz}) (cross-section 2) and the bending angles at the tail (α_{tail})(plane1) and lead end (α_{lead})(plane3) for each bend.

Once the angles α had been determined for each of the bends of the three planes under analysis, the end flare angles for the lead and tail end were calculated. Therefore, the calculation of the end flare angles for the lead end and the tail end was performed using equation 3.2 by subtracting the angles α in the stationary zone (α_{sz}) (plane 2) by the angles α of the section corresponding to the lead end (α_{lead}) (plane 1) or by the section corresponding to the tail end (α_{tail})(plane 3), respectively. Table 7 shows the end flare angle values obtained for both lead and tail end and for the four bends of the profile cross-sections.

Table 7 – End flare angles (α_{EF}) in degrees obtained for both lead and tail end and for the four bends of the profile cross-section[°].

Cross-Section	Left		Right	
	Bend 1 (α_{EF1})	Bend 2 (α_{EF2})	Bend 3 (α_{EF3})	Bend 4 (α_{EF4})
1 (Tail end)	2.5	4.5	4.5	2.0
3 (Lead end)	3.0	6.5	6.0	3.5
Average	2.8	5.5	5.3	2.8

Analysing Table 7, it can be verified that the end flare angle calculations reveal that bend 2 of the cross-sections is the one that presents the highest average value (5.5°) for the end flare angle, being therefore the most critical bend for this defect. Furthermore, the worst value of the end flare angle (6.5°) also occurs for bend 2 which is located between the web and the side flange of the profile. In turn, it should be noted that the best end flare values occur for bend 1 and 4 between the side flanges and the outer flanges. Although bend 1 and bend 4 have the lowest end flare values, they are still high. This leads to the conclusion that all bends need to be improved with respect to end flare. Comparing the lead end with the tail end, the lead end always shows worse end flare angle values. Furthermore, it can be verified that the part presents flare out at both ends, since all the values obtained for both lead end and tail end are positive. This behaviour is typically observed when HSS are used in the RF process, as already mentioned in section 2.4.2.

Finally, to measure the twist angle, it was necessary to fix the web of the tail end of the part in the table surface using a clamp, so that the web of the lead end rotated with an angle corresponding to the twist angle (Figure 69).



Figure 69 – Fixing the tail end web of the part for twist angle measurement.

Therefore, firstly the angle between the table surface and the side flange of the lead end (γ_f) (Figure 70 (a)) was measured. Subsequently, the angle between the web of the lead end and the side flange was also measured (γ_i) (Figure 70 (b)). Finally, the subtraction between the second and the first measurement was performed, obtaining a twist angle of 11° clockwise (equation 3.3).

$$\text{Twist angle } (\gamma_t) = \gamma_f - \gamma_i \quad (3.3)$$

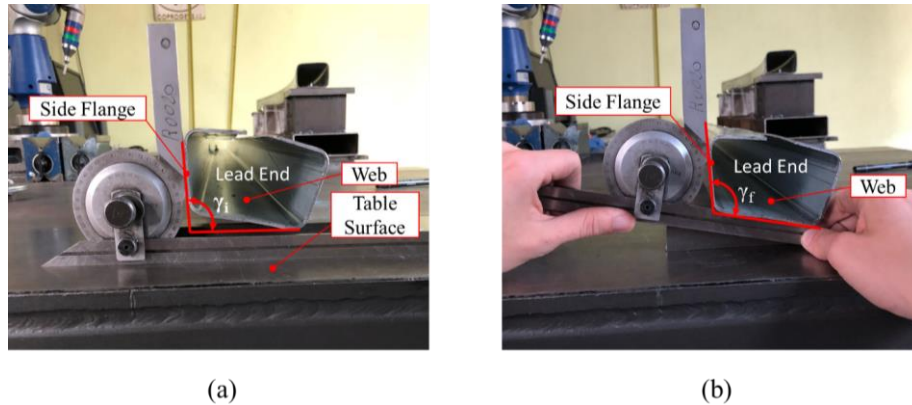


Figure 70 – Twist measurement: (a) Measurement of the angle between the table surface and the side flange; (b) Measurement of the angle between the web and the side flange.

3.5 Process Issues

During Coproget's roll forming process some problems are visible that need to be improved in order to obtain a part with better quality, namely:

- The contact between the outer flanges of the part, causes strong noises;
- The process is not as continuous and fluid as expected, as there is difficulty of the part entering the rolls (noise) due to the springback effect;
- The part has very worn areas due to the difficulty of entering the rolls of the process and due to lateral contact with the side bars (friction), accumulating a large amount of swarf throughout the process (Figure 71).

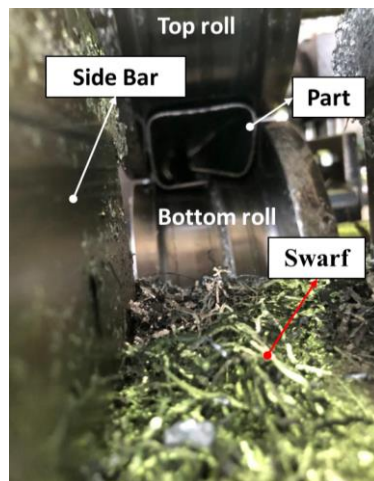


Figure 71 – Swarf due to part wear.

4 Numerical Simulation of Coproget's Roll Forming Line

The current chapter presents the numerical simulations of Coproget's CRF process to obtain the C-shaped profile corresponding to an automobile bumper beam. These simulations were developed using COPRA®RF, Marc® and COPRA®FEA RF. Therefore, the main goal of this chapter is to describe the steps taken to obtain an adequate simulation model to reproduce the roll forming line currently existing at Coproget and consequently the C-profile obtained from it. This chapter also presents the results and conclusions drawn from the simulations performed.

4.1 Base Model

4.1.1 Concepts

For the simulations performed for the C-section profile under study, the forming rolls were modelled as non-deformable rigid analytical bodies which move through space without changing their shape, while the steel strip was defined as a deformable model that can be meshed and deformed under load. Modelling the rolls as a rigid body does not enable the study of rolls deformation, but usually provides advantages at the level of computational efficiency (Halmos 2006; Forte 2021).

All bodies are deformable from a mechanical point of view. However, according to Kim (2015), since modelling is an abstraction of physical phenomena, it is possible to consider a body as a rigid body, which sometimes brings numerical advantages, since the numerical implementation of the deformable-rigid body contact formulation is much easier than the multi-body contact formulation. Furthermore, when two bodies have a large difference in stiffness, the stiffness matrix becomes ill-conditioned, and the matrix equation loses many significant digits, making it difficult to perform an exact calculation (Kim 2015).

The motion of rigid bodies is achieved by defining the position of their centre of rotation as a function of time. Rigid bodies are composed of a group of analytic NURBS surfaces and don't deform. Deformable bodies can contact rigid bodies but contact between rigid bodies is not generally considered (Marc 2021a). The treatment of rigid bodies as NURBS surfaces is quite advantageous since it provides a higher accuracy in the representation of the geometry and a more accurate calculation of the surface normal. Furthermore, the calculation of the frictional behaviour is better since the variation of the surface normal is continuous over the body leading generally to better convergence of contact results (Marc 2021a).

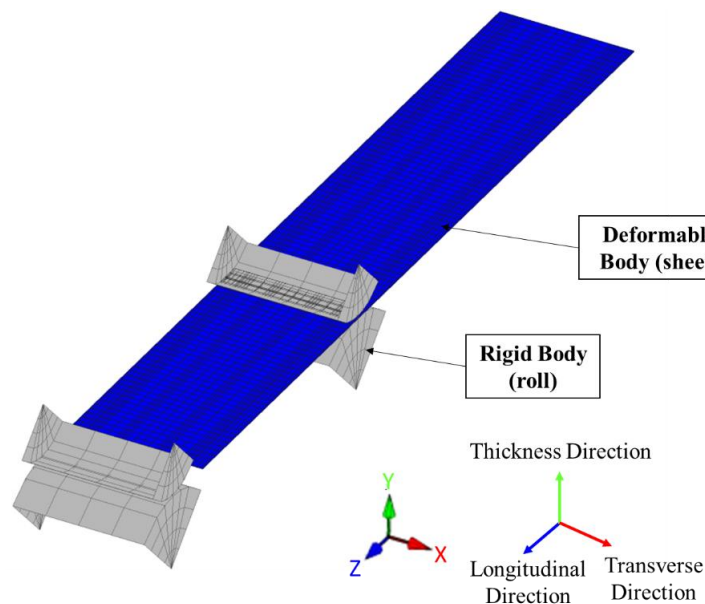


Figure 72 – Model geometry.

The standard global coordinate system (Figure 72) used for all the simulations was the following

- x for the horizontal direction perpendicular to the sheet rolling direction.
- y for the thickness direction when the sheet is flat (vertical);
- z for the sheet travel direction (forming direction).

In the simulation models conducted for the current C-profile, driven rolls were not used, that is, the frictional force between the rolls and the sheet was not considered. This consideration was made in order to reduce the computational time of the simulations performed. Therefore, in these simulations, the sheet remains fixed in place while the rolls move backwards in space without rolling, existing therefore a relative displacement between the rolls and the sheet (common simplification of the roll-forming process). For non-driven/non-friction models, the "speed" of the roll forming line is 1 mm / second. In turn, for the simulations with driven rolls, the rolls are fixed in space while the strip moves forward along the stations due to the frictional force, as it happens in reality (data M 2020).

4.1.2 Geometry, Flower and Rolls Design

The first step in the model design is the definition of the final profile shape. As represented in Figure 73, the final profile created for this project is a C-shaped profile with a length of 2345 mm, an initial thickness of 2.1 mm and a strip width of 231.35mm. Furthermore, this C-shaped profile is composed of 10 entities and presents the orientation of shown in Figure 74, both in the experimental process and in the simulations, in order to avoid the accumulation of lubrication and cooling fluid inside the part.

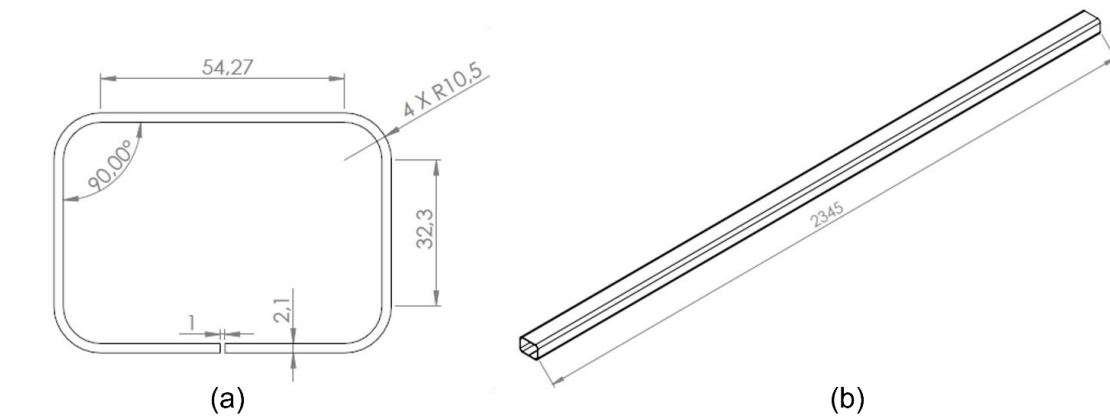


Figure 73 – (a) Cross-section of the C-section profile, (b) Isometric view of the C-section profile.

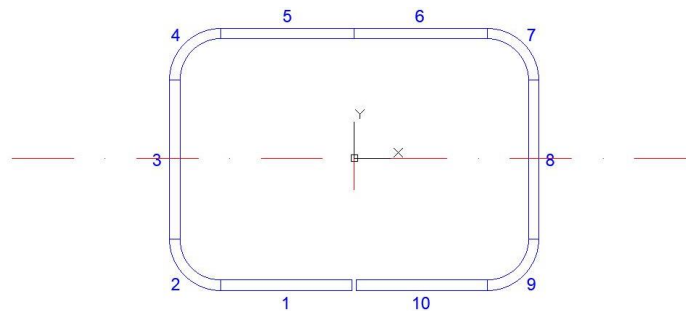


Figure 74 – C-section profile entities.

For a better optimization of the simulation time and computational costs (CPU time), a pre-cut sheet with a shorter length than the original one was used for the simulations performed. The length selected was 1400mm length (600×2.33mm). This sheet length was defined taking into account the distance between the main stations (600mm), in order to ensure the contact of the

sheet with the rolls in at least two successive stations (hence the multiplication by the value 2.33). This technique based on Data M's experience with numerical simulation of roll forming, provides better stability. The sheet was simulated without symmetry since the process is not symmetric from station eleven onwards, as represented in Appendix J, Figure J3.

The definition of the profile cross-section geometry, the flower pattern with the bending sequences, the machine stations and the development of the roll design is performed by COPRA®RF. In turn, the simulation models are automatically prepared by the COPRA®FEA RF package using the information previously developed in COPRA® RF.

- **Coproget's Roll Forming Line (16 stations)**

The initial Coproget's roll forming line for the production of the C-profile under study consisted of 16 stations, numbered from 0 to 15, where station 0 was the entry guide station and station 15 was the calibration station, as represented in Figure 75.

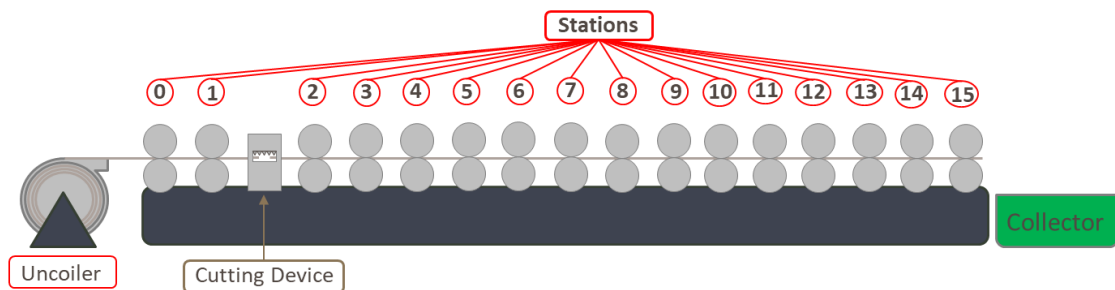


Figure 75 – Coproget's roll forming line with 16 stations.

Figure 76 shows the numerical model of Coproget's roll forming line with 16 stations to obtain the C-profile.

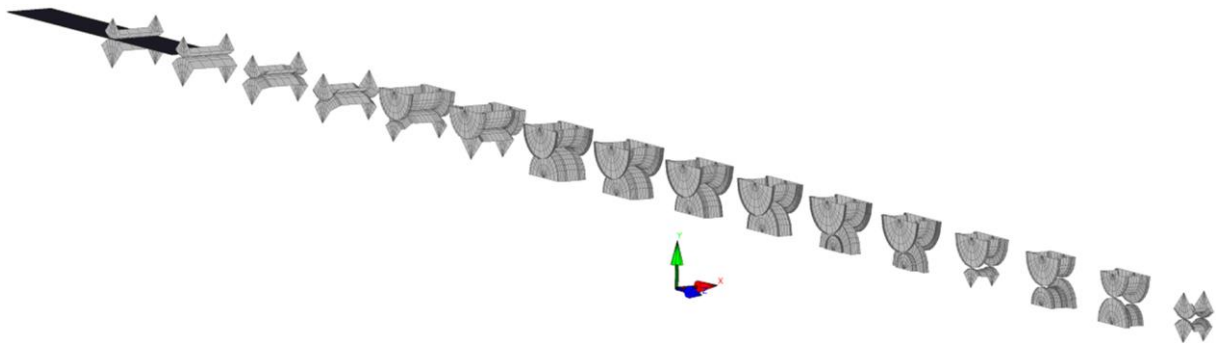


Figure 76 – Simulation model of Coproget's roll forming line with 16 stations.

The flower design for this line was not the most suitable (Appendix J, Figure J1), as it caused a sharp change in the position of the outer flanges between stations 13 and 14 (Appendix J, Figure J2), leading to pronounced contact problems during the strip travel between these stations. Consequently, this abrupt change of position and these contact problems between the outer flanges caused a large amount of waviness and twist on the final profile. These problems led Coproget to make changes to the flower design and subsequently to the line, namely adding 3 more principal stations, 4 sidebars, 2 side rolls and modifying 1 station, creating a new line with 25 stations. The first simulations conducted for the C-profile under study were performed for the roll forming line with 16 stations in order to verify if the behaviour previously presented experimentally by the C-profile was also represented by the simulations. The following simulations were performed for the company's current line with 25 stations as described following. The line with 25 stations is the line that will be studied and improved during this dissertation, since it is the current one.

- **Coproget's Roll Forming Line (25 stations)**

The flower pattern represented in Figure 77 depicts the forming steps of the profile cross-section currently produced by Coproget. The flower was developed by defining the bending sequence, Appendix J, Figure J3. This bending sequence is established by assigning relative angles between the profile entities of each station, starting from the station corresponding to the final profile until reaching the initial station whose profile corresponds to a flat strip. The design of the flower pattern plays an important role in the flow of the material and the magnitude of the stresses generated by the roll forming process. However, although the process consists of 25 stations, the stations corresponding to the side bars (12,14,16 and 19) were not accounted for the flower, since these components have variable cross-section.

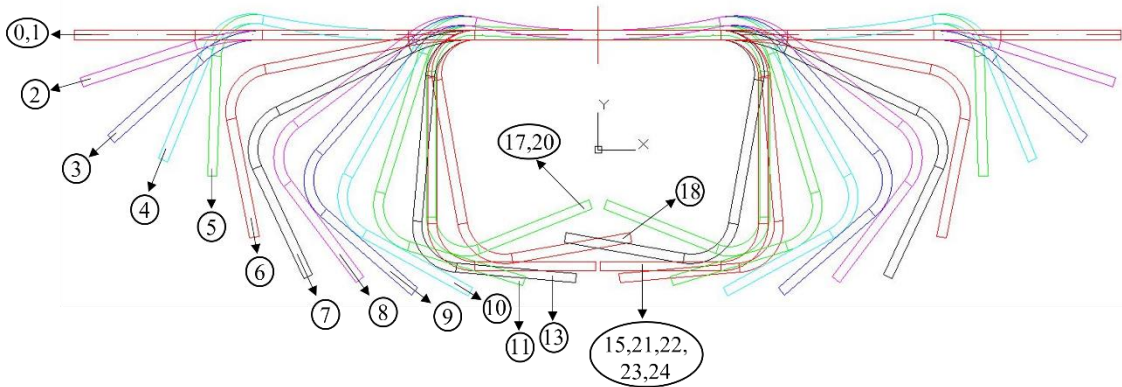


Figure 77 – Flower Pattern with the bending sequence of the C-section profile, for the process with 25 stations.

Coproget's current RF line used for the production of the C-profile under study is composed of 25 stations. The stations are numbered from 0 to 24, where station 0 is the entry guide station and station 24 is the calibration station, as represented in Figure 78. Furthermore, the distance between the main stations is 600mm and the distance between the main and secondary stations (which have side bars or side rolls) is 300mm.

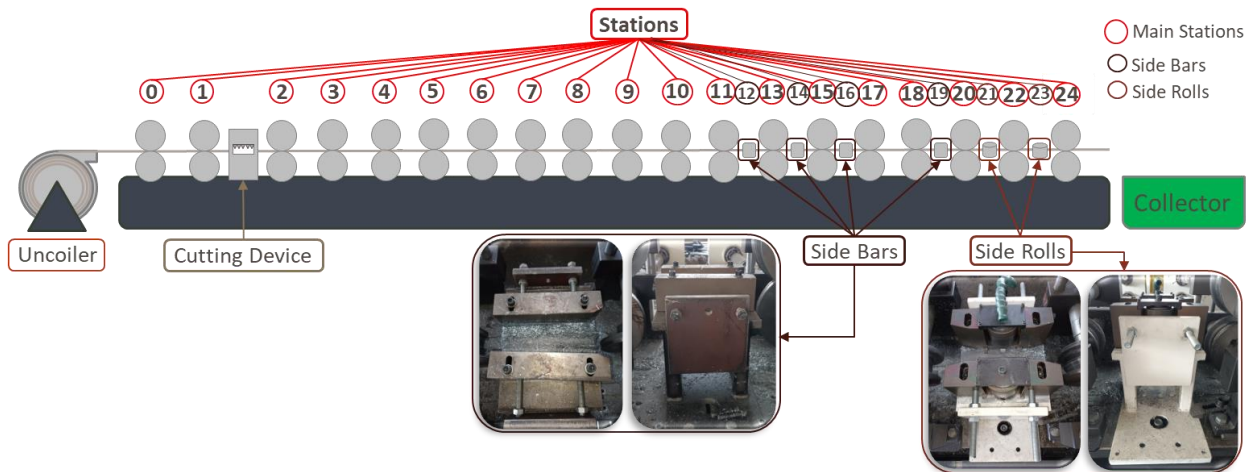


Figure 78 – Coproget's roll forming line (25 stations).

After the flower has been completed, it is necessary to define the drive diameters and check for maximum flange roll sizes and possible interferences with the rolling mill. The design of the stations and their respective rolls was made in order to replicate the experimental roll forming line existing in Coproget. In addition to designing the rolls (top, bottom and side rolls) it was also necessary to design the side bars present in Coproget's roll forming line (Figure 79).

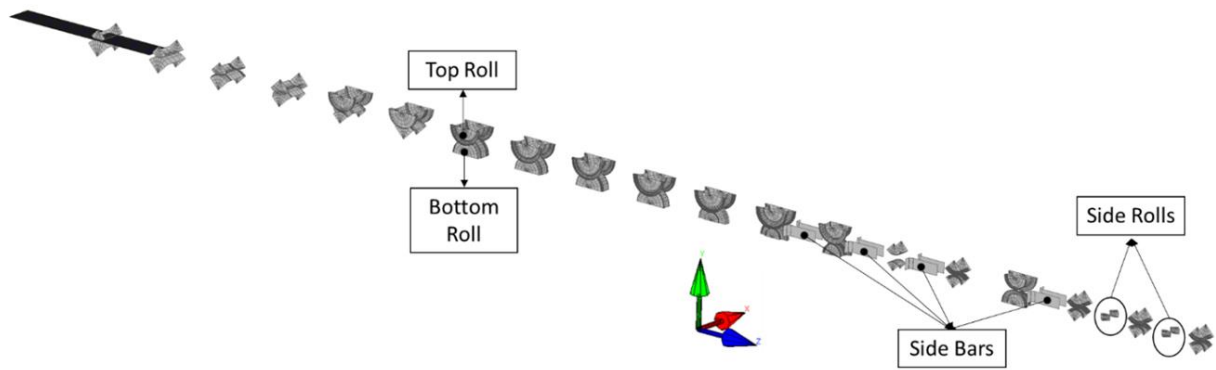


Figure 79 – Simulation model of Coproget's roll forming line (25 stations).

This task was extremely time consuming since it was necessary to perform the complete design of the line from the beginning using the information contained in the technical drawings of some rolls. In addition, for the side bars and some of the rolls, measurements were taken on the line in order to obtain its dimensions and then draw it. These measurements were necessary because some components were added at a later stage of the process to make some adjustments and therefore did not have technical drawings.

During the design phase of the RF process, it is essential to consider increasing the pitch diameters of the rolls from one roll station to the next in order to allow for successive increases in surface speed. This speed differential between passes is commonly referred to as "step-up" and allows the creation of a tension in the section material that eliminates the possibility of overfeeding or buckling between passes, which is common to appear particularly in the early stages of the process (Figure 80) (Paralikas et al. 2009).

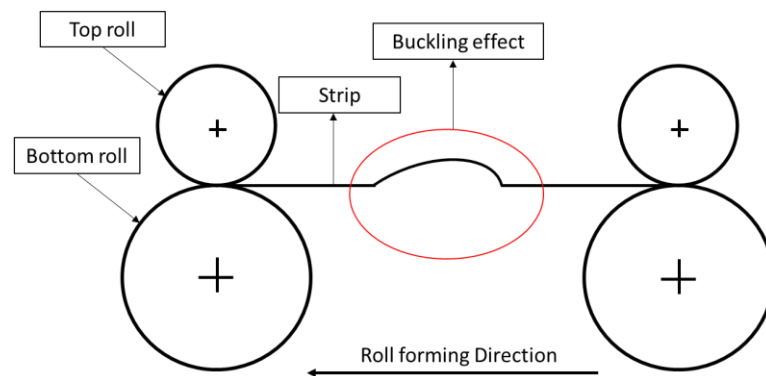


Figure 80 – Overfeeding or Buckling Effect.

This problem of overfeeding or buckling is caused when material from a previous pass is driving faster than the next. Therefore, the amounts of forming torque and surface contact on the rolls are the key factors in the occurrence of this problem. After the profile has ample column strength, the step up can be reduced or eliminated. Another factor to consider is that in pre-cut applications, over-increasing the drive diameters can lead to increased part lengths and/or distorted notches (Paralikas et al. 2013; Roll-Kraft n.d.; Halmos 2006). Therefore, the "step-up" consideration was also used for the roll design of the first stations of the RF process under study, since the bottom roll diameter increased slightly from station to station while the bottom roll diameter/top roll diameter ratio remained 1.395.

In Figure 81, it is possible to observe some precautions taken in the design of the rolls. For example, for the case of station 0 (Figure 81(a)), the top and bottom rolls were designed so that the ends of the part would be outside their contact surfaces. The part comes out of the rolls because in Coproget's roll forming line side spacers are used in this station that allow the adjustment of the rolls to the coil, since the coil can be supplied with slight variations in width.

If this technique were not used, any increase in the width of the coil in relation to the width defined in the roll design would make it very difficult for the part to enter the station. In turn, for the case of station 10 (Figure 81(b)), for example, it can be seen that for the inner surface of the top roll and the outer surface of the bottom roll (areas that contact the part) the sharp-edged corners have been eliminated and replaced by fillets with a small radius. This is done in order to avoid singularities detected by the software and that can generate numerical problems.

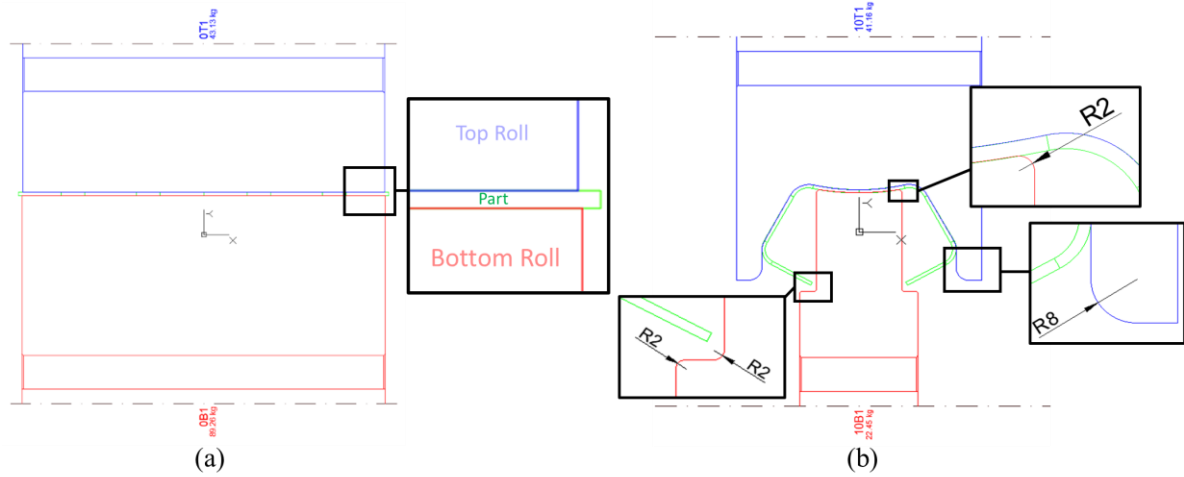


Figure 81 – Rolls design details: (a) station 0, (b) station 10.

4.1.3 Boundary Conditions

In order to prevent rigid body motion by the strip, giving more stability to the simulation, a Y-lock boundary condition was used on the tail end of the strip to restrain the displacement of the last three nodes in the Y direction (Figure 82). Only three nodes were selected, in order to allow the strip movement in this direction in the remaining nodes. The three selected nodes were the last three, since several experiments performed by data M proved that this location has the least influence on the RF process (Martins 2018). Furthermore, this restriction adds additional stiffness to the sheet and simplifies the computations in terms of convergence (GÜNER 2007).

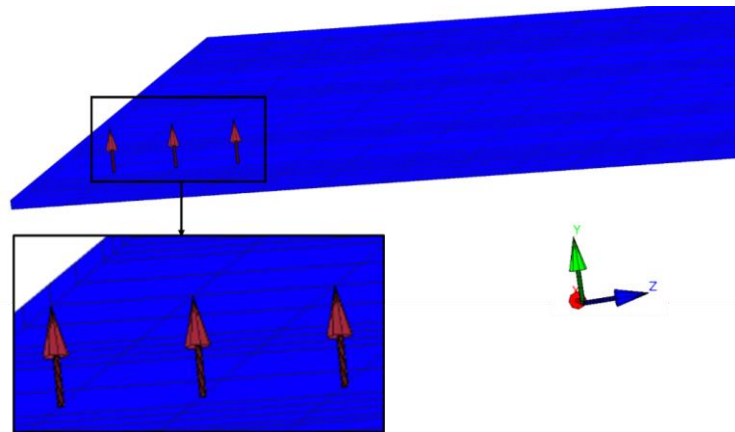


Figure 82 – Y- lock boundary condition: restriction of the three nodes in the middle of the tail end of the strip.

As depicted in Figure 83, at the tail end of the profile, an x-lock boundary condition was also used to contain the displacements in the x-direction of the last six nodes in the middle of the strip (three upper and lower nodes of the sheet layer) to prevent the strip from experiencing rigid body motions. The strip at the beginning of the process is very unstable and therefore this condition is critical to provide proper strip guidance at this stage.

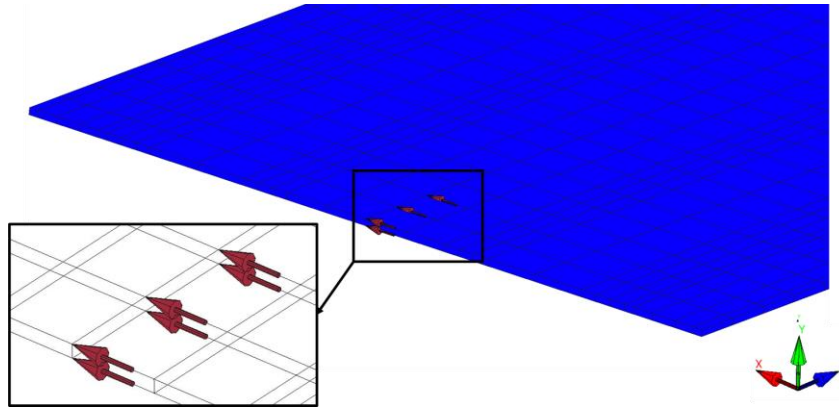


Figure 83 – X-direction boundary condition: restriction of the six nodes in the middle of the tail end of the strip.

In addition, as depicted in Figure 84, at the lead end of the strip, a z-lock boundary condition was used to fix the displacement of the six front nodes (three upper and lower nodes of the sheet layer) in the z direction.

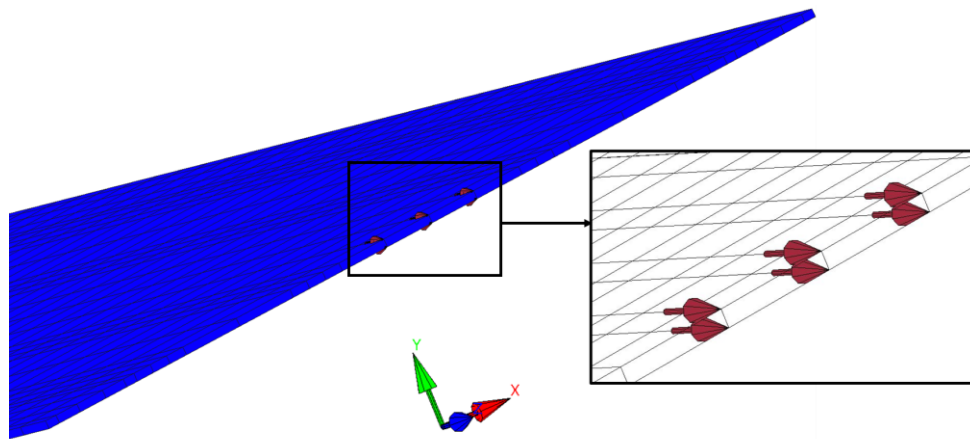


Figure 84 – Z-direction boundary condition: restriction of the six nodes in the middle of the lead end of the profile.

4.1.4 Element Type

Currently, there are 247 elements in the Marc element library. The element type chosen to perform all simulations of the C-profile under study, was the element type 7 of Marc element library. This element was chosen as it is the standard element used by data M in the COPRA® FEA RF package and typically used in most of their simulations since their practical experience shows it provides a good representation of the roll forming behaviour of steel materials. Furthermore, some previous studies and research conducted by data M showed that the use of shell elements is not appropriate for this type of analysis since the material behaviour is not constant through thickness and must be represented (Ferreira 2016; Marc 2021b). Therefore, element 7 used consists of a three-dimensional, eight-node, first-order, isoperimetric and arbitrarily hexahedral solid element with trilinear interpolation (Figure 85). Its nodes present three global degrees of freedom, which are the displacements, and don't account for rotations. Regarding the output variables, the element outputs six stresses and six strains (three normal and three shear) (Forte 2021). In addition, this element is used with the assumed strain formulation for a better representation of the bending behaviour and the element stiffness is determined using eight-point Gaussian integration (Marc 2021b).

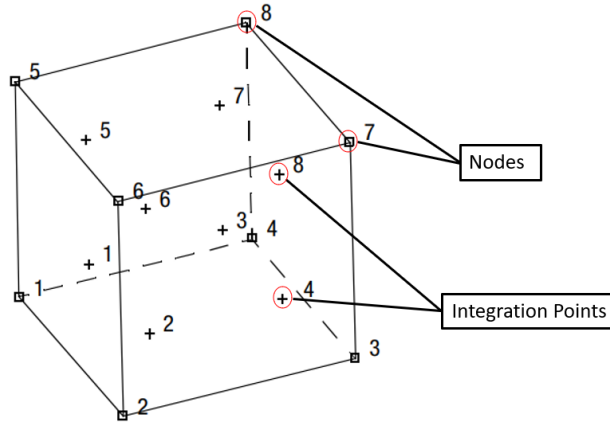


Figure 85 – Schematic representation of element 7 with eight-point gauss integration. Adapted From (Marc 2021b).

Since, this element uses trilinear interpolation functions, the strains tend to be constant throughout the element, which leads to a poor representation of the shear behaviour. Although there are other higher order elements available, which could be used as an alternative to this element, element 7 is recommended in contact analysis situation, which is the case of the present project (Marc 2021b).

Table 8 – Solid-7 element parameters(Marc 2021b).

Solid - 7	Nodes	Nodal degrees of freedom	Through-thickness integration layers	Points per integration layer	Stress outputs
	8	3	2	4	$\sigma_1, \sigma_2, \sigma_3,$ $\tau_{12}, \tau_{23}, \tau_{31}$

4.1.5 Mesh Definition

As described by Marc (2021a), “*mesh definition is the process of converting a physical problem into discrete geometric entities for the purpose of analysis. Before a body can undergo finite element analysis, it must be modelled into discrete finite element analysis*”.

According to Marc (2021a) to have a valid mesh definition it is necessary to place geometric coordinates and group nodes into elements. This can be accomplished in two ways:

1. Describing the element by entering the element number, the element type, and the node numbers that make up the element.
2. By entering the physical coordinates of the nodal points.

Mesh definition can be performed quickly using the COPRA2FEA pre-processing tool. This tool allows to perform and visualize the desired mesh refinement by interacting with the window in Figure 86. Furthermore, there is also the possibility of applying different mesh definitions for different areas of the strip.

The initial phase of this project of attempting to simulate the actual RF process existing at Coproget, involved a large number of simulations due to the various design modifications made. Thus, the mesh used for the base model was a coarse mesh, since a lower density of elements, although leading to less accurate results, provides shorter calculation times.

As represented in Figure 86, for the definition of the internal mesh size in COPRA2FEA the value 1 was used for the parameter "subdivisions of straight entities". In turn, for the number of subdivisions for arc entities the value 1 was selected and finally, for the number of subdivisions in rolling direction the value 0.3 was used. These parameters are initially set to the default value of 1 by COPRA2FEA. Over the width of the sheet, a refined mesh was used in the bend zones, since this is the area of higher strain values. In addition, a refined mesh was also used in the strip edge in order to model more accurately the interaction between the sheet and the roll, during the sheet's travel through the stations, particularly at the entrance of the rolls. Furthermore, the edge of the strip is also an area usually subject to longitudinal stress (Ferreira 2016).

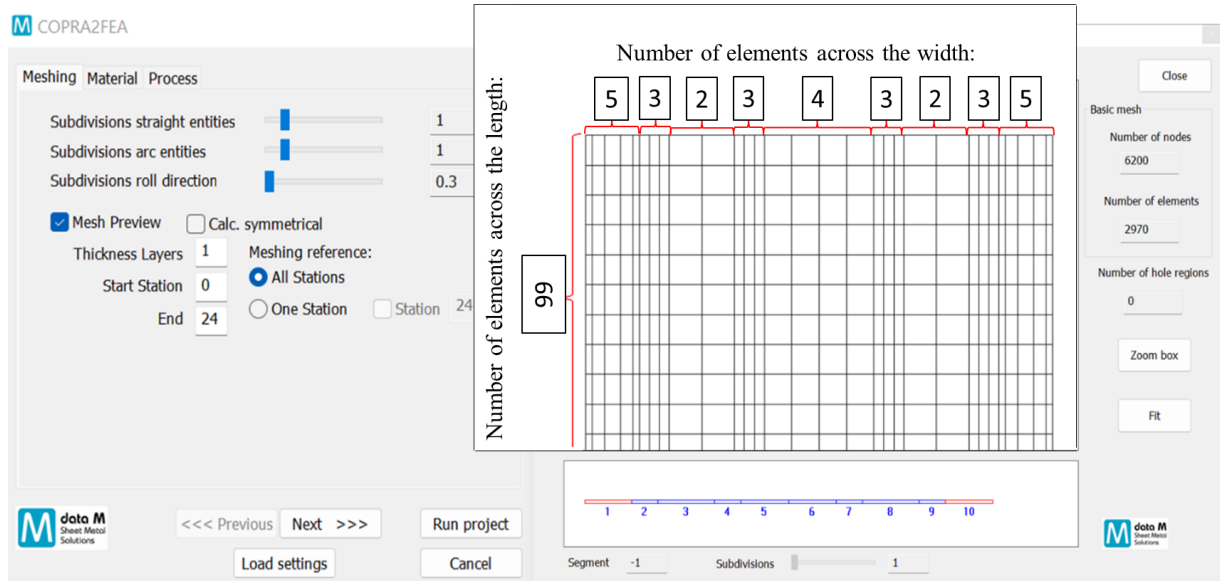


Figure 86 – Mesh preview in the mesh refinement tab.

In addition to the previously mentioned parameters, the number of element layers through thickness can also be defined. By default, the software also sets this value to 1. According to information provided by Data M, 1 element in thickness is sufficient to obtain geometrically accurate results. Forte (2021), also mentioned that only one element through thickness is sufficient to provide accurate results. As such, for the base model only one element through the thickness was used in order to reduce computational time. Therefore, the base model consists of 2970 elements and 6200 nodes.

4.1.6 Material Model

The material of the sheet was modeled as an elastic-plastic material with isotropic hardening, using the Swift's law (Swift 1952).

$$\overline{\sigma}_p = K(\varepsilon_0 + \overline{\varepsilon}_p)^n \quad (4.1)$$

Where:

- $\overline{\sigma}_p$ is the equivalent stress;
- $\overline{\varepsilon}_p$ is the equivalent plastic strain;
- K , n and ε_0 are material constants, determined usually in uniaxial tensile tests (Fernandes 1998).

The modelled material used for the reference simulation was Docol 1400M high strength steel.

The Swift's law parameters were calculated using the COPRA® FEA RF software, since the flow stress curve of the material was unknown. Thus, for the software to be able to describe the

plastic behaviour of the material, it was necessary to introduce some mechanical properties present in the technical data sheet of the material, namely the yield strength [MPa], the ultimate tensile strength [MPa] and the percentage of elongation [%] at the ultimate tensile strength. These mechanical properties introduced in the software are presented in Table 9:

Table 9 – Mechanical properties of Docol 1400 M introduced in the software.

Young`s modulus E [GPa]	Poisson`s ratio ν [–]	Yield Strength $R_{p0.2}$ [MPa]	Ultimate Tensile Strength R_m [MPa]	Elongation A_{80} [min %]
210	0.3	1150	1500	3

Based on the input values, the software is able to estimate the constants of Swift's hardening law. The calculated value for these constants are represented in Table 10.

Table 10 – Swift's hardening law parameters estimated by the software.

K [Mpa]	n [–]	ϵ_0 [–]
1828.8	0.03	0.0001

In the simulations performed, the Von Mises theory was used with isotropic hardening as the constitutive model since it is a common approach for roll formation simulations (Martins 2018). Regarding the sheet forming strategy, Data M recommended the use of the "pre-cut length" option with a value of 1400 mm instead of the "coil" option (continuous process). Although the raw material enters Coproget's RF process in coil form, the sheet cutting process is performed at a very early stage of the process (between station 1 and 2), where there is not yet any plastic deformation, hence the consideration made.

4.2 Results and discussion

4.2.1 Coproget`s Roll Forming Line with 16 stations

As previously mentioned, Coproget`s RF line with 16 stations (initial design phase of the current line) produced parts with twist and a large waviness on the outer flanges. These defects arose as a result of design problems in stations 13 and 14 that promoted a sudden transition in the position of the flanges, as well as the existence of contact between them.

In the simulations performed for this line it was verified exactly what was happening in reality. As can be seen in Figure 87(a), a significant contact was observed between the outer flanges due to the consecutive overbends at stations 13 and 14 (Appendix J, Figure J2). In addition, the existence of overlapping between the flanges was also observed due to the non-use of the contact strip function. According to data M experience, this function should only be used for simulations of specific profiles where there is contact due to 180 degree bends. In addition, the contact seen on the line was very unstable and therefore using this function would require a much more refined mesh on the edges of the component to accurately simulate the contact.

In addition, it was also verified that the profile obtained from the simulations showed waviness (Figure 87(b)) on the outer flanges as well as high twist (Figure 87 (c)), as happened in reality for the parts produced by Coproget's RF line with 16 stations.

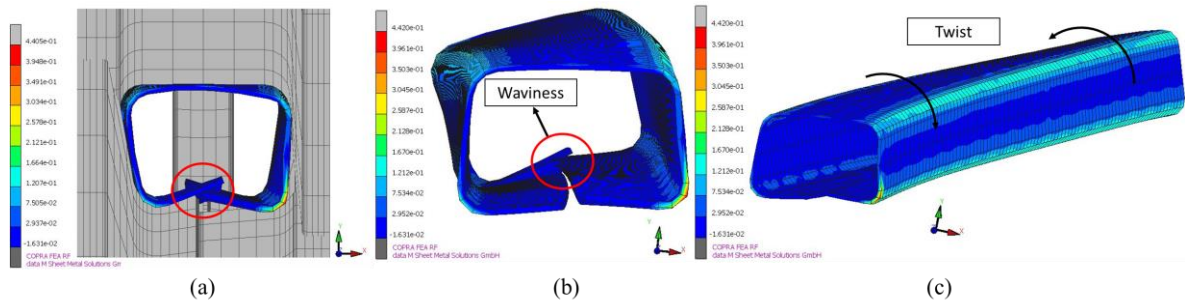


Figure 87 – Total Equivalent Plastic Strain Results: (a) Contact between the outer flanges at station 14; (b) Waviness on the outer flanges of the final part; (c) Twist in the final part.

4.2.2 Coproget`s Roll Forming Line with 25 stations

Since the current Coproget`s RF process, required the addition of several extra components (addition of 3 more principal stations, 4 sidebars and 2 side rolls and modification of 1 station) and several adjustments on them to become a relatively fluid process, the line replication in the simulations is extremely complex taking into account the finite element analysis software limitations. Therefore, in an attempt to simulate Coproget's RF line, these modifications were implemented in the simulation model. Since some components added to the Coproget`s RF line with 16 stations to form the actual process (rolls, side bars and side rolls) did not have technical drawings, it was necessary to perform measurements on the line in order to design them in Copra RF and then simulate them in Copra FEA RF. In turn, other components had associated technical drawings and were therefore designed based on these same drawings.

The simulations performed for the current line with the implemented modifications and added components revealed several collision problems of the profile with the rolls (Figure 88), demonstrating once again the difficulty of simulating the Coproget RF process due to the many manual adjustments made on the real line.

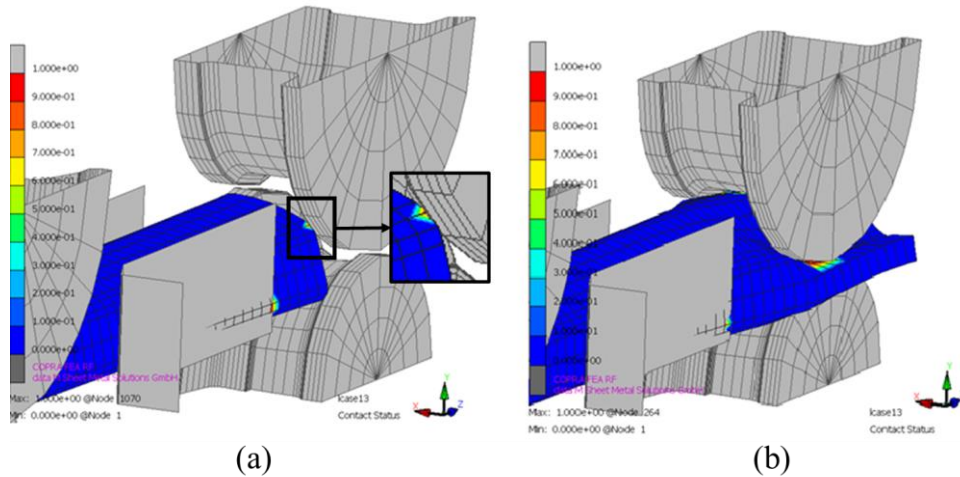


Figure 88 – (a) Contact status results of the part at the moment of collision with the roll of station 13; (b) Contact status results of the part after collision with the roll of station 13.

These problems in simulating the roll forming line are mainly due to the fact that it is practically impossible to accurately measure the dimensions of all the components added later to the line, as well as the relative position between the rolls and these same components. Due to the many manual adjustments on the line, the only possibility to accurately reproduce all components with the exact measurements in the simulation software would be through reverse engineering techniques (3D scanning), which unfortunately were not available for this dissertation.

- **Simulated Line Adjustments Stage**

Since it was not possible to simulate the process taking into account the technical drawings and the measurements of the components made on the line, data M advised to make manual adjustments to the sidebars in the simulation models, as was done in the experimental Coproget's RF line, in order to obtain a fluid and continuous process also in the simulations. These side bars do not introduce plastic deformation in the part (only elastic) and they help to guide the part into the gap between the top and bottom rolls in a fluid way. This adjustment procedure was necessary both experimentally and in the simulations because of the need to deal with high springback angles, common when working with high strength materials. Another recommendation provided by Data, was the use of drawing dies at the entrance to the rolls in order to avoid collision of the profile with the rolls and to make the profile entry into the gap between the top and bottom roll smoother. Drawing dies were added to all stations from station 13 onwards (except the stations that were side bars), as it was at this station that the first contact of the part with the rolls was observed (Figure 89).

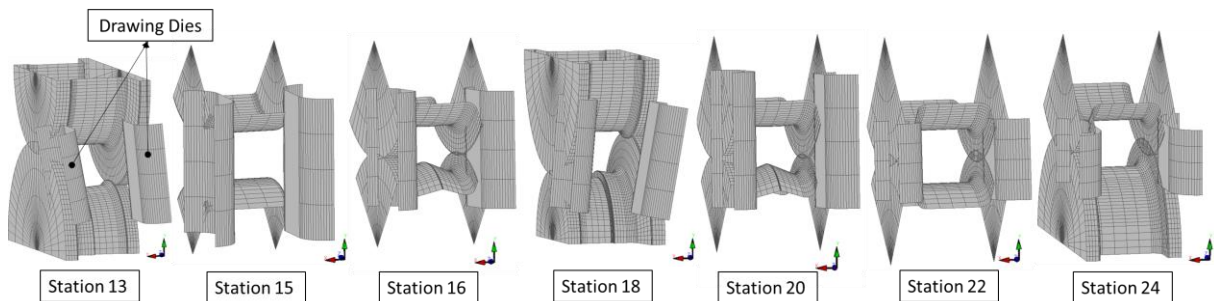


Figure 89 – Added drawing dies.

These components are not present in Coproget's RF line and are only useful for simulation purposes. According to data M, the drawing dies do not have significant influence on the final geometry of the profile obtained and are often used in numerical simulations to allow a smooth entry of the profile along the stations, particularly when it is intended to simulate lines that have several manual adjustments that cannot be represented numerically and therefore generate problems in the simulations performed. Thus, after performing simulations with drawing dies at the entrance of the rolls and with adjustments on the side bars, it was verified that the profile was able to reach the last station without colliding with the rolls (Figure 90).

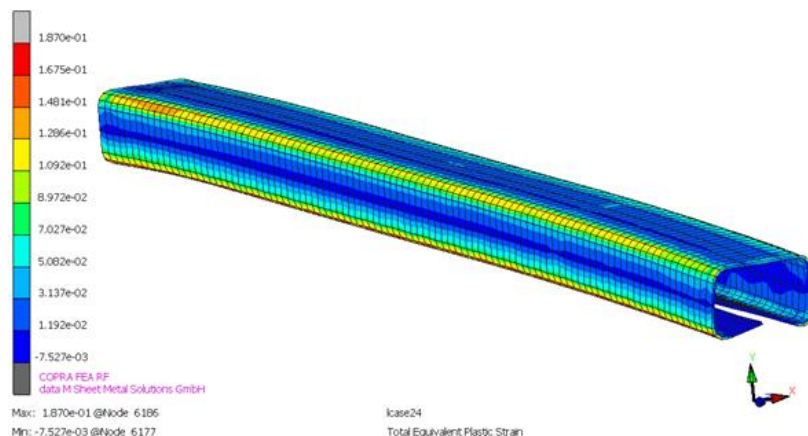


Figure 90 – Profile obtained after adjusting the side bars and adding drawing dies (Total equivalent Plastic Strain Results).

As can be seen in Figure 91, the addition of drawing dies allowed a better understanding of the additional adjustment needed to be made to the sidebars in order for the profile to pass through all stations without colliding with the rolls.

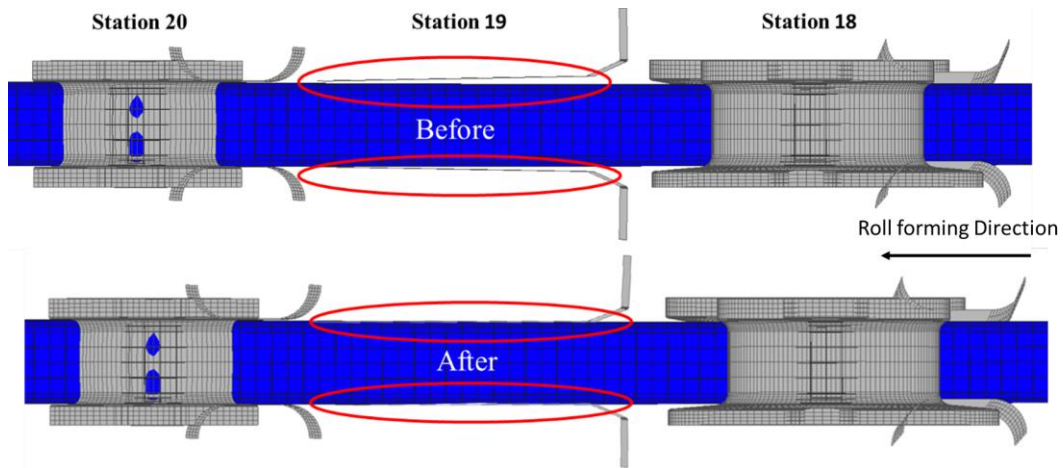


Figure 91 – Re-adjustment performed on the side bars.

Thus, a simulation was performed with the side bars adjusted, without drawing dies at the rolls' entrance, and it was verified that the profile reached the end of the simulation without colliding with the rolls, thus avoiding the need to use drawing dies (components that do not exist on the experimental line) in the following simulations. However, in the last stations (stations 22 and 24) it was verified that some nodes of the part got stuck in the rolls generating peaks as shown in Figure 92.

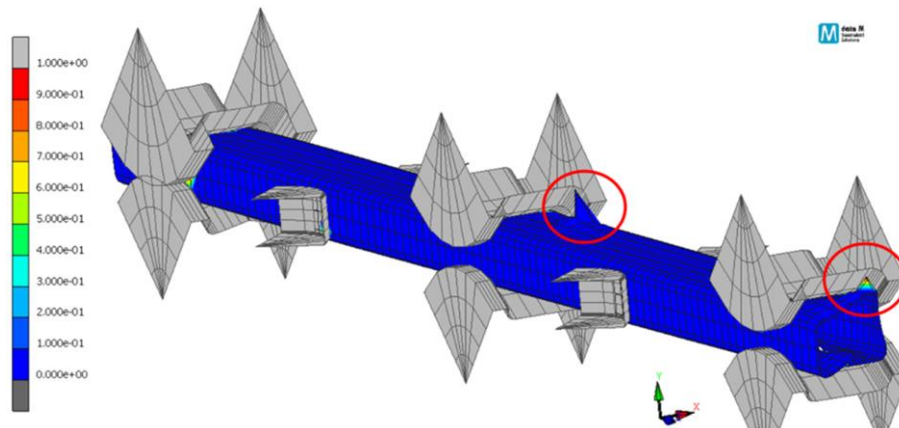


Figure 92 – Nodes stuck in the rolls and consequent peak generation (contact status results).

Once again, it was found that it would be very complicated to obtain a profile even with the adjustment of the components actually present on Coproget's RF line, due to the very tight restrictions of the process. Therefore, to solve this problem sidebars were added between station 17 and 18 in order to better adjust the sheet path that was a bit unstable between these stations (Figure 93).

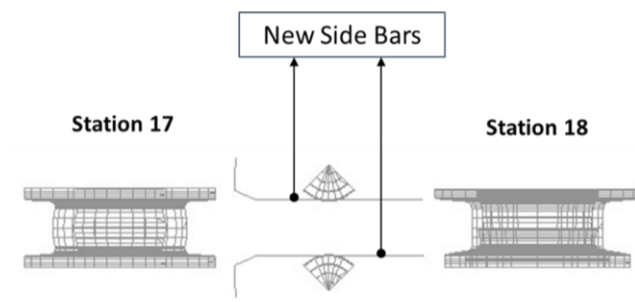


Figure 93 – (a) Side bars added between station 17 and 18.

With these new side bars the sheet was able to reach the end of the line. However, the profile geometry obtained was not similar to the profile obtained experimentally (Figure 94).

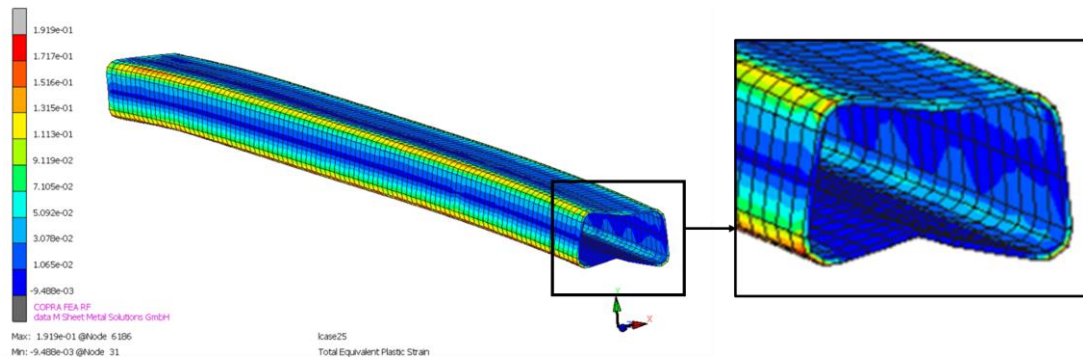


Figure 94 – Profile obtained after adding side bars between station 17 and 18 (Total Equivalent Plastic Strain Results).

- **Simulated Profile issues**

The first simulations were performed in order to position the various components of the line in an appropriate way, namely the side bars, so that the profile would reach the end of the simulations without the occurrence of collisions with the rolls. However, it was concluded that although the profile was able to reach the end of the simulations, it did not present similarities with the profile obtained from Coproget's RF process. This may be due to the fact that Docol 1400M is a high strength material with a springback of about 10° and therefore any station where the behaviour of the material is not being reproduced properly can have a drastic influence on the behaviour of the material in the following stations and consequently on the final profile obtained. Therefore, for the following simulations, a comparison of the behaviour of the simulated profile with the behaviour of the experimental profile in each forming stage was performed, in order to identify problems existing in the simulated process and thus obtain a profile similar to the profile currently produced by Coproget. Therefore, whenever numerical problems were identified in the simulations performed, or whenever the behaviour of the simulated profile was far from that observed for the experimental profile, the simulations were stopped at that point, the station immediately before the problem occurred was adjusted (improved) so that the problem was solved, and only after the behaviour of both profiles was identical were the next stations simulated.

Analysing the simulations performed for Coproget's RF line from the first station (station 0), it was found that there was no problems in the process until station 5. However, it was found that lateral edge contact is prone to occur in some stations of the RF line (from station 5 to 11), starting at station 5. This lateral edge contact is also observed for the same stations in Coproget's RF line, such as station 7 (Figure 95). However, although this contact is also observed in the experimental line, it should be avoided or reduced in order to prevent excessive deformation of the flange edge of the strip and thus avoid defects such as waviness. Furthermore, the existence of this contact should be taken into consideration for process improvement. However, since the objective in this section is to reproduce a simulated profile identical to the experimental profile and not an improved profile, no change was made in this regard.

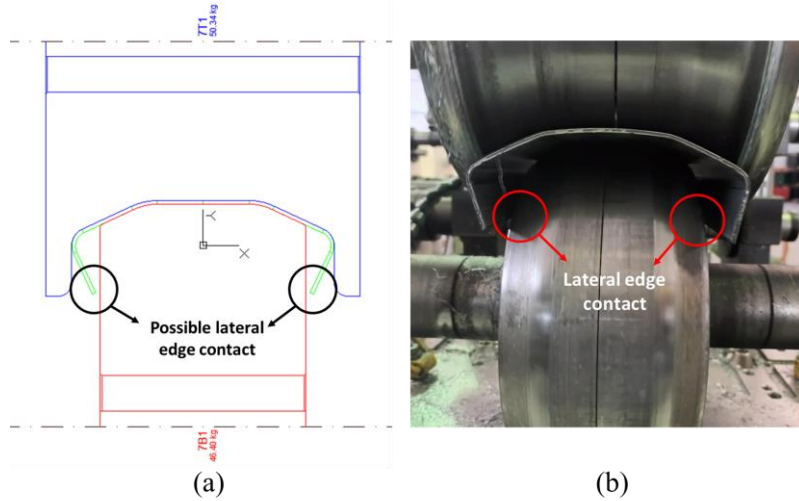


Figure 95 – (a) Possible lateral edge contact due to roll design of station 7; (b) Lateral edge contact at station 7 of Coproget's RF process with 25 stations.

Figure 96(a) shows the contact status of the nodes, highlighting the existing lateral edge contact for station 7. The red areas indicate that a node is establishing contact with a roll. As depicted in Figure 96(b), these nodes are subjected to a lateral contact force F_c whose magnitude is calculated as:

$$F_c = \sqrt{F_{cX}^2 + F_{cY}^2 + F_{cZ}^2} \quad (4.2)$$

Where:

- F_{cX} , F_{cY} and F_{cZ} correspond to nodal quantities of the contact normal force in the X, Y and Z directions respectively.

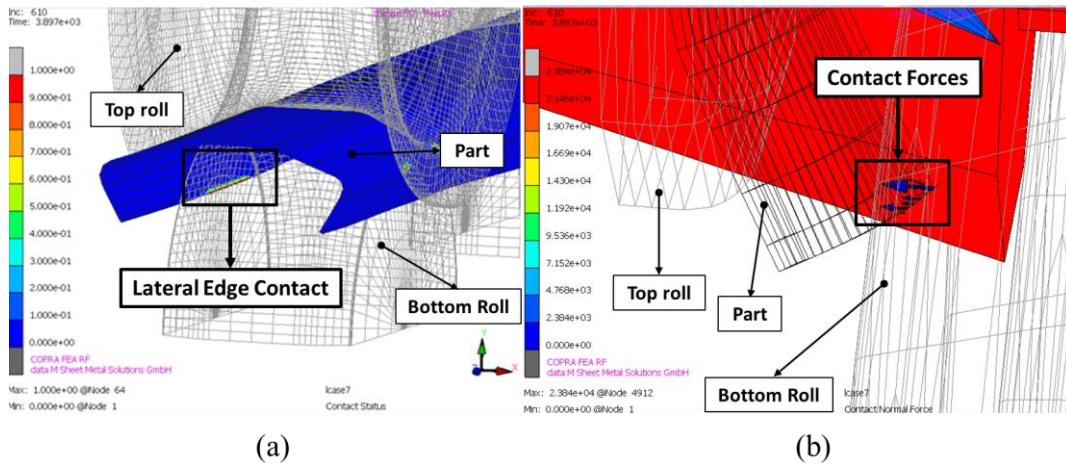


Figure 96 – Situation of lateral edge contact in station 7: (a) Contact status results; (b) Contact normal force results. Vectors indicate the contact forces in each node.

Furthermore, during the simulations performed it was verified that at some stations, the profile cross-section geometry was far from the experimental profile cross-section and even further from the desired cross section (flower cross-section), due to forming problems associated with the high strength of the material.

After a simultaneous analysis of the simulations performed and the experimental process, it was found that up to station 9 both the experimental and the simulated profile always present an identical geometry that perfectly follows the contour of the rolls at each station, i.e., the profiles cross-section presents always the desired shape (flower cross section) at each station.

However, as can be seen in Figure 97, at station 10, the profile does not deform according to the roll contour (desired cross-section shape of the flower) and there is a penetration problem between the part and the bottom roll.

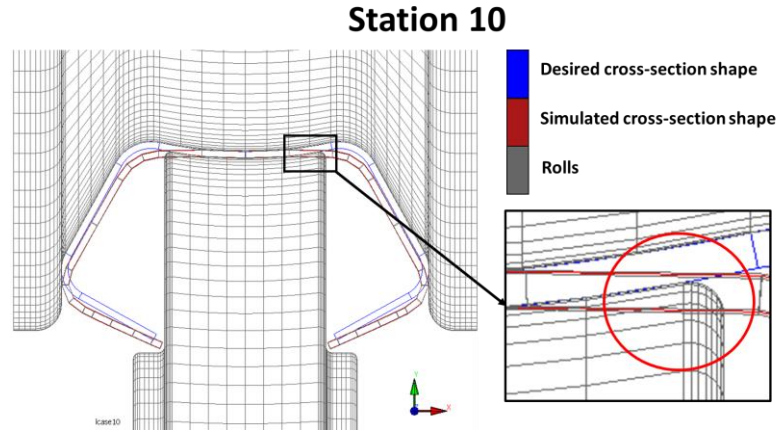


Figure 97 – Penetration problem at station 10.

In numerical simulations, two bodies in contact are distinguished using the master-slave concept, with one of the bodies being referred to as the slave and the other as the master. The slave body is controlled by a contact condition that ensures that it does not penetrate the master body (Fernanda 2017). Therefore, since this contact condition is only implemented in the slave body, the master body can penetrate the slave body during simulations, although this is physically impossible in reality. In the case of flexible-rigid body contact, the rigid body is selected as the master body and the flexible body as the slave body (Kim 2015). Thus, as can be seen in Figure 98, when a curved boundary with a fine mesh is selected for the master (rolls in the case of the simulations performed) and a flat boundary with a coarse mesh is set for the slave (strip in the case of the simulations performed) a significant amount of penetration is visible without the node of the slave body (strip) penetrating the master body (rolls), as happens in station 10 during the simulations. Thus, according to Fernanda (2017) to minimize numerical errors, the master body (rolls in the case of the simulations performed) should have a coarser mesh and the slave (strip in the case of the simulations performed) should have a finer mesh.

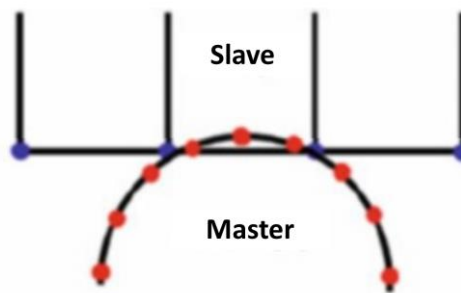


Figure 98 – Definition of master and slave in numerical simulations. Adapted from Kim (2015).

In order to investigate whether the penetration problem was due to the mesh used being too coarse, two simulations with an intermediate refinement mesh (Figure 99 (a)) and a refined mesh (Figure 99(b)) were performed, also using an element in thickness. The number of elements used along the strip length was 99 for both meshes, as for the base model mesh.

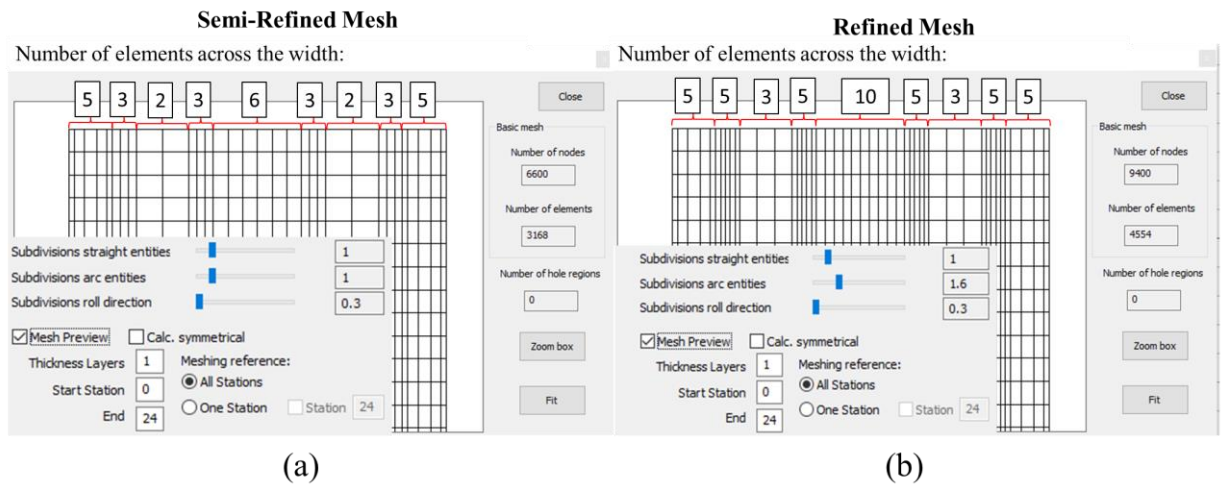


Figure 99– (a) Semi-refined mesh parameters; (b) Refined mesh parameters.

The penetration results obtained for the semi-refined mesh and for the refined mesh under study is represented in Figure 100.

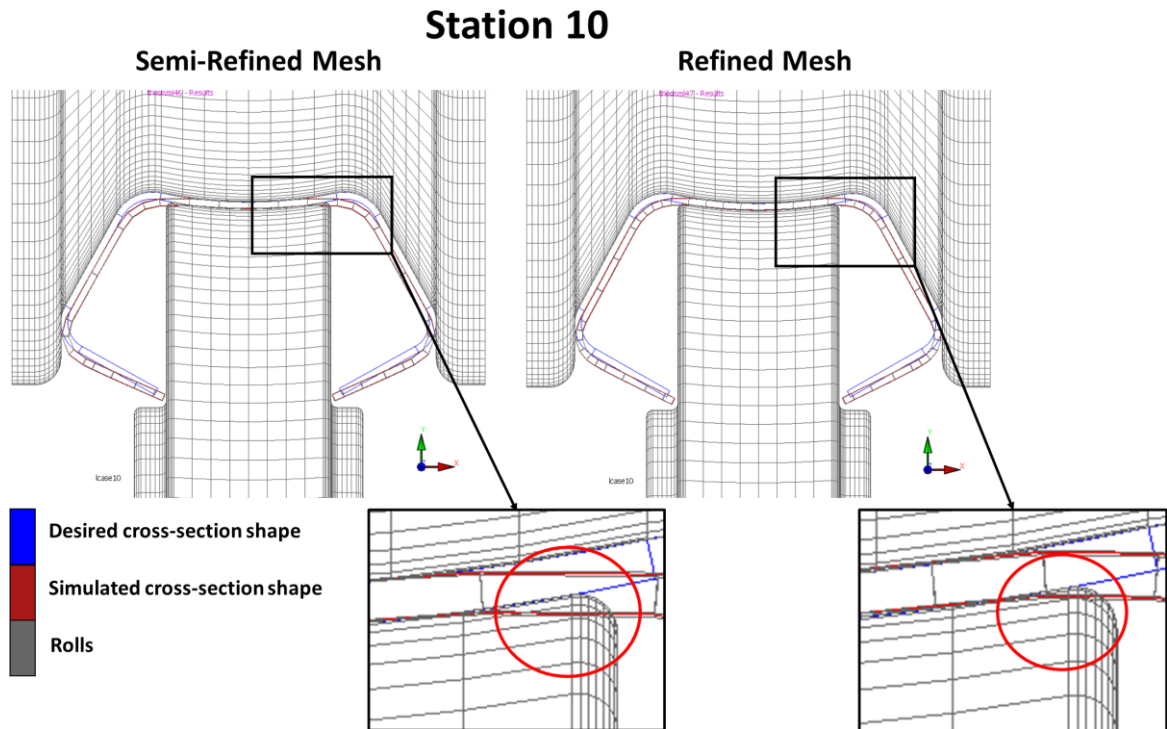


Figure 100 – Penetration problem results for the semi-refined and refined mesh (station10).

It can be seen that the penetration problem was due to the mesh, as further mesh refinement greatly reduced this effect. Although the more refined mesh shows better penetration results than the semi-refined mesh, the differences in terms of cross-section shape are negligible. The profile still does not follow the contour of the rolls (flower cross-section).

However, as can be seen in Figure 101, the experimental profile does not follow the contour of the rolls either, which means that the profile is being well simulated up to this station.

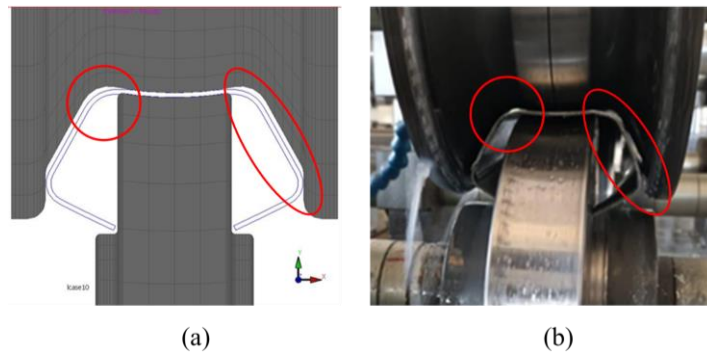
Station 10

Figure 101 – (a) Simulated profile cross-section (station 10); (b) Experimental profile cross-section (station 10). Subsequently, at station 11, the same penetration problem occurred (Figure 102).

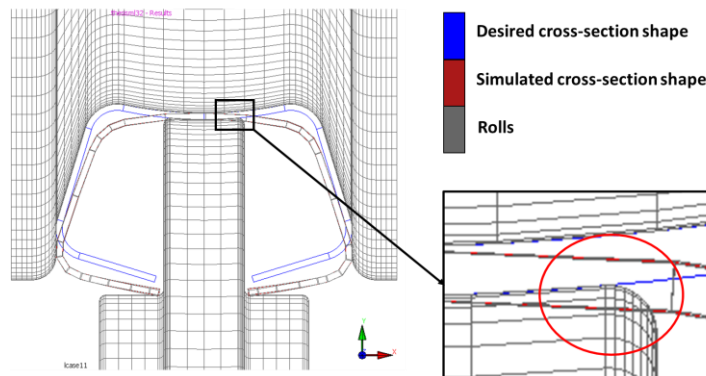
Station 11

Figure 102 – Penetration problem at station 11.

In order to confirm that the penetration problem was due to the mesh, two more simulations were also performed with the same semi-refined and refined mesh used for the station 10 simulations. As can be seen in Figure 103, the penetration problem was reduced greatly compared to the simulation with a coarse mesh (base model mesh). However, comparing the semi-refined mesh with the refined mesh, there were no significant differences in the penetration dimension.

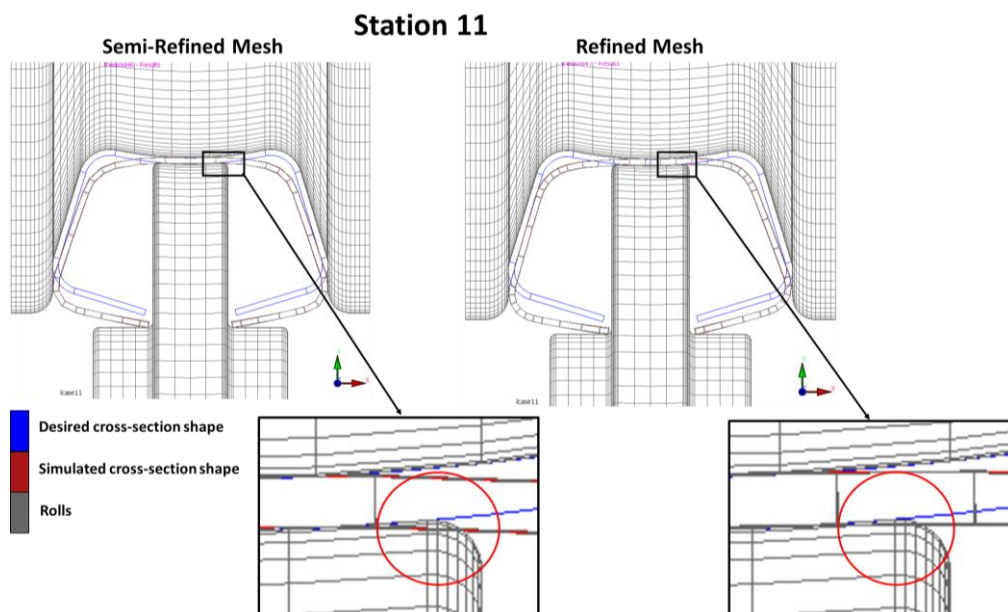


Figure 103 – Penetration problem results for the semi-refined and refined mesh (station 11).

Although the penetration phenomena have been greatly reduced with mesh refinement, the shape of the cross-section of the profile still remains far from the desired shape (contour of the rolls) (Figure 104 (a)). However, as can be seen in Figure 104(b), the experimental profile also does not follow the roll contour adequately, which means that the profile is also being well simulated up to this station.

Station 11

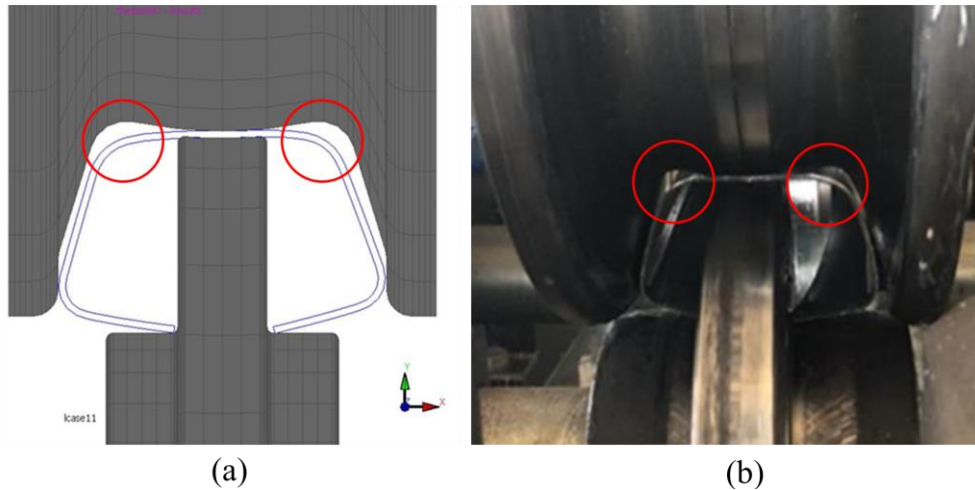


Figure 104 – (a) Simulated profile cross-section (station 11); (b) Experimental profile cross-section (station 11).

Subsequently, analysing station 13, after the profile had passed through the first sidebar (station 12), it was found that the cross section of the simulated profile (Figure 105(a)) was far from the cross section of the experimental profile (Figure 105(b)), namely in the web and in the side and outer flanges of the right, as can be seen in the areas surrounded in red.

Station 13

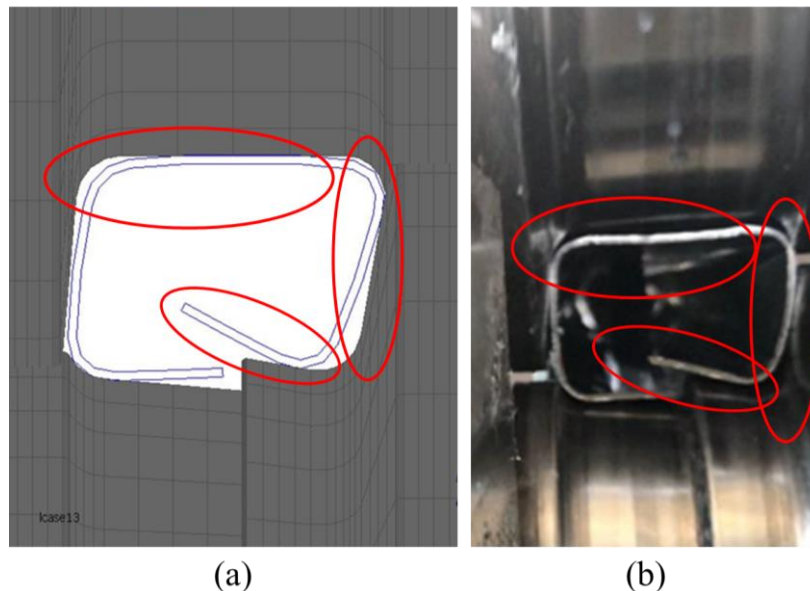


Figure 105 – (a) Simulated profile cross-section (station 13); (b) Experimental profile cross-section (station 13).

Thus, two more simulations were also performed, one with an intermediate refinement mesh and another with a refined mesh, in order to check whether the profile shape was close to the desired one or not.

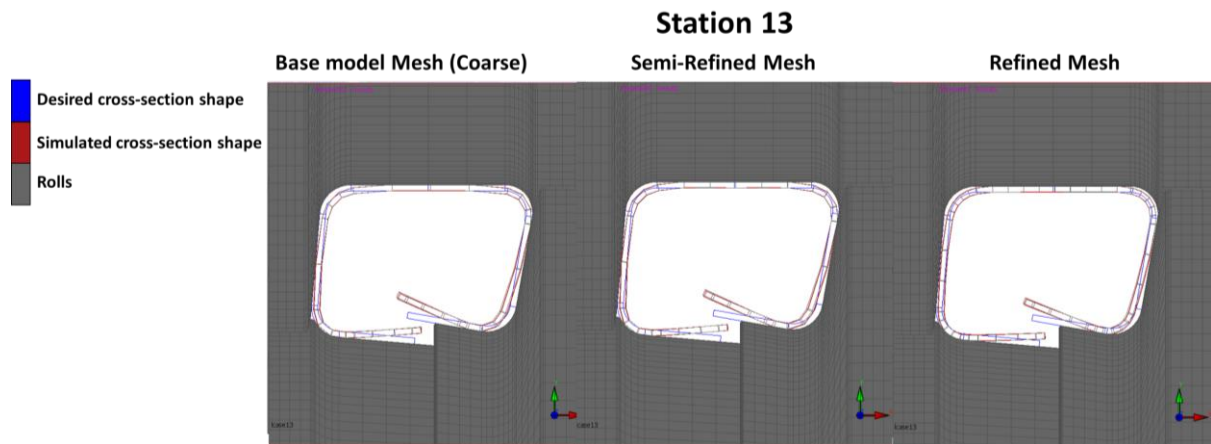


Figure 106 – Cross section variation at station 13 with mesh refinement.

By testing different mesh types, it was possible to conclude that increasing mesh refinement did not cause significant improvements in the profile cross section at this station.

• Upcoming Challenges in C-Profile Simulation

Since adequate results were not obtained for station 13 with further mesh refinement, it was decided to perform a parametric study in order to understand how other process parameters influence the simulations of the profile under study and in order to understand which process parameters should be used or modified to bring the simulated profile closer to the intended profile. To perform the parametric study a set of stations should be considered for which the cross section of the simulated profile is identical to that of the experimental profile and which follows the contour of the rolls at each station (the cross section obtained should be equal to the flower cross section for each station).

As previously mentioned, the simulations performed in the present chapter revealed that up to station 9 the profile exhibits exactly the same forming behaviour as the experimental profile. Moreover, in both the experimental and simulated processes, the profile cross sections at each station present the desired shape until station 9 (the obtained cross section is equal to the flower cross section). These results indicate that apparently the profile is well simulated up to station 9. However, in order to check if the profile is really well simulated up to this station, a comparative analysis was performed between the vertical displacement of the simulated and the experimental part along the RF line.

Figure 107 shows the graph of the vertical displacement of the profile along the path between two stations. This path begins at the increment corresponding to the moment when the profile passes through the median plane of the rolls at the first station and ends at the increment immediately before the contact between the profile and the rolls at the next station.

Through this analysis, it was found that the vertical movement of the profile in the simulations is identical to that observed in the experimental line. Analysing Figure 107, it is possible to observe that for the paths between stations 2 and 3 and between stations 3 and 4 there is a greater oscillation of the vertical displacement of the strip. These oscillations verified in the initial stations of the process also occur in the experimental process due to the greater instability during the entry of the strip in these stations. Furthermore, it was found that the most accentuated upward movement of the strip occurred for the path between stations 4 and 5 and between stations 5 and 6. In turn, the most pronounced downward movement occurred for the path between stations 6 and 7 and for the path between stations 7 and 8. As can be seen in Figure 108, the vertical upward movement of the profile was also higher for the paths between stations 4 and 5 and between stations 5 and 6, as observed in the experimental process and in Figure 107. In stations 5 and 6, the strip contacts the top roll at a high y-axis position in both

the experimental and simulated process indicating a sharp upward movement (Figure 108). The same similarity was found for the downward movement of the part between stations 6 and 7 and stations 7 and 8. In stations 7 and 8, the part contacts the top roller at a low y-axis position for both the real and simulated process indicating a sharp downward movement (Figure 108).

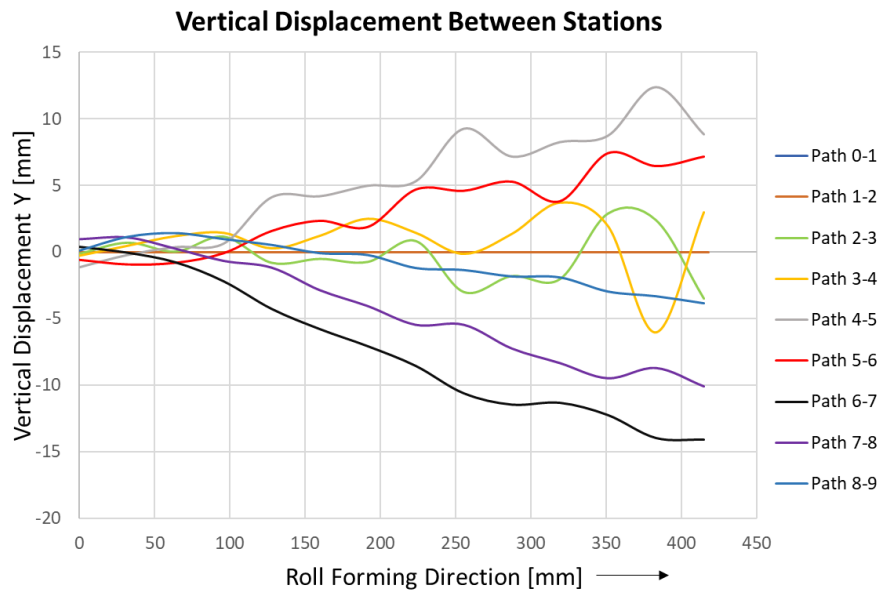


Figure 107 – Vertical Displacement y between stations (paths) [mm].

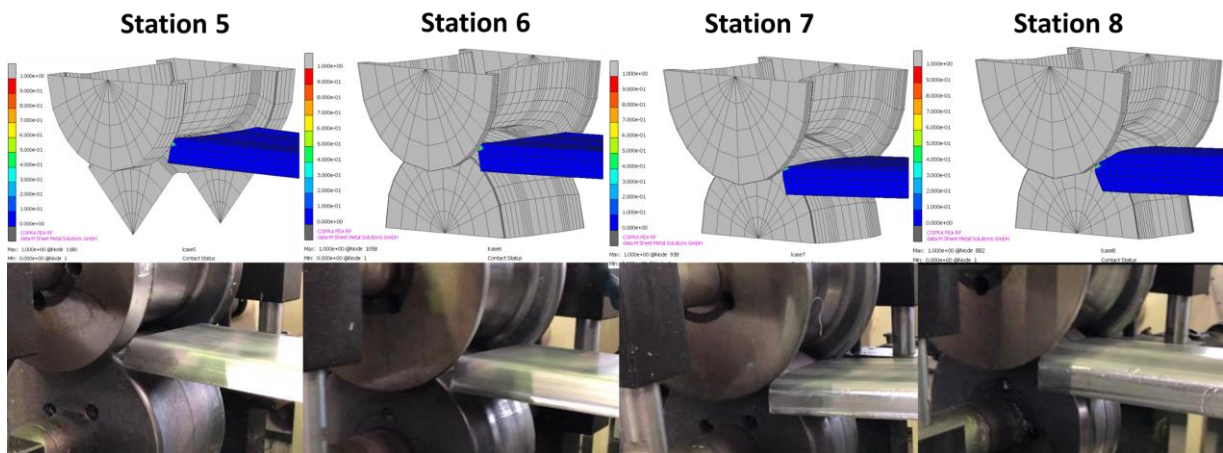


Figure 108 – First contact of the rolls with the stations.

Therefore, for the parametric study only the first 10 stations of the process (0-9) were considered, since the simulations performed in the present chapter revealed that until station 9 the profile presents exactly the same formation behaviour as the experimental process. This parametric study is presented in Chapter 5.

However, according to Data M's experience, the results obtained from the parametric study should be used, not to try to reproduce a simulated profile close to the experimental one, but to obtain a simulated profile that follows the roll contour (cross section of the flower) in an appropriate way at each forming stage, that is, a simulated profile with a better forming than the experimental profile. This advice provided by Data M is due to the fact that the RF process under study is extremely difficult to simulate as in reality, due to the numerous manual adjustments made on the line. According to Data M, simulation software is primarily used to help improve the design of roll forming lines and not to try to simulate the processes exactly as they are in reality. Furthermore, according to Data M, a simulated profile obtained from

improving the design of the process stations will be quite identical to the experimental profile obtained from Coproget's roll forming process if the design modifications made in the simulated process are also imposed on the experimental line.

In this sense, chapter 6 of this dissertation presents the steps for improving the process starting at station 10. Whenever at a forming stage, the profile presents a cross section far from the desired cross section (floral cross section) the immediately preceding station or the station in question is corrected. The aim of these simulations is to obtain a profile with a better forming and, consequently, with less significant defects than those currently observed in the C-profiles produced by Coproget. These improvement solutions should be implemented later on Coproget's experimental RF line to be validated.

5 Parametric Study of Coproget's Roll Forming Line

In the present chapter are presented the simulations performed for the parametric study of the first 10 stations (0-9) of Coproget's RF line, as well as the respective parameters under study (Table 11). The parametric study was carried out only for the first 10 stations of Coproget's RF line, since for the previously simulations presented in chapter 4, the profile did not present any numerical or forming problems during the path between these stations. Simulation 1 is the reference simulation of this study, since all the following simulations are obtained through this one, varying only one parameter at a time. All simulations performed have the same mesh and element type as the reference simulation. The aim of these simulations is to study the influence that different process and profile parameters have on the C-profile produced by Coproget, during its travel between station 0 and station 9. After understanding the influence of different parameters on the process and on the profile in question, it is intended to make a selection of the most suitable parameters for a fast and accurate reproduction of the material behaviour in order to be subsequently used for the improvement simulations of the following stations of the line.

Table 11 – Parametric study proposed for the first 10 stations of the roll forming line used for the production of the C-shaped profile under study.

Simulation Number	Material	Number of Stations	Radius/Thickness ratio	Roll Diameter	Driven Rolls	Cut Type	Shaft Type
1	Docol® 1400M	10	4	Standard	No	Pre-cut	Rigid
2	MartINsite® 1500 ^a	10	4	Standard	No	Pre-cut	Rigid
3	Domex 500MC ^b	10	4	Standard	No	Pre-cut	Rigid
4	Docol® 1400M	13 inc ^c	4	Standard	No	Pre-cut	Rigid
5	Docol® 1400M	13 non-inc ^d	4	Standard	No	Pre-cut	Rigid
6	Docol® 1400M	10	8 (standard radius/ reduced thickness)	Standard	No	Pre-cut	Rigid
7	Docol® 1400M	10	8 (standard thickness/ increased radius)	Standard	No	Pre-cut	Rigid
8	Docol® 1400M	10	4	Increased ^e	No	Pre-cut	Rigid
9	Docol® 1400M	10	4	Standard	Yes ($\mu=0.2$) ^f	Pre-cut	Rigid
10	Docol® 1400M	10	4	Standard	No	Coil with final cut	Rigid
11	Docol® 1400M	10	4	Standard	No	Pre-cut	Deformable

^a Mechanical properties of MartINsite® 1500 steel are presented in section 3.1.1.

^b Mechanical properties of Domex 500MC steel are presented in Appendix B, Table B1-B2.

^c 13 incremented stations. The new stations were added, between stations 6 and 7, 7 and 8, and 8 and 9 of the reference mode. The increment of the bending angles was reduced by half starting at station 6.

^d 13 non-incremented stations. The new stations were added, between stations 6 and 7, 7 and 8, and 8 and 9 of the reference model. However, the stations added for this new model do not have a gradual bending angle, but rather a bending angle for each entity exactly the same to that of the immediately preceding station.

^e The diameter of the bottom rolls was increased by 40 mm and the bottom roll diameter/ top roll diameter ratio was maintained at 1.395.

5.1 Base Model (reference model)

The base model used for the simulations of the first ten stations of the process is identical to the base model previously presented in section 4.1, varying only the mesh and boundary conditions.

5.1.1 Concepts

- The forming rolls were modelled as non-deformable rigid analytical bodies while the steel strip was defined as a deformable model;
- Driven rolls were not used, that is, the frictional force between the rolls and the sheet was not considered, in order to reduce the computational time of the simulations performed;
- A pre-cut sheet with 1400mm length was used for the simulations performed in order to save computational time;
- The strip was simulated with symmetry since the process is symmetric until station 13;
- The rolls have the dimensions of Coproget's roll forming line without any changes in design.

5.1.2 Boundary Conditions

For the base model of the parametric study, a boundary condition was used to contain the displacement in the Y direction of the last three nodes at the tail end of the profile (as had been done previously for the base model of section 4.1) (Figure 109(a)), so that the strip did not experience rigid body motion, giving more stability to the simulation. In addition, as depicted in Figure 109 (b), at the lead end of the strip, a z-lock boundary condition was also used to fix the displacement of the nine front nodes (three nodes per layer) in the z direction.

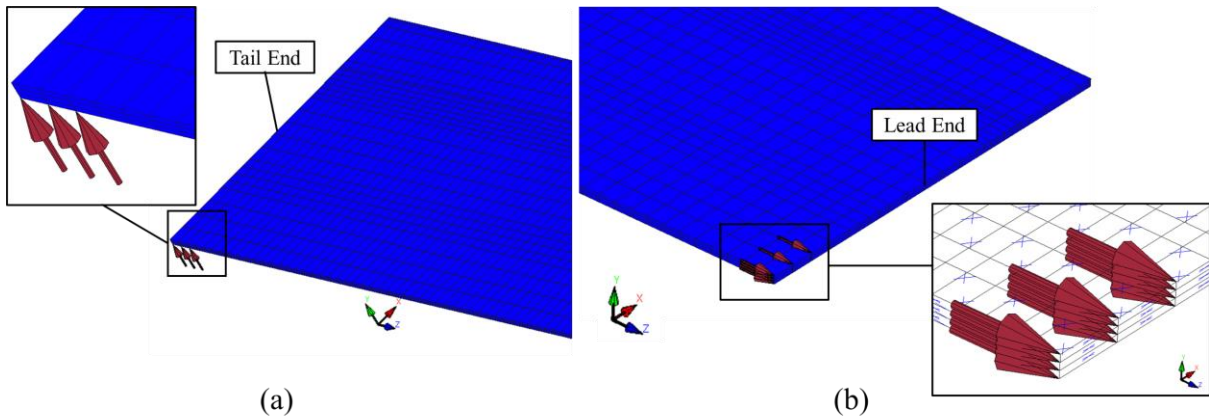


Figure 109 – (a) Y- lock boundary condition: restriction of the three nodes in the middle of the lead end of the strip; (b) Z-direction boundary condition: restriction of the six nodes in the middle of the lead end of the profile

Since the profile is symmetric up to station 9 (last station of the parametric study), only half of it was simulated. Therefore, an X-direction boundary condition applied to all nodes along the symmetry line of the profile was added to fix the strip displacement in that direction (Figure 110).

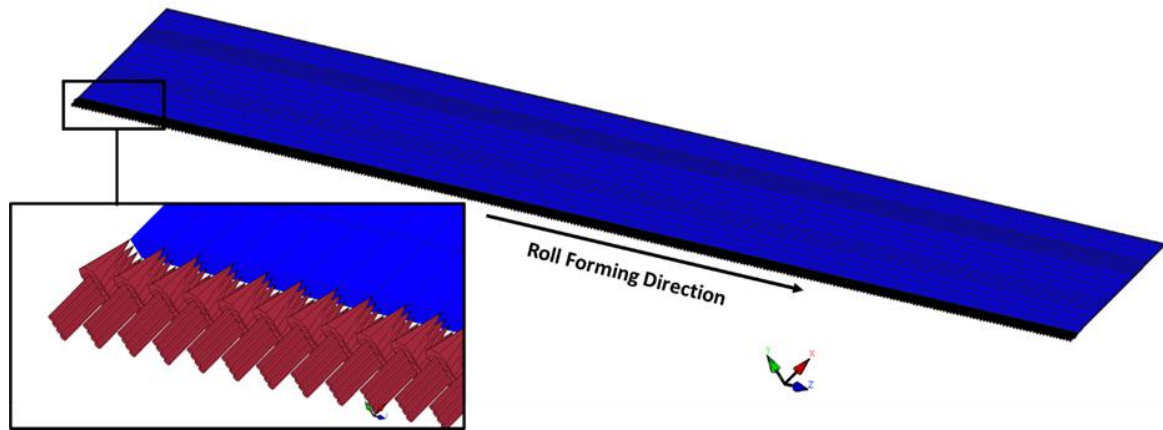


Figure 110 – X-direction boundary condition due to the symmetry.

5.1.3 Mesh Definition

As represented in Figure 111, for the definition of the internal mesh size in COPRA2FEA the value 3 was used for the parameter "subdivisions of straight entities". In turn, for the number of subdivisions of arc entities the value 2.2 was selected and finally, for the number of subdivisions in rolling direction the value 0.9 was used. These values were chosen taking into account other parametric studies previously performed, namely in Martins (2018), Souto (2020) e Forte (2021). Over the sheet width, a refined mesh was used in the bend zones, since this is the area of higher strain values, as well as on the strip edge in order to model more accurately the interaction between the sheet and the roll. The type of element used was also the solid element type 7, already described previously in section 4.1.4. In addition, it was tried to use elements with an aspect ratio close to 1:1, since the contact normal stress distribution is better represented when a low proportion of elements is used in the possible contact zones (Fernanda 2017). One element in thickness is sufficient to represent the bending behaviour accurately in some cases. However, the main disadvantage of solid elements is the prominence of locking under bending loads, in other words, to present an over stiffing behaviour. Therefore, more layers of solid elements should be used to better describe the behaviour of the sheet fibres, the through thickness stress gradient involved in bending and to avoid locking phenomena (Forte 2021). Furthermore, in a study conducted by Souto (2020), it was found that 3 layers of elements show a smooth transition of stresses across the thickness paths and that 4 elements lead to more dispersion in the results. In this regard, 3 elements were used across the strip thickness, for the reference simulation, resulting in 23400 elements and 32508 nodes.

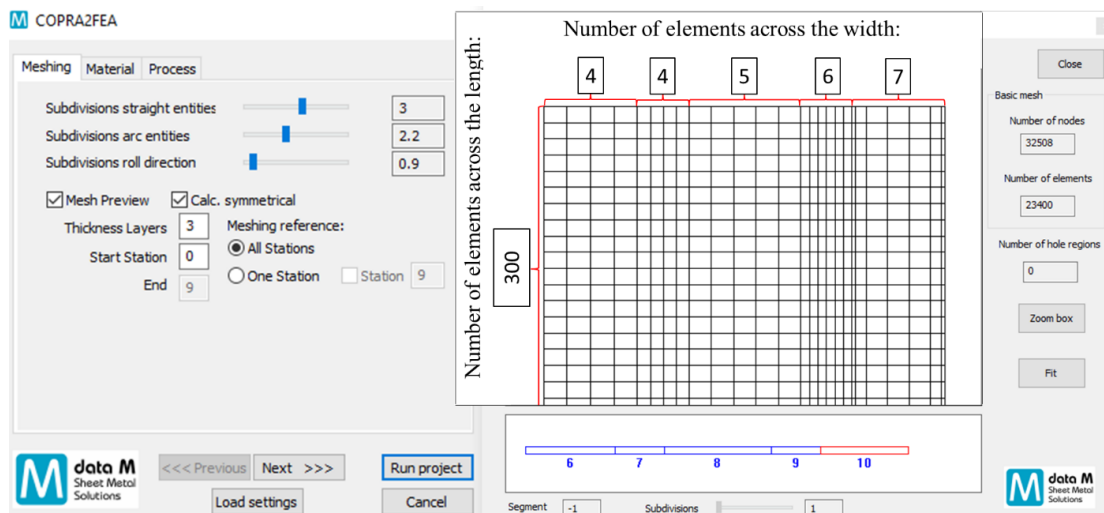


Figure 111 – Mesh preview in the mesh refinement tab used for the parametric study.

5.2 Measurements

This section illustrates the different terms and nomenclature used in describing a C-Shaped profile, as well as the methodology used in measuring the results of the different simulations.

5.2.1 Residual stresses along x and z direction of each element

The Copra FEA RF software allows the extraction of results considering a customised coordinate system. Therefore, for the study of residual stresses along the x and z direction was performed considering the local/element coordinate system, that is, a curvilinear coordinate system that follows the path of the elements along their bending trajectory. This consideration was taken into account since the x direction of each element (Figure 112 (a)) does not always coincide with the x direction of the global coordinate system (Figure 112 (b)). This fact is visible in Figure 112 (c), where the global coordinate system does not coincide with any local coordinate system of the three represented nodes.

The z-axis of the element was also used in the measurements to obtain the longitudinal residual stresses. Although in Figure 112(c), it seems that the z-axis of the element is the same as the global coordinate system for each of the three nodes, there are actually small variations due to the different inclinations of the elements for the different areas of the section, resulting from the forming operation (different longitudinal strains directions in each element).

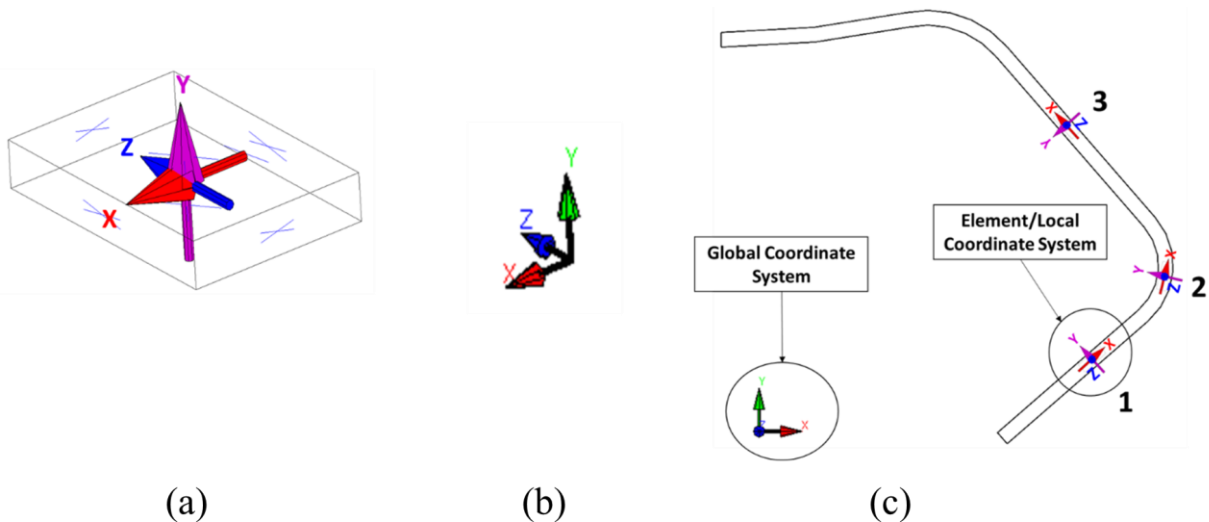


Figure 112 – (a) Local/Element Coordinate System; (b) Global Coordinate System; (c) Existing positioning differences for the local and global coordinate system for three different nodes located in the front cross-section of the profile.

For the measurement of the residual stresses along the x and z axis of each element, measurement paths were established in three distinct cross-sections (planes).

As shown in Figure 113, plane 2 is located in the median plane of the part, while planes 1 and 3 are located approximately 300mm away from the lead and tail ends, respectively. The transverse residual stresses were measured on the outer (path o) and inner (path i) surfaces of the profile for each of the sections.

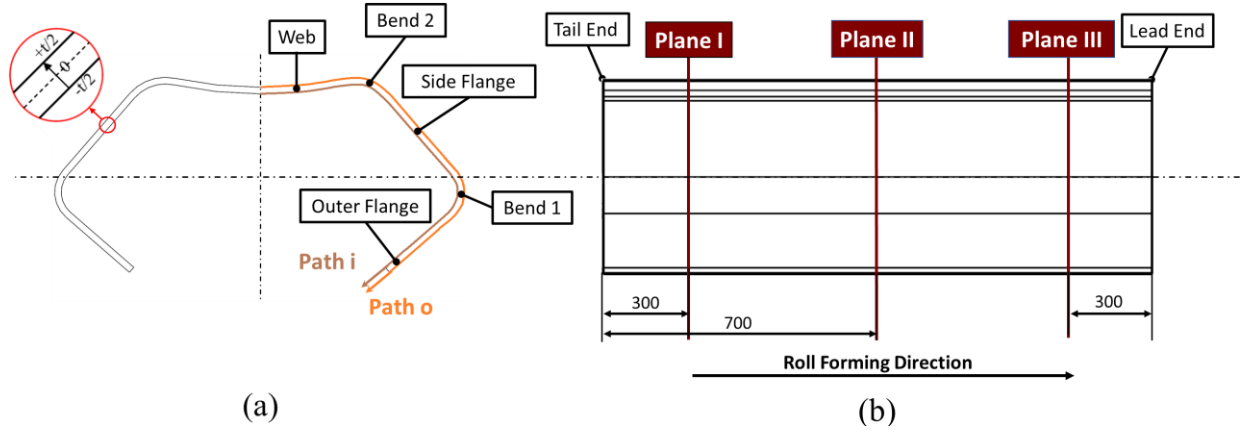


Figure 113 – (a) Profile cross-section paths created to measure residual stresses (front view); (b) Profile sections where residual stresses were measured along the length of the part (left view).

For the study of residual stresses in the bending zone (bend 1), seven paths along the thickness were considered to extract results, as represented in Figure 114. The residual stresses in the bending zones is one of the most important parameters to be studied in the roll forming process as these stresses influence the load-displacement response and ultimate strength of cold formed steel members Figure 114.

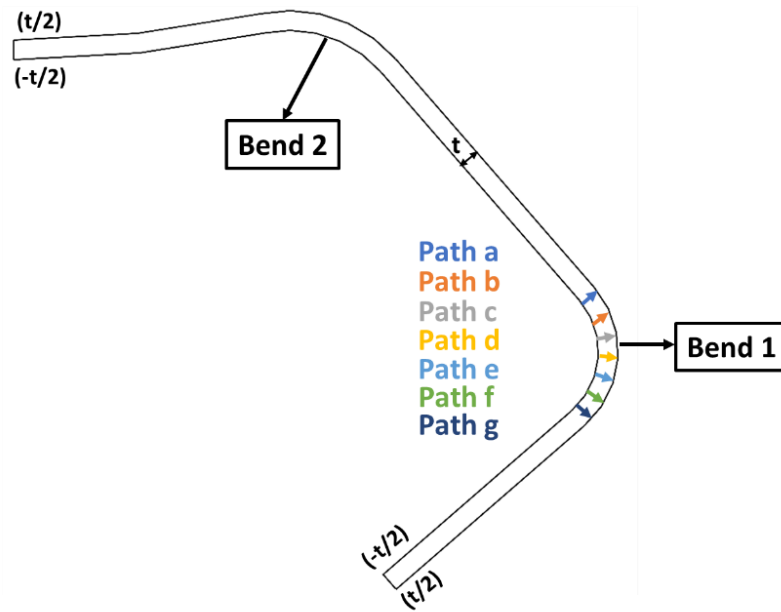


Figure 114 – Paths in the bending zone used for the measurements.

The stresses were analysed at the final increment of each simulation when the part was already out of the rolls.

5.2.2 Longitudinal strain (z direction)

The longitudinal edge strain (z direction) was measured on the outer flange at the node closest to the edge (location 1), as represented in Figure 115 by the red point. This point is located in the outer flange, approximately in the middle of the profile length (700mm from the ends) and at the node closest to the edge (at 1.05 mm from the edge), as was done in a study conducted by Bui and Ponthot (2008).

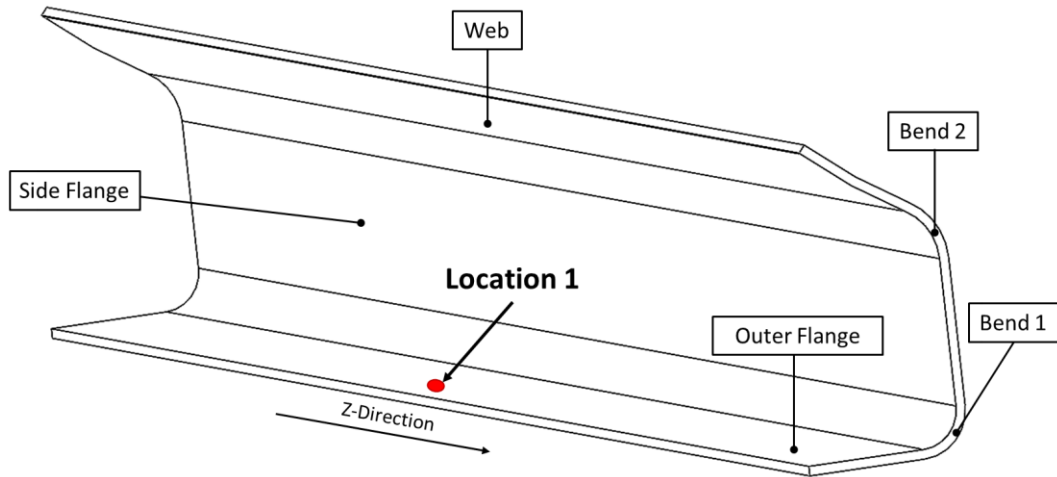


Figure 115 – Location of the region where longitudinal strain was measured.

5.2.3 Equivalent plastic strain in the bend zone

The equivalent plastic strain was measured at the last simulation increment for the paths corresponding to the middle zones of the two bends along the length of the sheet, both for the inner and the outer surface. The red lines in Figure 116 illustrate the node paths where the equivalent plastic strain was measured in the bending zone.

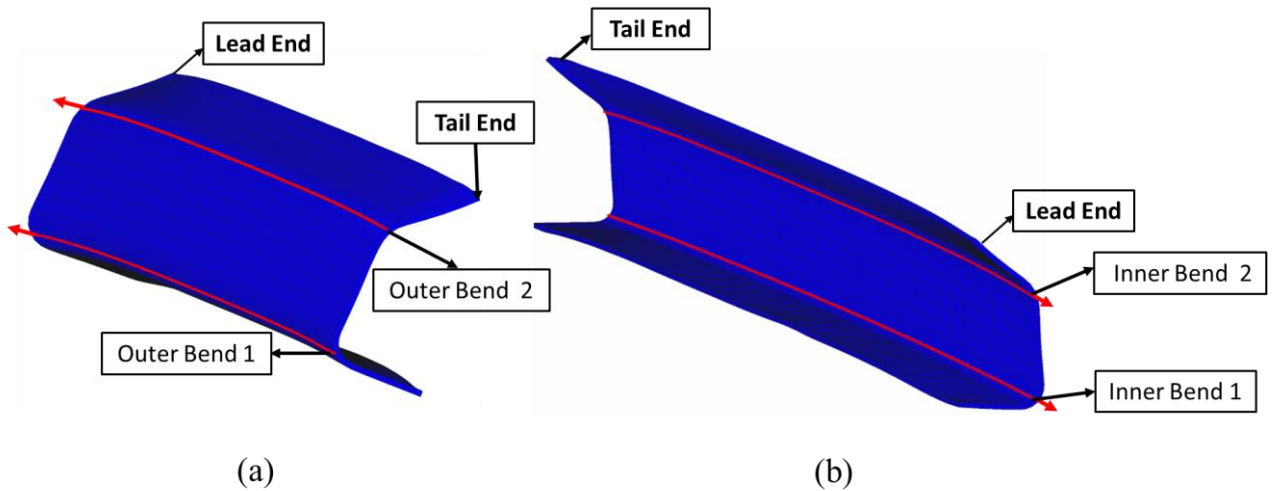


Figure 116 – Equivalent Plastic Strain Measurement: (a) measurements along the outer bends; (b) measurements along the inner bends.

5.2.4 Springback, End Flare and Twist

In order to calculate the springback and end flares angle for the different models and thus analyse their geometric accuracy, the angles β_1 and β_2 represented in Figure 117(a) were measured. For the measurement of angles β_1 and β_2 , two vectors ($\vec{u} = [x_1, y_1, z_1]$ and $\vec{v} = [x_2, y_2, z_2]$) were calculated for each bend using the coordinates of two points (Figure 117(b)).

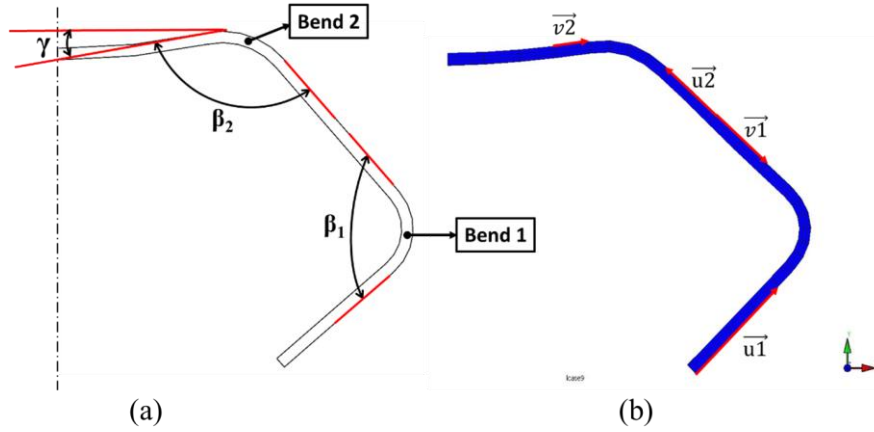


Figure 117 – (a) Measured bending angles for the calculation of end flare, springback and twist; (b) vectors used to calculate the angles β_1, β_2 and γ .

The, the angle β between the two vectors was calculated using the equation 5.1.

$$\beta = \arccos\left(\frac{\vec{u} \cdot \vec{v}}{|\vec{u}||\vec{v}|}\right) = \arccos\left(\frac{x_1x_2 + y_1y_2 + z_1z_2}{\sqrt{x_1^2 + y_1^2 + z_1^2} \times \sqrt{x_2^2 + y_2^2 + z_2^2}}\right) \quad (5.1)$$

Where:

- β , is the angle between the side flange and outer flange (β_1) or between the side flanges and web (β_2);
- $[x_1, y_1, z_1]$ are the coordinates of vector $\vec{u}$;
- $[x_2, y_2, z_2]$ are the coordinates of vector $\vec{v}$.

Therefore, for the springback calculation, these angles were measured in two different increments. The first measurement was performed at the last station in the increment corresponding to the moment when the transverse section intended for measurement is in the middle of the roll plane (Figure 118). In turn, the second measurement was performed for the same cross-section as in the first measurement but for the last increment of the simulation, i.e., when the final product is already outside the rolls in a stationary area.

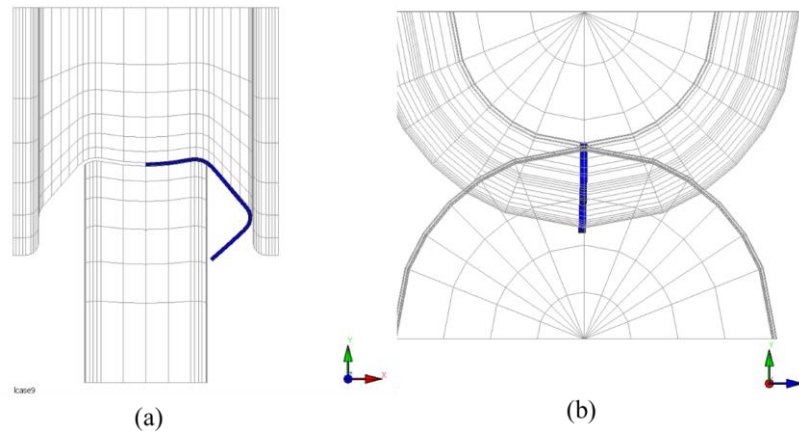


Figure 118 – Location of first springback measurement: (a) Front view; (b) Left view.

The measurement of these angles for the springback calculation was performed in this way for the same three sections for which the transverse residual stresses were measured (see section 5.2.1), so that the angles were not influenced by end-flare phenomena as advised in the literature by Akbar Abvabi (2014). After measuring the bending angles β_1 and β_2 , the springback angle was calculated according to equation 5.2.

$$Springback(\theta_s) = \beta_f - \beta_i \quad (5.2)$$

Where:

- β_f is the bending angle measured in the last simulation increment (stationary zone);
- β_i is the bending angle measured in the last station for the increment corresponding to the moment when the section intended to be measured is in the mid-plane of the rolls.

The end flare angles were analysed with the sheet already out of the rolls by measuring the bending angles β_1 and β_2 for three sections. Two of them were measured approximately at 10 mm from the lead and tail ends of the strip, and another at a stationary zone at the mid-length of the part, as recommended by Akbar Abvabi (2014) and as represented in red in Figure 119.

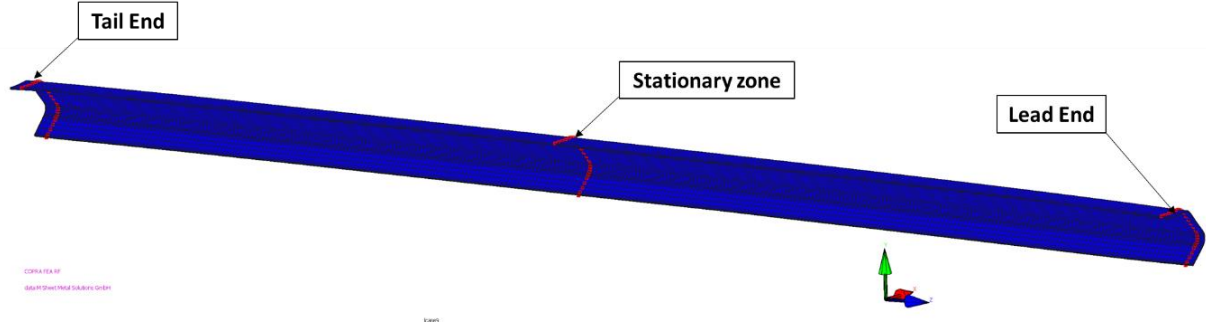


Figure 119 – Measurement locations used for the calculation of the end flare angle.

Therefore, the end flare angles were calculated by equation 5.3.

$$End\ Flare(\alpha_{EF}) = \beta_{lead/tail} - \beta_{Stationary} \quad (5.3)$$

Where:

- α_{EF} , is the end flare angle measured for the planes 10 mm from the lead and tail end;
- $\beta_{lead/tail}$, is the measured bending angle for sections at 10 mm from the lead and tail end;
- $\beta_{Stationary}$, is the measured bending angle for the section corresponding to half the length of the part (stationary zone).

The twist angle (γ_T) was determined by subtracting the angle γ (Figure 117 (a)) measured for a section of a plane located approximately 10 mm from the lead end by the same angle measured for a section of a plane located approximately 10 mm from the tail end (equation 5.4). The γ measurement was performed by measuring the angle between the vector $\vec{v}_2$ and the horizontal axis (x-axis).

$$Twist(\gamma_T) = \gamma_{lead} - \gamma_{tail} \quad (5.4)$$

5.2.5 Computation Time

At the end of each simulation a file is generated by the Msc Marc software where it is possible to extract data regarding the computational time, namely the CPU and the Wall time.

Wall time is the real time that the simulation took until it was finished and therefore includes the influence of external factors such as the tasks that are being executed by the computer at the same time that the simulation is running. In turn, CPU time (process time) is the amount of time for which a central processing unit (CPU) was used to process simulation instructions. This time corresponds to the effective simulation time and therefore does not include the influence of external factors such as tasks that are running simultaneously with the simulation. The total CPU time to be compared with the effective simulation time (wall time) has to be divided by 4, which was the number of CPUs used in the simulations performed.

However, for this thesis it was only considered the analysis of the Total CPU time values and CPU time distribution values instead of wall time values, since CPU times do not take into

account the influence of other tasks that may be running at the same time as the simulation, and therefore are comparable parameters between simulations (data M 2020).

5.3 Results and discussion

The current subchapter presents the results obtained and the discussion about them for each of the simulations that compose the parametric study of the first 10 stations of Coproget's roll forming process. Initially, some relevant results for the reference simulation (simulation 1) will be presented, since it is from this simulation that the other simulations are based. Afterwards, the results of the following simulations will be discussed, as well as their comparison with the reference simulation.

5.3.1 Reference Simulation

Figure 120 depict the total equivalent plastic strain obtained for the reference simulation (simulation 1) and for the last simulation increment (increment 3250), when the part was already out of the rolls action. It can be seen that the most plasticized areas of the strip after the part exits the action of the rolls were the bends. The total equivalent plastic strain is a good indicator of the material's plastic yielding, since it is a scalar value that represents the magnitude of the accumulated plastic strain to which the material was subjected, considering the strain in all directions.

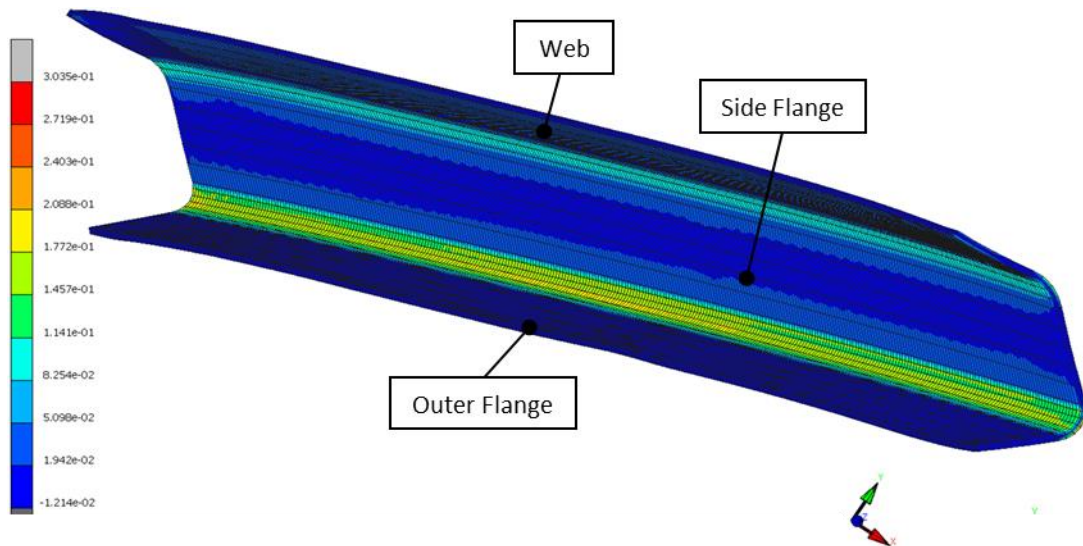


Figure 120 – Total equivalent plastic strain in the last increment of simulation 1 (increment 3250).

Figure 121 shows a generic bend obtained from a RF process. In a RF process, the amount of strain in the areas away from the bending zone (point B) is low (usually about 1%). In turn, for the bending zones (point A) there is a high amount of strain (usually about 20%) (Akbar Abvabi 2014). Some shape defects in the RF process, such as edge wave, are often due to very small plastic strains at the flange edge in the longitudinal direction. As can be seen in Figure 121, the variation of the longitudinal strain at the edge in a RF process is close to the elastic limit of the material. Other defects such as oil canning, for example, are due to the variation of small longitudinal strains across the strip width. Therefore, for these reasons it is important that the material behaviour is close to the yield point (Akbar Abvabi 2014). However, If during the RF process the elastic domain of the material is not exceeded, the strain and stretching return to their original length when the profile leaves the stand (Martins 2018).

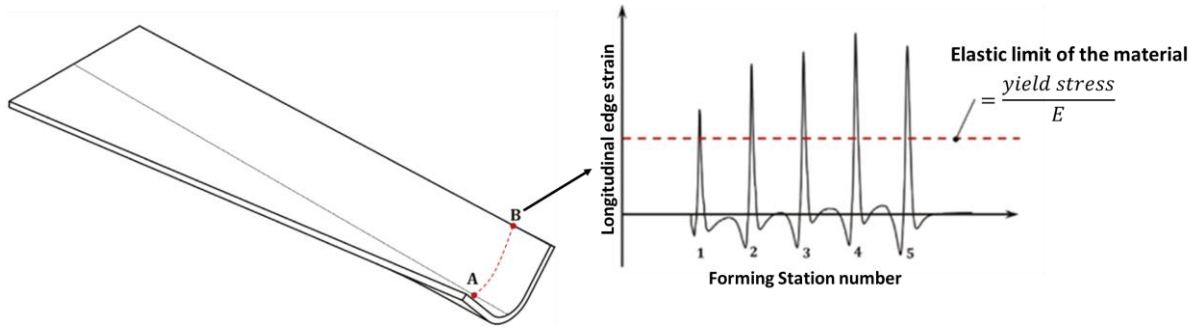


Figure 121 – Variation of the longitudinal strain at the edge of the strip in a generic roll forming process.

The edge wave is a defect that results from the elastoplastic buckling of the material near the edge of the sheet and is associated with high magnitudes of longitudinal strains that are prone to appear in the profile, mainly due to the longitudinal bending and to the different flow lengths of the material, as mentioned in section 2.4.4 (Halmos 2006).

The longitudinal edge strain values for the first 10 stations of the process were taken for location 1, as described in section 5.2.2. The software considers the longitudinal strain at the first station (station 0) to be null, so this station does not appear in the longitudinal strain graphs.

The analysis of the longitudinal strains at the selected locations for the different stations of the line allows to understand the evolution of the longitudinal strain along the rolling direction and to detect the critical stations, i.e. the stations with a higher magnitude of the longitudinal strain and therefore more likely to induce waviness. Analysing Figure 122, relative to the reference simulation (simulation 1), it can be seen that the peak longitudinal edge strain for location 1 is approximately 1,050% and occurred for station 4 and is therefore the critical station considering the first 10 stations of the process.

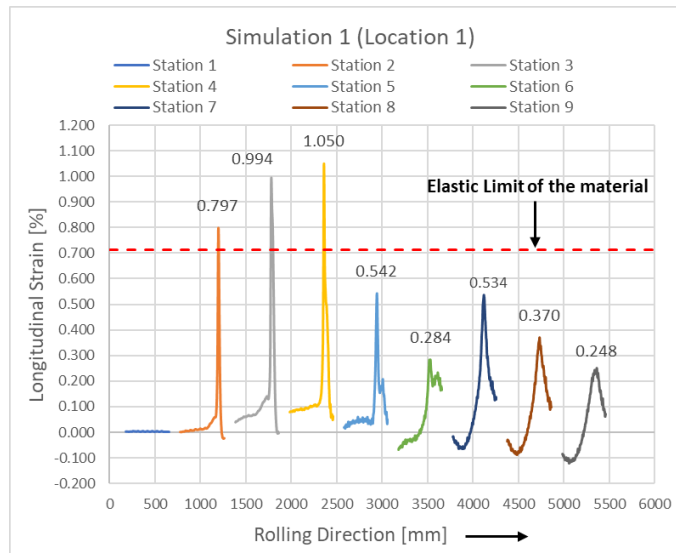


Figure 122 – Longitudinal edge strain for simulation 1 (reference).

As can be seen, there is an initial sharp rise in longitudinal strain at each station until a peak is reached. As mentioned in section 2.3.4, the variation in the longitudinal strain values is caused by the longitudinal bending phenomenon (Figure 123). When the sheet is initially bent at the entrance of the stations, the top layer is subjected to high tensile stresses while the bottom layer undergoes slight compressive stresses. In turn, when the sheet is bent back as it progresses in the longitudinal direction through the gap between the rolls, the top layer is subjected to high compressive stresses while the bottom layer is subjected to high tensile stresses. This explains the abrupt increase in longitudinal strain values verified for the graph of Figure 122 until the peak is reached, since the point chosen for longitudinal strain analysis is located on the bottom

layer. The peak value appears at the moment just before the node under analysis passes through the roll axis. After this peak, the longitudinal strain suffers a sharp drop due to the springback effect (Martins 2018).

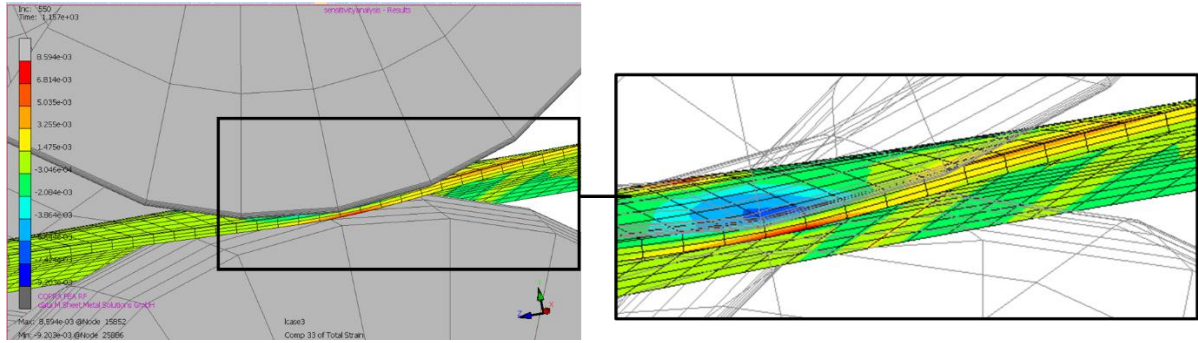


Figure 123 – Longitudinal strain in station 3 (comp 33 of total strain results). The sheet undergoes longitudinal bending when entering the rolls.

5.3.2 Material Docol 1400M vs MarteNSite 1500M vs Domex 500MC

In this section a comparison is made between three simulations modelled with different materials, Docol 1400M steel corresponding to the reference simulation (simulation1), MarteNSite1500 steel (simulation 2) and Domex 500MC steel (simulation 3). For the material model of MarteNSite1500 steel and Domex 500MC steel the yield strength, ultimate tensile strength and elongation were also introduced into the software. The properties of Docol 1400 M and MarteNSite1500 steel are given in section 3.1.1, while the properties of Domex500MC are given in Appendix B, Table B1-B2. In Figure 124, are represented the stress-strain curves automatically estimated by the software based on the properties introduced for the three materials.

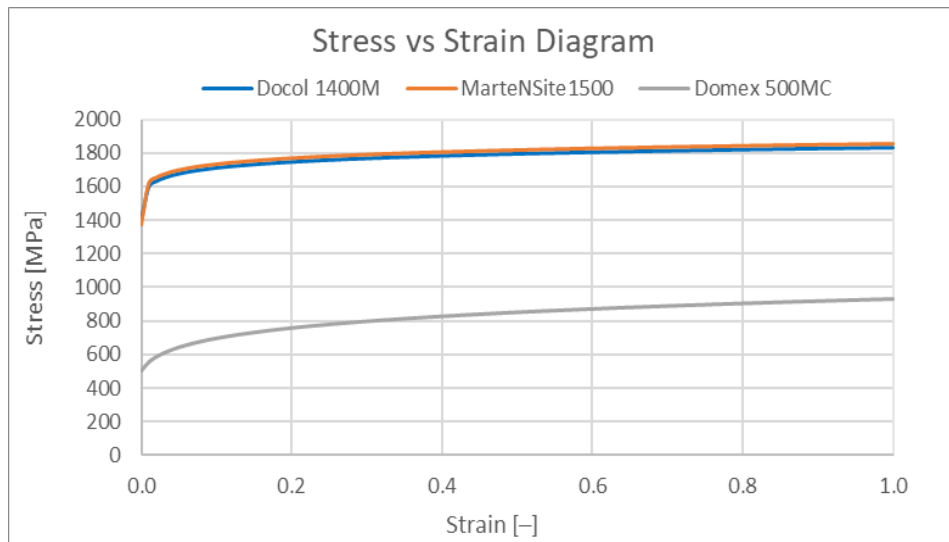


Figure 124 – Stress vs Strain diagram for the three materials under study.

The materials under study will be identified in this section based on their yield strength, as was done in previous studies in Han et al. (2001; 2005).

The results obtained show that increasing the strength of the material leads to higher transverse and longitudinal residual stresses across the width, both for the internal and external surfaces of the profile cross-section, as represented in Figure 125 (a) and Figure 125 (b), respectively. This behaviour is observed not only for plane II (middle), but also for planes I (tail end) and III (lead end) (Appendix C, Figures C1- C2).

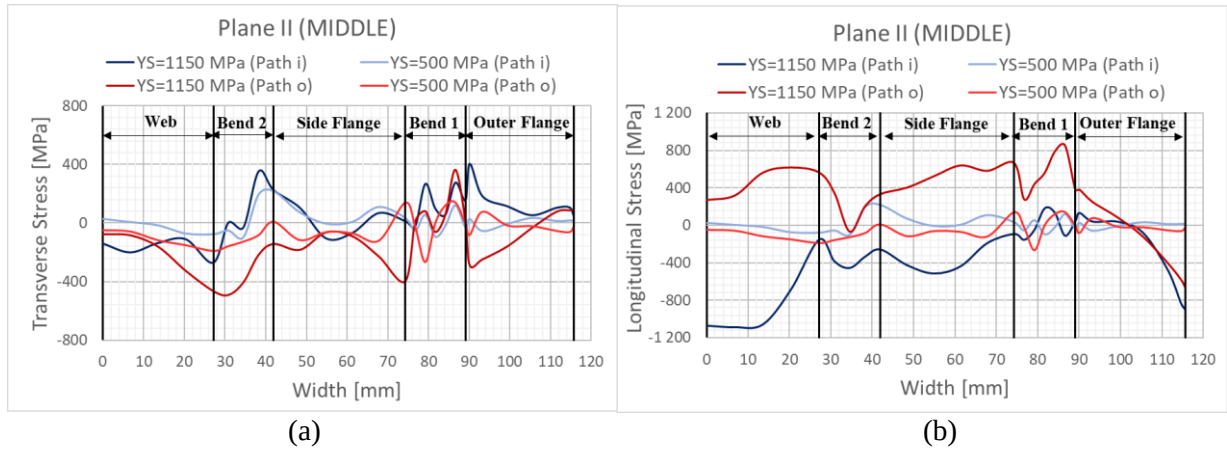


Figure 125 – (a) Transverse residual stresses across the width in plane II (Middle) for the models with YS=1150 MPa and YS=500MPa; (b) Longitudinal residual stresses across the width in plane II (Middle) for the models with YS=1150 MPa and YS=500MPa.

Considering the distribution of the transverse and longitudinal residual stresses through the thickness, the same behaviour is verified. While for the material with higher strength, the magnitude of the transverse stresses across the thickness observed for plane II (middle) vary between 400MPa (tensile) and -400MPa (compression) approximately, for the case of the material with lower strength these maximum stresses vary between 200 MPa (tensile) and -250 MPa (compression), i.e. approximately half (Figure 126).

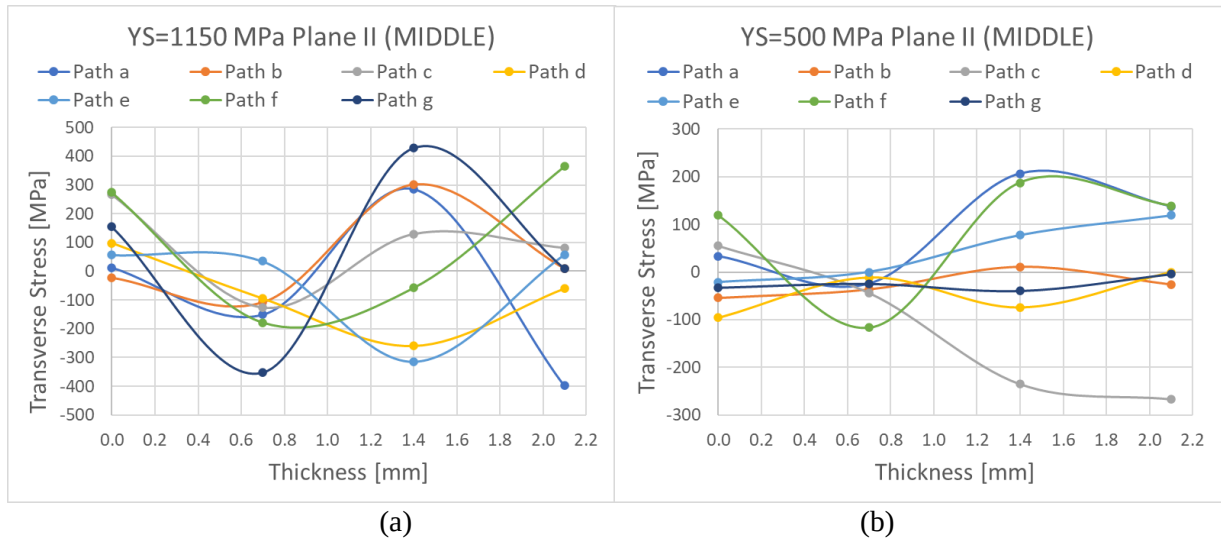


Figure 126 – (a) Transverse residual stresses across the thickness in plane II for the model with YS=1500MPa (reference model); (b) Transverse residual stresses across the thickness in plane II for the model with YS=500MPa.

In turn, analysing the longitudinal stresses across the thickness (Figure 127) for plane II (middle) it can be seen that for the high strength material the residual stresses vary between -200 MPa (compression) and 800 MPa (tension), while for the material with lower strength these values vary between -100 MPa (compression) and 500 MPa (tension), showing once again, the huge difference in the stresses magnitude for both materials.

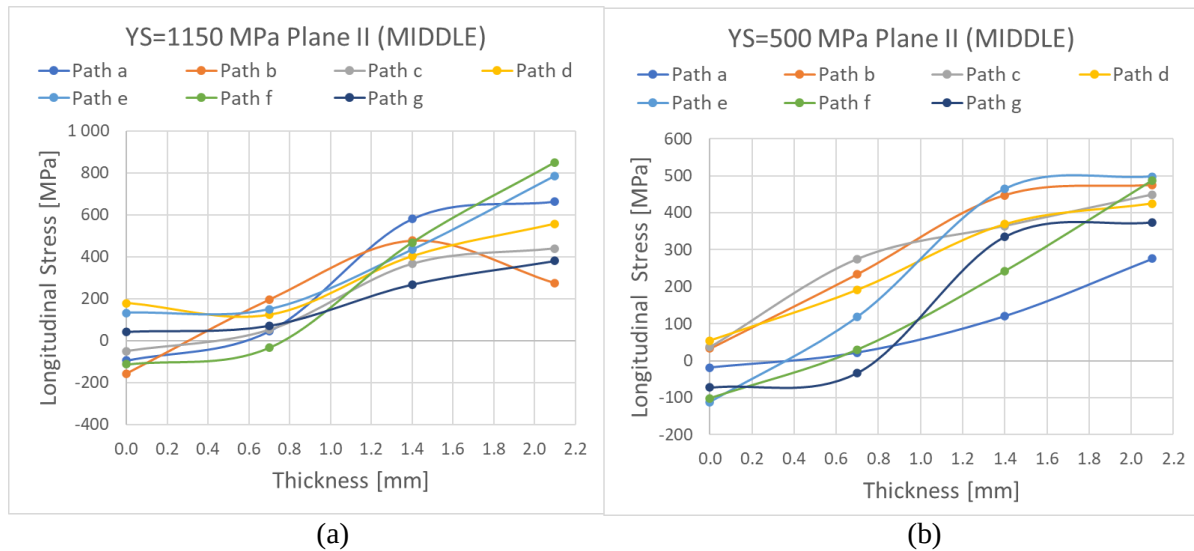


Figure 127 – (a) Longitudinal residual stresses across the thickness in plane II for the model with YS=1500MPa (reference model); (b) Longitudinal residual stresses across the thickness in plane II for the model with YS=500MPa.

As mentioned previously, high strength materials lead to higher end flare values and usually exhibit flare out at both ends (Halmos 2006). However, this is not observed for the profile under study. As can be seen in Figure 128, the end flare values for the lower strength material (YS=500MPa) were much higher when compared to the higher strength materials (YS=1370 MPa and YS=1150 MPa). This may be due to the fact that pre-cut was used instead of coil with final cut. End flare is caused by the release of internal stresses that are balanced while the section is continued. However, when the part is cut, these stresses become unbalanced (Forte 2021). Since higher strength materials have higher internal stresses (as demonstrated above) it is expected a higher release of these stresses when cut is made at the end and consequently higher end flare values are also expected for these materials in this case. However, as in the models under study pre-cut was used, the cut was performed at the beginning and not at the end of the process and therefore the residual stresses remained in balance, hence the end flare values for the higher strength materials were lower than expected.

Another aspect to consider is that a positive value of end flare indicates flaring out, whereas a negative indicates flaring in. Therefore, bend 1 showed flare in for all three materials under study for both the tail and the lead end, while bend 2 showed flare out.

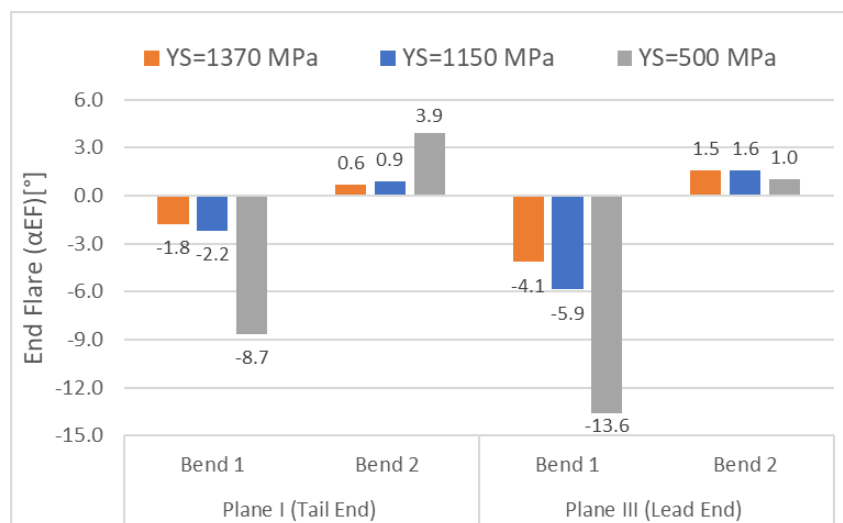


Figure 128– Comparison of end flare angles(αEF) [°] obtained for the three materials, two bends and two planes under study.

A study conducted by Han et al. (2001) for a profile with an outer edge, revealed that increasing the material yield limit increases the peak longitudinal strain. Also some investigations indicates that the peak longitudinal edge strain increases with material yield strength (Z. W. Han et al. 2005; Buddhika Abeyrathna et al. 2017).

In fact, comparing the graphs obtained for the longitudinal edge strain for the material with higher yield strength (YS=1370MPa) and for the material with lower yield strength (YS=500MPa), it can be seen that for most stations the peak longitudinal strain is higher for the higher strength material (Figure 129). Furthermore, it can also be seen that the peak longitudinal edge strain obtained for the higher strength material (1.100%) is higher than the peak longitudinal edge strain obtained for the lower strength material (1.061%).

Comparing the longitudinal edge strain values obtained for the reference simulation (YS =1150 MPa) (see section 5.3.1, Figure 122) with those obtained for the materials with YS =500 MPa and YS= 1370 MPa, it can be seen that these values for the material with YS =1150MPa are lower for most stations when compared to the material with YS=1500MPa and higher for most stations when compared to the material with YS=500 MPa, thus confirming the theory that the peak longitudinal edge strain increases with the yield strength of the material. However, it should be noted that the peak longitudinal strain for the material with YS=500 MPa (1.061%) is higher than that obtained for the reference simulation material with YS=1150 MPa (1.050%).

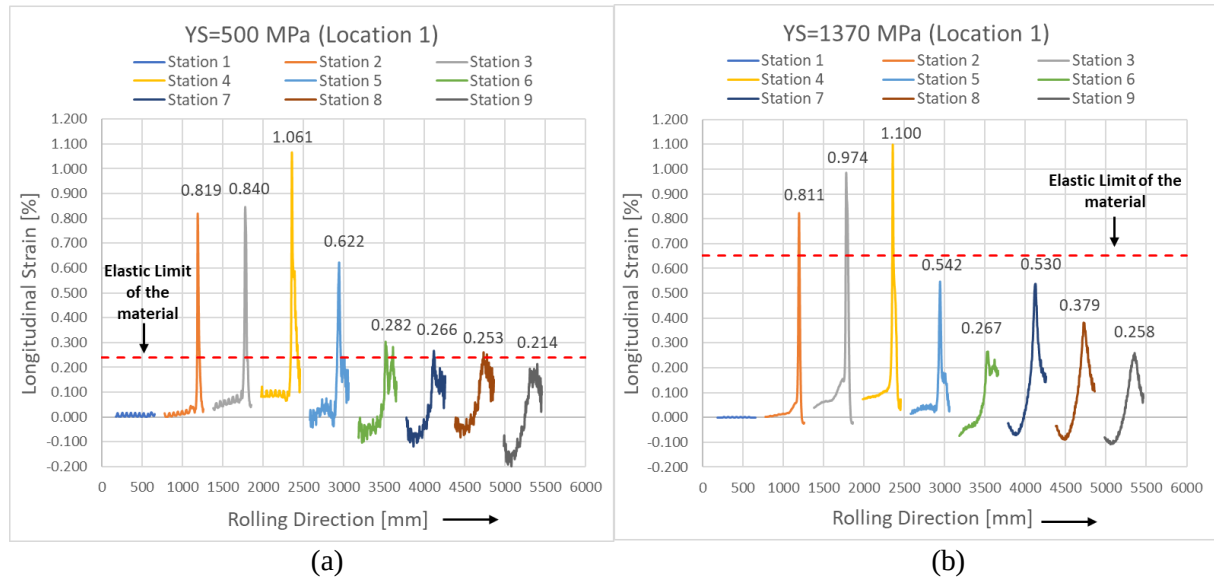


Figure 129 – Longitudinal edge strain results: (a) model with a material of YS=500MPa; (b) model with a material of YS=1370 MPa.

As previously mentioned, waviness is formed due to the permanent plastic strains produced in the edge zone, i.e, when the stress in the edge exceeds the yield point, especially after the last station. A study carried out by Bui and Ponthot (2008), showed that the amplitude of edge waviness appears to be higher for high strength materials and for highly work hardening (lowest hardening exponent n).

However, according to Halmos (2006), materials with higher yield strength and lower elastic modulus are less likely to be wavy. This is due to the fact that during the RF process, the sheet follows an real path that is usually longer than the theoretical path, due to springback (Ferreira 2016). As such, if this elongation exceeds the elastic limit, then the permanently strained edges of the final product will be wavy or the product will exhibit a bow, camber or twist.

In order to understand the influence that materials with different yield strengths have in the creation of waviness on the outer flange edge, two measurements were performed for each material model considering the part already out of the rollers' action. First, the x-position of the

external nodes of the strip edge along the path corresponding to the length of the part was measured. Then the y-position of these same nodes along the length of the part was also measured in order to have a better perception of the shape presented by the strip edge in both vertical and horizontal directions.

As can be seen in figures Figure 130(a) and Figure 130(b) by the areas surrounded in red, it was verified that for the case of the profile under study, the material with lower strength (YS=500 MPa) is the one that generates a more pronounced edge wave.

In turn, the materials with YS=1150 MPa and YS=11370 MPa present a very similar behaviour between them and an edge wave much smaller than that observed for the material with lower strength. Thus, it was verified that these results are in accordance with the previously mentioned theory present in Halmos (2006).

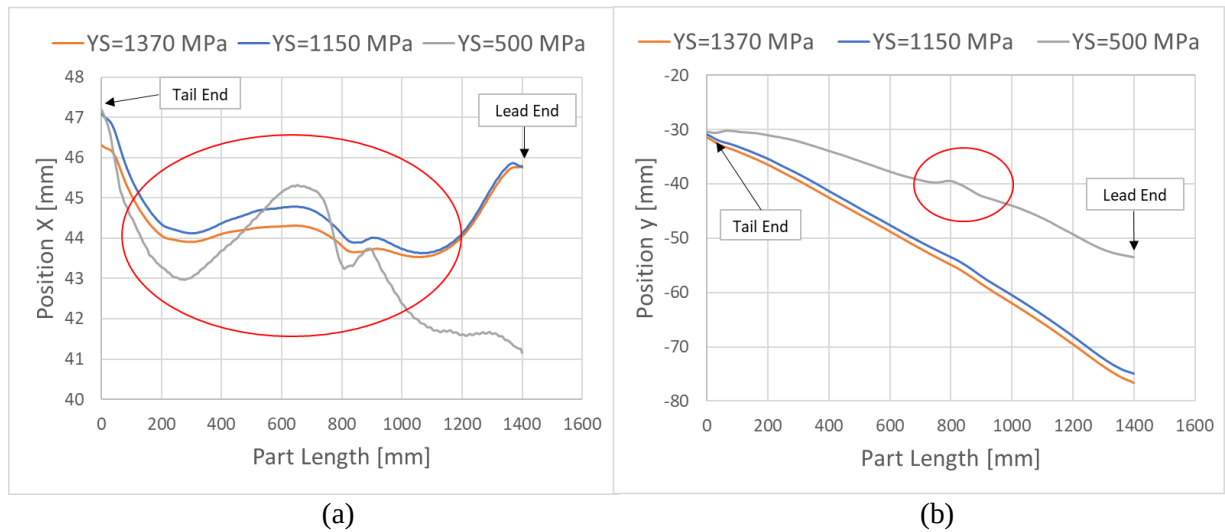


Figure 130 – Waviness defect on the strip edge: (a) Comparison of the x-position of the external nodes of the outer flange edge along the length of the part for the three materials under study; (b) Comparison of the y-position of the external nodes of the outer flange edge along the length of the part for the three materials under study.

According to the literature, more springback can be observed with high strength materials as the elastic limit of the material is higher and consequently the elastic recovery will also be higher (Bui and Ponhot 2008).

As evidenced by Figure 131, the results are in agreement with the literature. The higher strength materials with YS=1150 MPa and YS=1370MPa not only show very similar springback angles, but also much higher springback angles than those observed for the lower strength material (YS=500 MPa).

The most pronounced differences between these values are found for bend 2, particularly for the lead end, where there is a difference of almost 4° between the springback angle obtained for the higher strength materials (YS=1150 MPa and YS= 1370MPa) and the springback angle obtained for the lower strength material (YS=500 MPa). Furthermore, it can be also seen that the springback angles obtained vary between 0.7° and 1.6° for bend 1 and between 2.1° and 6° for bend 2.

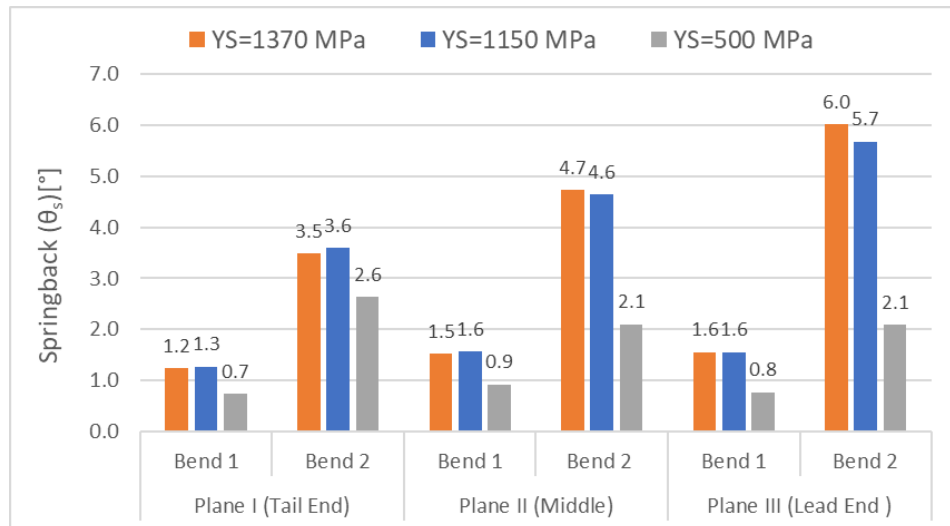


Figure 131 – Comparison of the springback angles (θ_s) [°] obtained for the three materials, the two bends, and the three planes under study.

Regarding the twist angles (Table 12), it was found that the influence of this defect was practically insignificant for the three models under study. However, it should be noted that the highest twist value occurred for the lowest strength material (YS=500MPa) and with a twist direction opposite to that verified for the models of higher strength materials (YS=1370MPa e YS= 1150MPa).

Table 12 – Twist angles (γ_T) [°] obtained from the three materials under study.

Twist(γ_T) [°]	YS= 1370MPa	YS=1150 MPa	YS=500MPa
	0.1	0.1	-0.4

Analysing the vertical displacement of the part along the direction of the RF line (Figure 132), it can be seen that the part with the lower strength material has more stability in its vertical movement (less pronounced oscillations) when compared to the higher strength materials. This highlights the complexity of forming the material used in the bumper beams produced by Coproget.

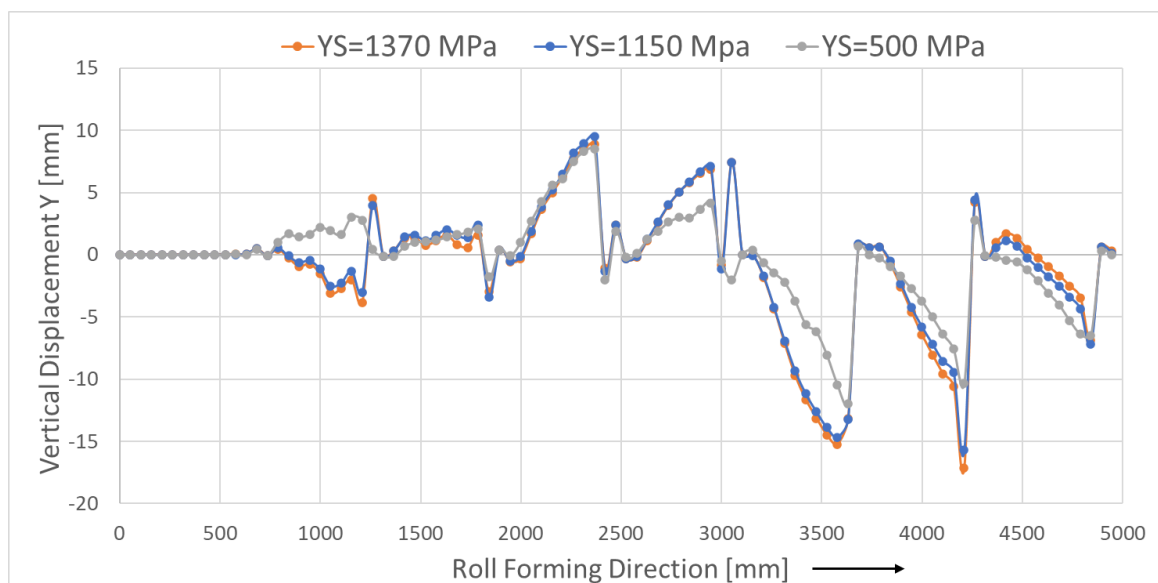


Figure 132 – Comparison of the vertical displacement along the RF process, obtained for the three materials under study.

5.3.3 10 stations vs 13 stations

In this section a comparison is made between two models, the reference model with 10 stations (numbered 0-9) and a new model with 13 stations (numbered 0-12). For the model with thirteen stations, three stations were added between stations 6 and 7, 7 and 8, and 8 and 9 of the reference model. Furthermore, as the number of stations doubled from station 6, it was decided to reduce the bending angle increment between stations for each entity by half as represented in Appendix J, Figure J4, to study its influence on the produce profile. Therefore, this model with 13 incremental stations is referred to in this section as “13 stations inc”.

By analysing the transverse stresses across the width (Figure 133 (a)), it is possible to verify that the three planes under study exhibit the same behaviour. The web is under compression both in the inner surface (path i) and in the outer surface (path o). As can be seen, the bends are the zones that present a more irregular distribution of residual stresses in relation to the other zones of the profile. For the bend between the web and the side flange (bend 2), half of the inner surface (path i) of the bend is under compression and the other half under tension, while the outer surface of the bend (path o) is completely under compression. On the other hand, the side flange presents most of its nodes under compression, both for the inner and outer surfaces. However, the key point to note is the large increase in transverse residual stresses in the bend between the side flange and the outer flange when increasing the number of stations from 10 to 13. In turn, increasing the number of stations seems to have no influence on the transverse residual stresses in the outer flange, as the curves for the two models are almost coincident. In this zone, most of the nodes of the inner surface are under tension, while most of the nodes for the outer surface are under compression. Regarding the longitudinal stresses for plane II (middle) (Figure 133 (b)), there are no significant differences between the two models. There is only a slight difference in the longitudinal stresses obtained for bend 1 since these values are slightly higher for the outer surface of the model with 10 stations and for the inner surface of the model with 13 incremental stations. The same behaviour as these two described graphs is observed also for plane I (tail end) and plane III (lead end) (Appendix D, Figures D1-D2).

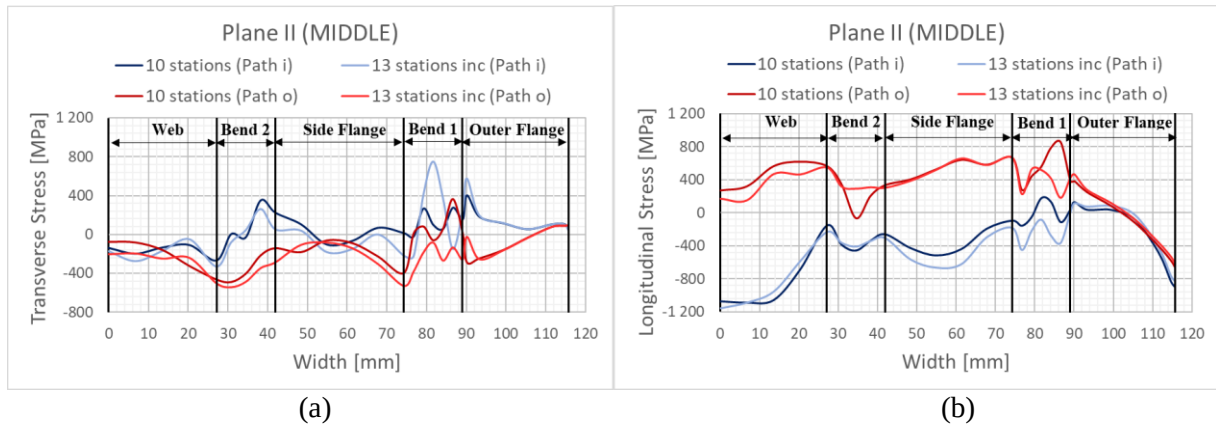


Figure 133 – (a) Transverse residual stresses across the width in plane II (Middle) for the models with 10 stations and 13 stations incremented; (b) Longitudinal residual stresses across the width in plane II (Middle) for the models with 10 stations and 13 stations incremented.

Regarding the transverse residual stresses through thickness for plane II (middle) (Figure 134), it is verified that for the model with 10 stations, most of the nodes of the inner surface of the bend are under tension. In turn, for the outer surface, it is verified that some of the nodes are under tension and others under compression. The opposite happens for the process with 13 stations incremented, since for the internal surface of the bend, some of the nodes are under tension and others are under compression and for the outer surface all nodes are under compression. It should also be noted that the transverse residual stresses obtained for the inner

surface of the bend for the process with 13 stations incremented are much higher than those obtained for the inner surface for the process with 10 stations.

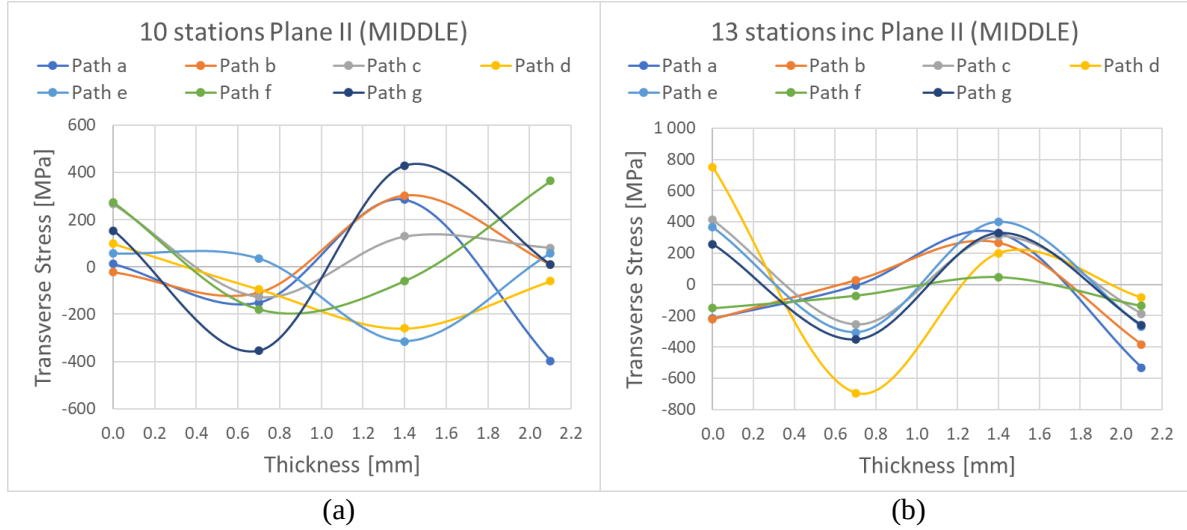


Figure 134 – (a) Transverse residual stresses across the thickness in plane II, for the model with 10 stations (reference); (b) Transverse residual stresses across the thickness in plane II for the model with 13 stations incremented.

Analysing the longitudinal residual stresses through the thickness of the tail end (Figure 135), it can be seen that as happened for the longitudinal stresses across the width, there are no significant differences between the two models both in terms of distribution and magnitude. This behaviour is also observed for plan II (middle) and III (lead end), presented respectively in Appendix D, Figures D3- D6.

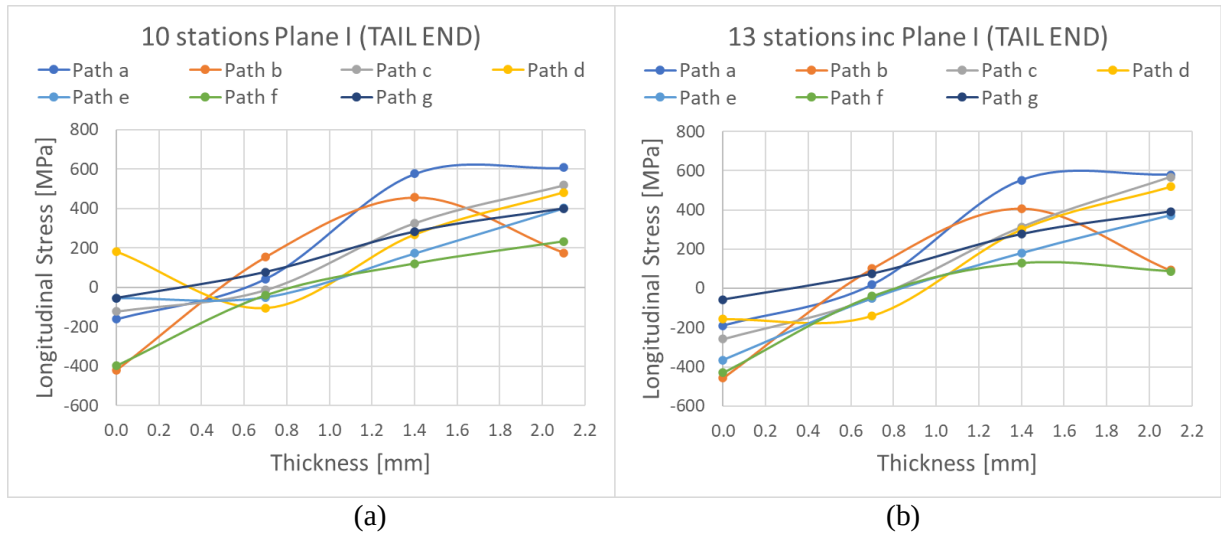


Figure 135 – (a) Longitudinal residual stresses across the thickness in plane I for the model with 10 stations (reference model); (b) Longitudinal residual stresses across the thickness in plane I for the model with 13 stations incremented.

According to the literature, longitudinal peak membrane strains increase with the bending angle increasing (increased bending angle increment), since the higher the bending angles, the higher the stretching of the flange, i.e. the flange edge travels a higher distance (Zhu et al. 1996; Buddhika Abeyrathna et al. 2017). Analysing Figure 136(a), concerning the longitudinal edge strain for location 1 of the model with 13 stations incremented, it can be seen that the results obtained are in agreement with the literature. As expected, for a larger number of stations, the peak longitudinal membrane strain decreased as the applied bending was more gradual, leading to a reduction in strains. For this model, the peak longitudinal strain from station 6 reaches a

maximum value of 0.377%, while for the reference simulation it reaches a maximum value of 0.534 % (see section 5.3.1).

Adding stations with more gradual bending increments requires redesigning the rolls for the stations that have been added, which is a time-consuming task. In practical terms, the addition of new rolls is not only a time-consuming task since it requires the design of a new roll, but also a costly task. In this regard, a new model was created with 13 stations as well and with the new stations added in the same way, between stations 6 and 7, 7 and 8, and 8 and 9 of the reference model. However, the stations added for this new model do not have a successive gradual bending angle for each entity of the profile, but rather a bending angle for each entity exactly equal to that of the immediately preceding station, as represented in Appendix J, Figure J5. Thus, for this model, station 7 is equal to station 8, station 9 is equal to station 10, and station 11 is equal to station 12. This model thus also allows a more gradual bending and avoids the design of new rolls since the added stations are the same as the immediately preceding ones. This model is referred to in this thesis as “13 stations non-inc”.

Analysing the graph of the longitudinal edge strain obtained for this model for location 1 (Figure 136(b)), it can be seen that the peak longitudinal strain greatly reduces in the transition between two equal stations, i.e. from station 7 to 8, from station 9 to 10 and from station 10 to 11. However, at the station that immediately follows the two equal stations, it can be observed that the longitudinal strain peak increases again to values identical to those observed in the reference model (see section 5.3.1).

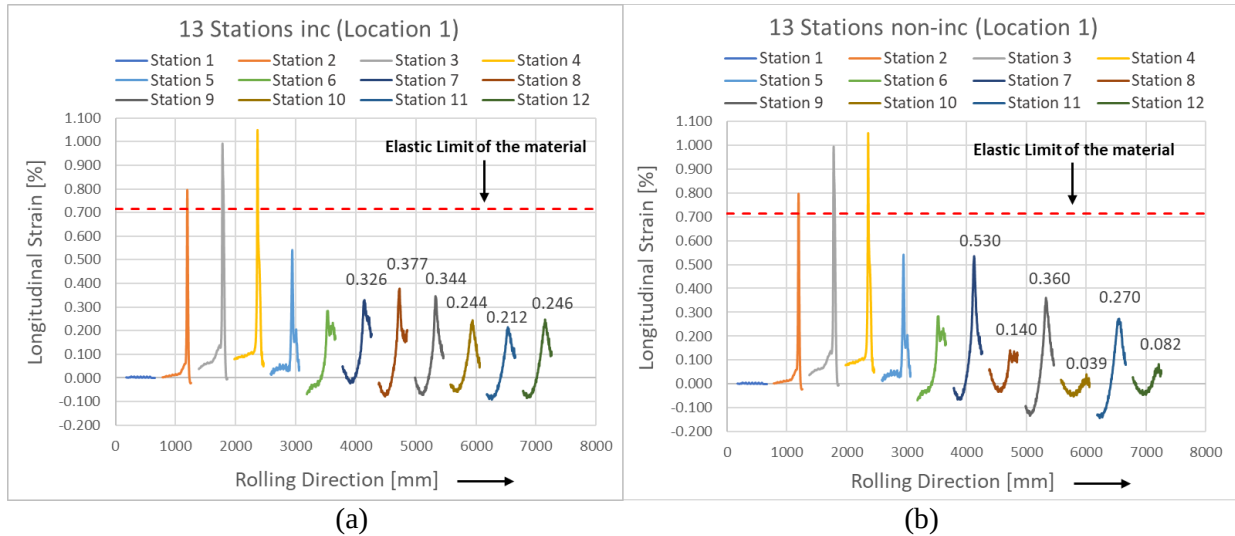


Figure 136 – Longitudinal edge strain results: (a) model with 13 stations incremented; (b) model with 13 stations non-incremented.

Most of the information present in the literature including a study conducted by Akbar Abvabi (2014) reveal that with fewer passes, the forming is more abrupt and therefore the end flare is higher. The results obtained for the end flare (Figure 137), are thus in agreement with the literature. As can be observed, increasing the number of stations leads to a reduction of the end flare relative to bend 1. Comparing the model with 13 stations non-incremented and the model with 13 stations incremented, it can be seen that the end flare values relative to bend 1 are lower for the latter, as would be expected, since the forming is more gradual. For the case of the end flare relative to bend 2, it is also verified a reduction with the increase of the number of stations. Furthermore, lower end flare values are again seen for the model with 13 stations incremented when compared to the model with 13 stations non-incremented, although the difference between these values is not significant. Another aspect to observe is the fact that the end flare values obtained for bend 1 are much higher than those obtained for bend 2.

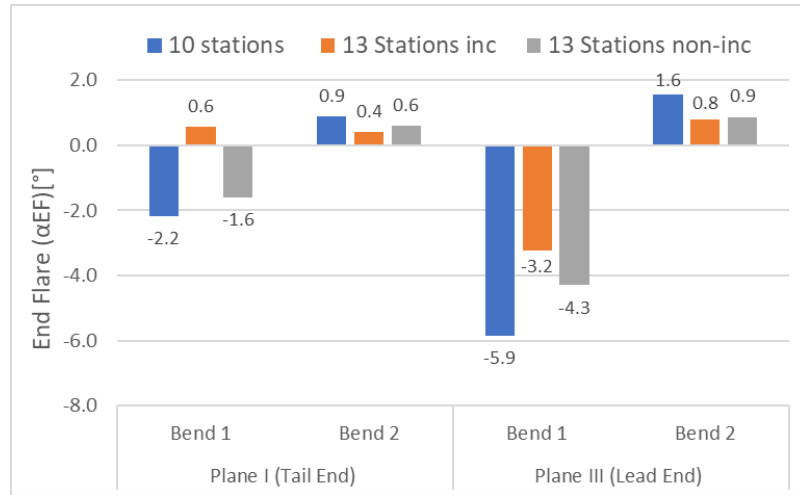


Figure 137 – Comparison of the models with 10 stations, 13 stations incremented and 13 stations non-incremented considering the end flare angles (α_{EF}) [°] obtained for the two bends and two planes under study.

In a study conducted by Buddhika Abeyrathna et al. (2017), no simple trend was observed between the decrease in forming angle and springback. For most cases, springback varied within $\pm 1^\circ$ when the forming angle decreased from 30° to 20° , but for the 1.5mm thick MS900 material and the 2mm thick DP600 material, there was a large increase in springback with decreasing forming angle (Figure 138).

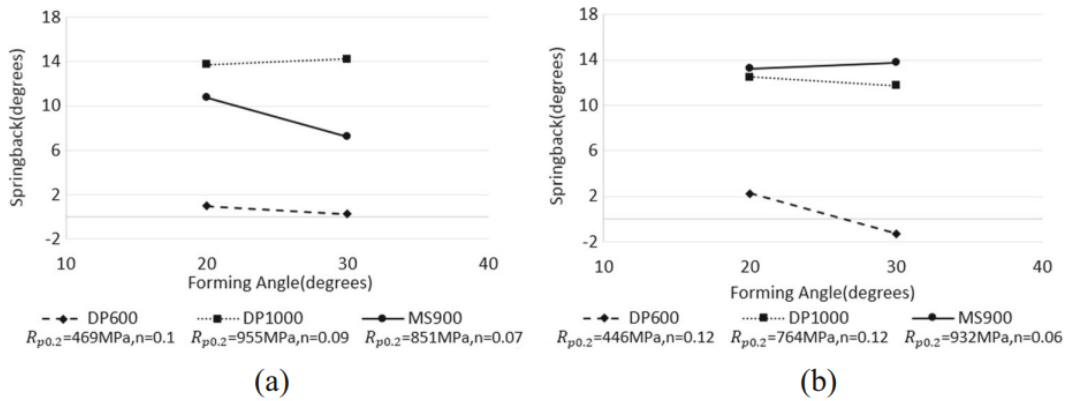


Figure 138 – Effect of the forming angle on the springback for three different materials: (a) 1.5mm material thickness; (b) 2 mm material thicknesses.

The material used for the three models under study in this section was Docol 1400M with 2.1 mm thickness. Therefore, in order to make a comparison with the results previously presented from the literature (Figure 138), the springback values obtained for the reference model (10 stations) and for the model in which the forming angle was reduced by half from station 6 ("13 stations inc" model), were analyzed. As can be seen in the graph of Figure 139, a high increase in springback was observed with the reduction of the forming angle for all the bends and planes under study, as, had been verified in the literature for the MS900 material with 1.5 mm thickness and for the DP600 material with 2 mm thickness. This increase was most pronounced in bend 2 of the lead end, since the springback value increased from 5.7° (value for the reference model with 10 stations) to 8.4° (value for the "13 stations inc" model). This indicates that an increase of 2.7 degrees of springback occurred in bend 2 of the lead end with the decrease of the forming angle by half from station 6.

However, a study conducted by Badr et al. (2014) revealed that increasing the number of stations leads to a decrease in springback, which means that springback can be influenced by plastic strains in the bend region.

Analyzing once again the springback values obtained for the three models under study (Figure 139), it was concluded that increasing the number of stations led to an increase in the springback angle, contrary to what happened in the study performed by Badr et al.(2014). This increase was observed for both bends and for all planes under study, except for bend 1 of the plane III where the "13 stations non-inc" model showed a reduction of 0.1 degrees of springback compared to the reference model (10 stations model), which is insignificant. In turn, comparing the two models with 13 stations, there is a tendency for the model with 13 stations incremented to have higher springback values compared to the model with 13 stations non-incremented. Furthermore, it can also be observed that the springback angles obtained for bend 1 are quite similar, while for bend 2 there is a greater discrepancy in these values.

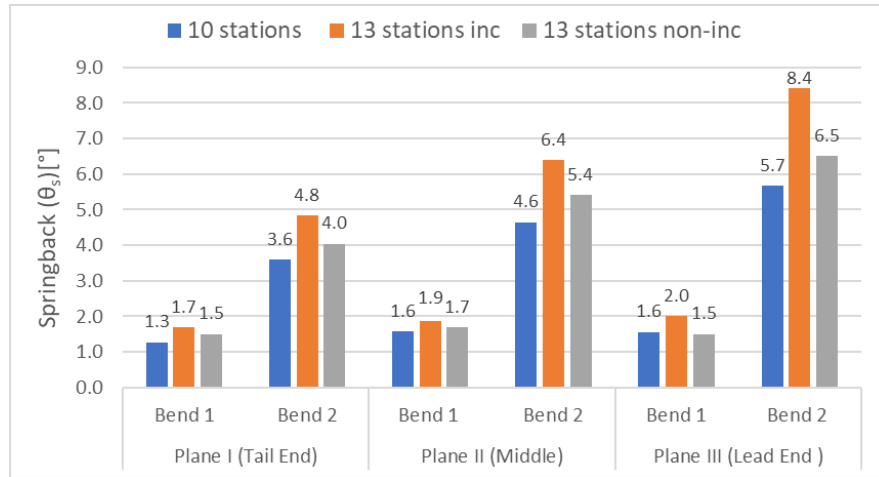


Figure 139 – Comparison of the models with 10 stations, 13 stations incremented and 13 stations non-incremented considering the springback angles (θ_s) [°] obtained for the two bends and three planes under study.

According to Martins (2018), higher plastic strains in the bend zones lead to a decrease in springback and vice-versa. Analysing the graph in Figure 140(a) relative to the outer bend 1 (see section 5.2.3), it can be seen that the model with 10 stations, despite having less forming steps, has a higher plastic strain in the bend zone than the models with 13 stations, showing fairly identical values to the model with 13 non-incremented stations starting at approximately 450 mm from the tail end. This explains the lower springback values obtained for the model with 10 stations when compared with the models with 13 stations. Furthermore, it also explains the closeness of the springback values obtained for the model with 10 stations and for the model with 13 non-incremented stations. Within the models with 13 stations, the model with 13 incremented stations is the one that presents lower values of plastic strain in the bend zone and is the model that presents higher springback values, as was observed in Figure 139.

In turn, analyzing the graph of Figure 140(b) relative to the outer bend 2, it is verified that the equivalent plastic strains for the three models present more pronounced differences than those verified for outer bend 1. This difference is even more significant when comparing the curve obtained for the model with 13 incremented stations ("13 stations inc") with the curves of the other two models, since the curves for this two models present equivalent plastic strain values at bend 2 much higher than those obtained for the model with 13 incremented stations.

The behavior described for the equivalent plastic strain curves is also observed in the plot of the springback values. As can be seen in Figure 139, there is also a greater difference in the springback values obtained for the model with 13 incremented stations when compared to the values obtained for the other two models, especially for bend 2. Furthermore, there is again a relationship between the equivalent plastic strain and the springback values in the bends. For example, the model with 13 incremented stations presents the lowest values of equivalent plastic strain at bend 2 and consequently presents the highest springback values, for the three planes under study.

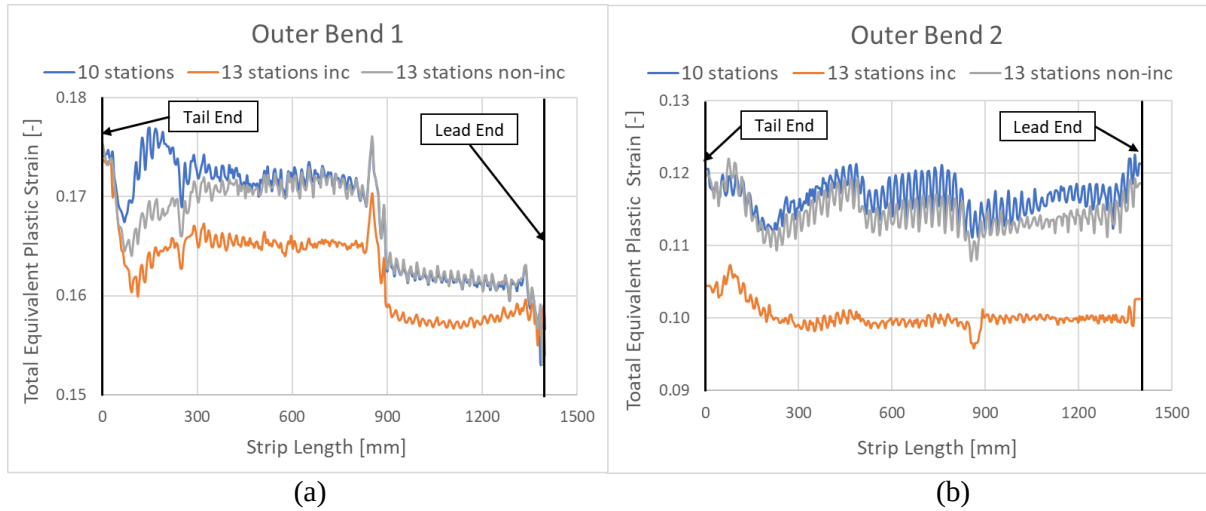


Figure 140 – (a) Total equivalent plastic strain along the length of the outer bend 1; (b) Total equivalent plastic strain along the length of the outer bend 2.

Comparing the vertical displacement of the part for the model with 13 incremented stations, with the vertical displacement of the part for the model with 13 non-incremented stations (Figure 141), it can be seen that the model with 13 incremented stations presents a more abrupt vertical movement (greater oscillations) throughout the roll forming process, which can lead to a greater propensity for defects to appear in the part. The vertical displacement of the two models differs only from the contact of the sheet with the roll of station 7, since this is the first station changed between the two models.

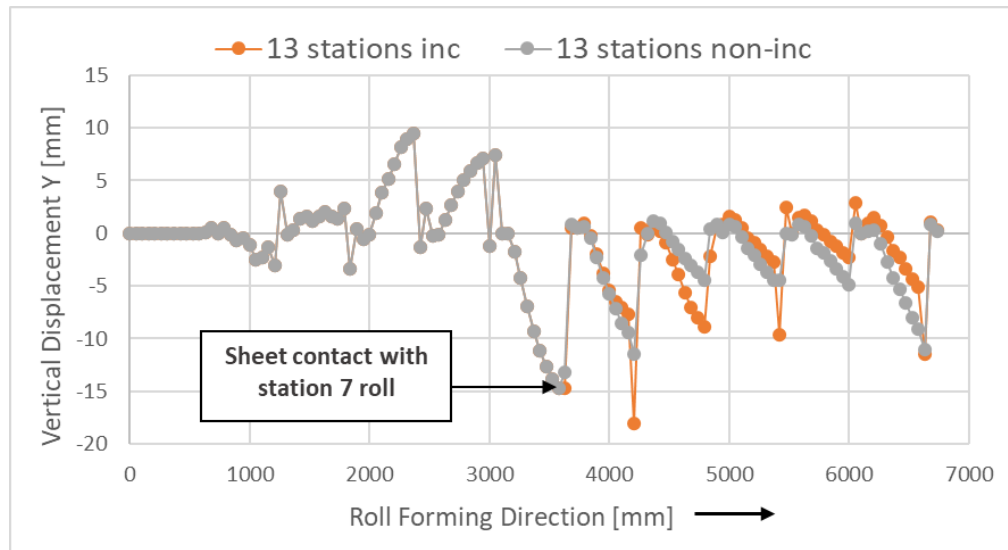


Figure 141 – Comparison of the vertical displacement along the RF process, obtained for the two models with 13 stations.

Regarding the twist angle, there was a slight increase in its value with the increase in the number of stations, but it was not significant (Table 13).

Table 13 – Twist angles (γ_T) [°] obtained from the model with 10 station (reference) and from the models with 13 stations.

Twist(γ_T) [°]	10 stations	13 stations inc	13 stations non-inc
	0.1	-0.2	0.3

5.3.4 Radius/Thickness=4 vs Radius/Thickness=8

The C-profile under study currently produced by Coproget has a thickness of 2.1 mm and an internal bending radius of 8.4 mm for each bend. However, at the exit of station 9, the profile has a bend radius of 12.88 mm for the bend between the web and the side flange (bend 2) and a bend radius of 8.4 mm for the bend between the side flange and the outer flange (bend 1).

According to Olsson et al. (2006), the minimum internal bending radius that can be obtained without cracks for Docol 1400 M steel is $4.0 \times t$, where t is the thickness of the profile (this is valid for all directions of curvature). As the C-profile produced by Coproget has a thickness of 2.1 mm it can be concluded that the internal bending radius of the final part (8.4 mm) already corresponds to the minimum value allowed ($4.0 \times 2.1 = 8.4$ mm). Since, Coproget produces other profiles besides the one in focus in this dissertation, with different thicknesses and bending radius, it was decided to study the influence that varying these two parameters have on the final product obtained. In this sense, firstly, a model with half the thickness as the reference simulation was created, i.e., a model with 1.05 mm of thickness (the original bending radius was maintained).

Figure 142(a) and Figure 142(b) present respectively the values of the transverse and longitudinal residual stresses across the width of the part, obtained for the reference simulation ($R/T=4$) and for the simulation with thickness reduction ($R(\text{standard})/T(\text{reduced}) = 8$), considering the plane I. According to Safdarian and Moslemi Naeini (2015) with the decrease in the strip thickness, the residual stress is increased after the roll stand.

Analysing the transverse residual stresses across the width obtained for plane I (tail end) (Figure 142(a)), it was verified that the main differences between the two models occur at the bends. For bend 2, it can be seen that the stresses along the outer surface (path o) are quite similar for both models. However, for the inner surface of bend 2 (path i), it can be seen that the models have opposite behaviours. While the reference model ($R/T=4$) has the inner surface (path i) of the corner between web and bend 2 subject to high compressive stresses (-457 MPa), the model with reduced thickness ($R(\text{standard})/T(\text{reduced})=8$) has the corner between bend 2 and the side flange subject to high tensile stresses (330 MPa). In turn, for bend 1 it is verified that the magnitude of the transverse residual stresses is higher for the model with thickness reduction, both for the inner (path i) and outer (path o) surfaces of the profile. This behaviour is also visible in the graphs obtained for plane II (middle) and plane III (lead end), represented in Appendix E, Figures E1-E2.

Analysing the longitudinal stresses across the width of the sheet (Figure 142(b)), it can be seen that the model with thickness reduction presents much lower magnitudes of longitudinal residual stresses for the web and side flange area compared to those observed for the reference model. In turn, the bends present a more irregular stress distribution, and therefore, it is not possible to distinguish the two models based on the longitudinal stress values observed for them. In turn, the longitudinal residual stresses for the outer flange are quite similar for the two models, since the curves are practically coincident in this zone. This behaviour is also visible in the graphs obtained for plane II (middle) and plane III (lead end), represented in Appendix E, Figures E1-E2.

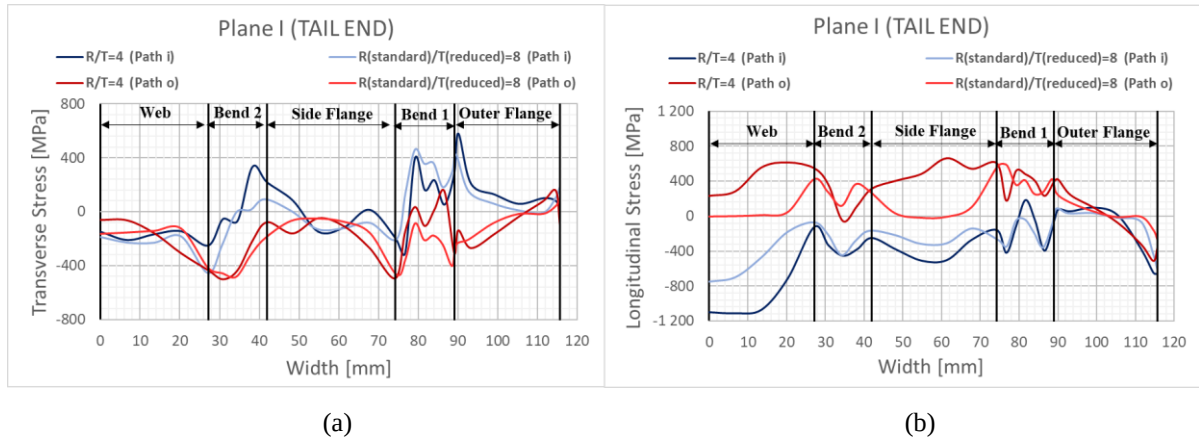


Figure 142 – (a) Transverse residual stresses across the width in plane I (Tail end) for the reference model ($R/T=4$) and for the model with thickness reduction ($R(\text{standard})/T(\text{reduced})=8$); (b) Longitudinal residual stresses across the width in plane I (Tail end) for the reference model ($R/T=4$) and for the model with thickness reduction ($R(\text{standard})/T(\text{reduced})=8$).

Subsequently, another model was created, with an internal bending radius of 16.8 mm, keeping thickness constant ($R(\text{increased})/T(\text{constant})=8$), in order to verify the influence of this parameter on the final product obtained. Figure 143 presents the values of the transverse residual stresses across the sheet thickness for plane III (lead end), obtained for both the reference model ($R/T=4$) and the model in which the internal bending radius was increased to doubled ($R(\text{increased})/T(\text{standard})=8$).

Analysing the graphs, it can be seen that although the transverse stress distribution became more uniform with the increase of the radius-thickness ratio, their values in terms of magnitude did not undergo significant differences. This conclusion was also drawn in a study conducted by Martins (2018) in which the increase in the internal bending radius of a U-shaped profile was analysed. The graphs regarding the transverse residual stresses for planes I (tail end) and II (middle) are presented in Appendix E, Figures E3-E4 and are quite similar to the graphs analysed here.

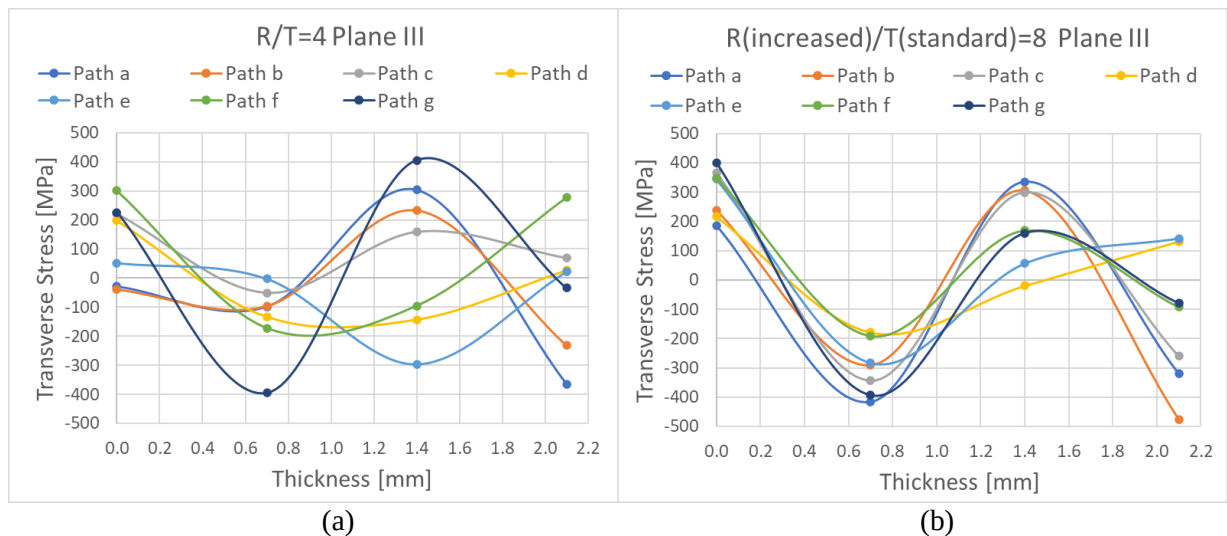


Figure 143 – (a) Transverse residual stresses across the thickness in plane III, for the model with $R/T=4$ (reference model); (b) Transverse residual stresses across the thickness in plane III, for the model with increase of the internal bending radius to double ($R(\text{increased})/T(\text{standard})=8$).

Figure 144 presents the longitudinal residual stresses across the thickness obtained from the reference model ($R/T=4$), as well as from the model with increased internal bending radius ($R(\text{increased})/T(\text{standard})=8$), considering the plane II (middle). As can be seen in Figure

144(b), increasing the internal bending radius does not produce major changes in the longitudinal strains across the thickness, since both the distribution and magnitude of the longitudinal stress values are identical to those represented in Figure 144(b) for the reference model. The greatest difference between the distributions obtained for the two models occurs essentially for the inner surface of the bend. This behaviour is also visible in the graphs obtained for plane I (tail end) and plane III (lead end), represented in Appendix E, Figures E5-E6.

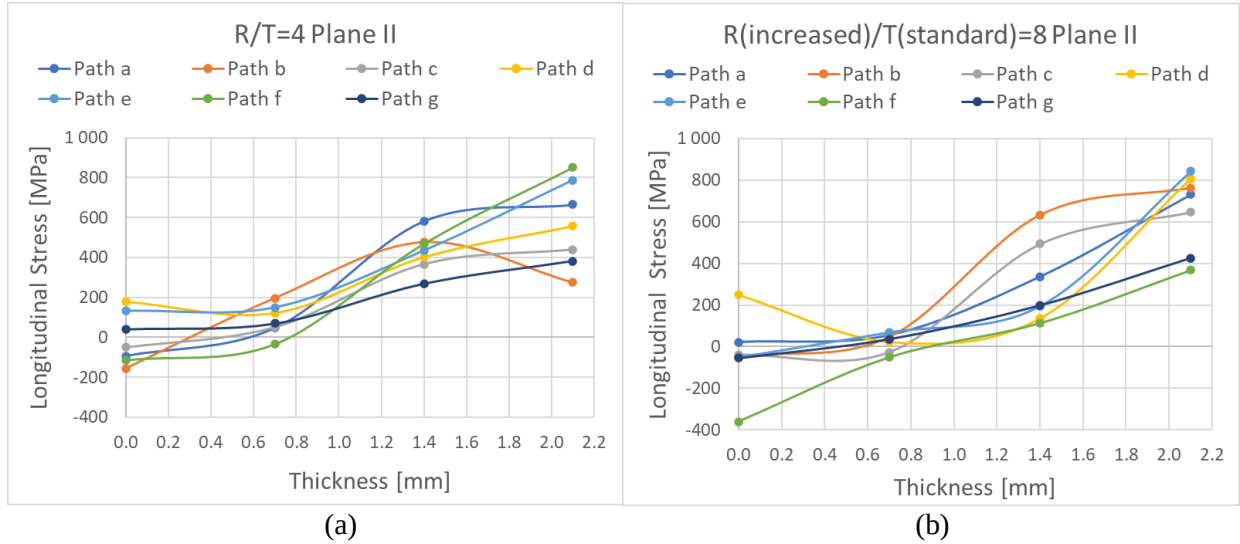


Figure 144 – (a) Longitudinal residual stresses across the thickness for the model with $R/T=4$ (reference model), considering plane II (middle); (b) Longitudinal residual stresses across the thickness for the model with $(R(\text{increased})/T(\text{standard}))=8$, considering plane II (middle).

Figure 145 presents the graphs of longitudinal edge strain obtained for the model with increased bending radius (Figure 145(a)) and for the model with reduced thickness (Figure 145(b)), for location 1. Comparing the values obtained for these two models with those previously presented for the reference simulation (see section 5.3.1), it can be seen that the model with increased radius has much higher longitudinal strain peaks than the reference model. While for the case of the reference simulation, the maximum peak longitudinal strain occurs for station 4 and has a value of 1.050%, for the case of the simulation with increased internal bending radius, the maximum peak longitudinal strain occurs for station 5 and has a value of 1.482%. This means an increase of 0.432% with respect to the reference simulation.

In turn, the model with thickness reduction presents lower longitudinal strain peaks for each station than those observed for the reference model. While the reference simulation shows a maximum peak longitudinal strain for station 4 of 1.050%, the simulation with thickness reduction shows a maximum peak longitudinal strain also for station 4 but at a value of 0.712%. This means a decrease of 0.338% of the peak longitudinal strain at station 4 compared to that observed for the reference simulation. According to most of the studies present in the literature a reduction in strip thickness decreases the peak longitudinal membrane strain, which confirms the results obtained (Safdarian and Moslemi Naeini 2015; Buddhika Abeyrathna et al. 2017). Furthermore, according to Zhu et al. (1996) the reduction in the strip thickness increases the transition length and decreases the slope at the point of contact with the rolls, hence inducing less longitudinal strain.

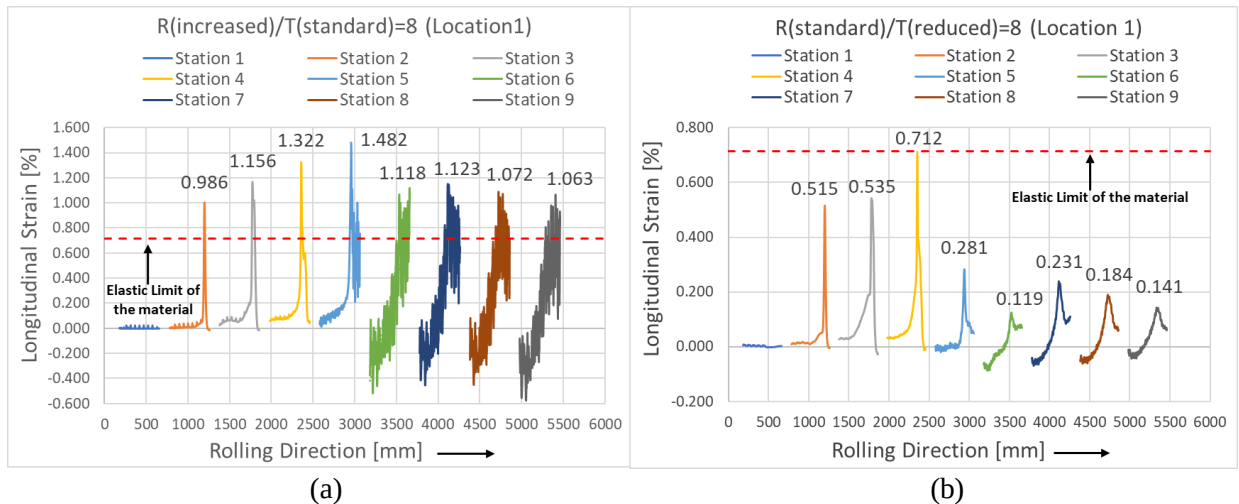


Figure 145 – Longitudinal edge strain results: (a) model with increased inner bending radius to double $R(\text{increased})/T(\text{standard})=8$; (b) model with thickness reduction $R(\text{standard})/T(\text{reduced})=8$.

In order to transform a flat strip into the desired final profile, the stresses in the bent elements must exceed the yield point of the material to generate permanent deformation and permanent elongation. Stresses that exceed the yield point and result in permanent deformation develop permanent elongation greater than 0.2%. To achieve permanent deformation, the outside fibre of the bending line should be stretched from a minimum of approximately 1 to 2% to the maximum strain attainable without material failure. Roll designers therefore prefer to use bending lines with relatively small radius, since smaller radius present a large elongation of the outside fibre of the bend line, which consequently generates stresses well over the yield point, reducing the springback of the profiles. For large radius, the stresses will be barely above the yield point and the elastic strain/permanent strain ratio will be high, which will generate more elastic springback when compared to small radius (Halmos 2006). Also a study developed by Bui and Ponthot (2008), showed that a larger bending radius leads to a higher compression and stretching area, which consequently increases springback values.

Regarding the simulation with thickness reduction, a study conducted by Xiaoli Liu et al. (2017), showed that the magnitude of springback decreases with increasing strip thickness both in the simulations performed and in the experimental results. In Bui and Ponthot (2008), it is also mentioned that the thicker the material, the lower the springback observed.

The results obtained also show that the springback observed for the profile under study increases with increasing radius and decreasing thickness, as mentioned in most of the literature (Figure 146). Therefore, it can be concluded that the higher the radius/thickness ratio the higher the springback. Analysing the springback values obtained, it can be seen that for bend 1, the springback values obtained for the three models are relatively similar for the three planes under study, although there are always larger springback values for a higher R/T ratio. However, the influence of the variation of the parameters under study on springback is mostly noticeable for bend 2, with as much as 12.5° of springback being reached in this bend. Furthermore, bend 2 of the tail end is the one in which a greater influence of the parameters under study is observed, as there was an increase of 8.9° for the model with increased radius and an increase of 5.5° for the model with reduced thickness compared to the springback value obtained for the reference simulation.

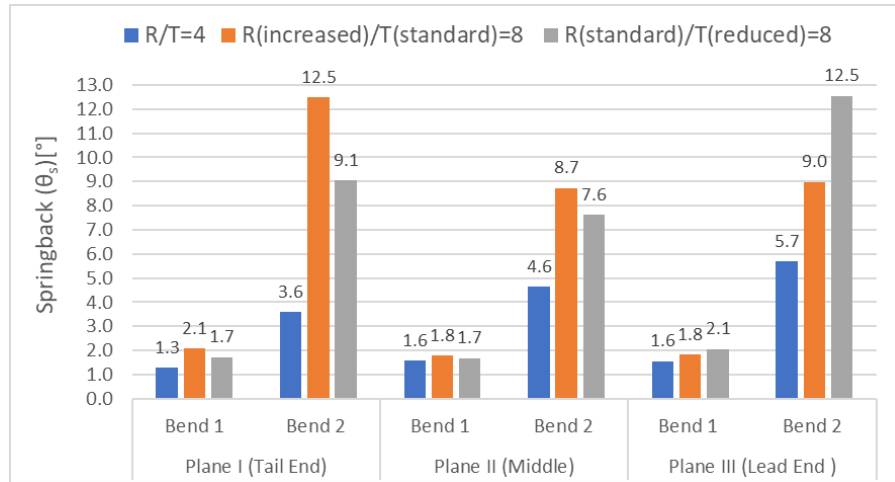


Figure 146 – Comparison of the models with $R/T=4$, with increased bending radius ($R(\text{increased})/T(\text{standard})=8$) and with reduced thickness ($R(\text{standard})/T(\text{reduced})=8$) considering the springback angles (θ_s) [°] obtained for the two bends and three planes under study.

In general, it is also found that the end flare angles are higher for a higher ratio/thickness ratio, as can be seen in Figure 147. This correlation was not observed only in bend 2 of the tail end for the model with increased radius. Another factor to take into account is the high amount of end flare observed for bend 1 of the lead end.

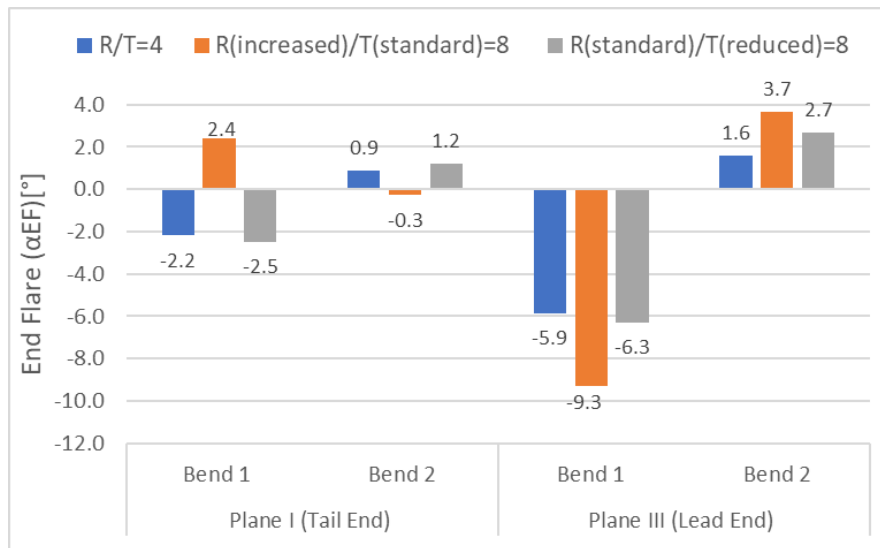


Figure 147 – Comparison of the models with $R/T=4$, with increased bending radius ($R(\text{increased})/T(\text{standard})=8$) and with reduced thickness ($R(\text{standard})/T(\text{reduced})=8$) considering the end flare angles (α_{EF}) [°] obtained for the two bends and two planes under study.

As can be seen in Table 14, the only model that presented a significant twist was the model with the increased internal bending radius, with a value of 1.8° degrees.

Table 14 – Twist angles (γ_T) [°] obtained from the model with 10 station (reference) and from the models with 13 stations.

Twist(γ_T) [°]	R/T=4	R(increased)/T(standard)=8	R(standard)/T(reduced)=8
	0.1	1.8	0.0

5.3.5 Standard Roll Diameter vs Increased Roll Diameter

The roll radius is a design parameter, since as the diameter of the bottom roll changes, the contact point is also alternated (Paralikas et al. 2013). Increasing the diameter of the bottom roll increases the contact length between strip and roll if other forming variables are kept constant.

This factor allows for a decrease in the rate of angle change and, consequently, a reduction in the forming severity (Zhu et al. 1996). In order to analyse the influence of roll diameter on the profile produced by Coproget, a new model was created in which the diameter of the bottom roll was increased by 40 mm at all stations. As Coproget uses a bottom/top diameter ratio of 1.395 for the design of its rolls, the diameter of the top rolls was also increased, considering this same ratio.

Analysing the residual transverse stresses (Figure 148(a)) and the longitudinal residual stresses (Figure 148(b)) across the width of the part for plane II (middle), it was verified that the curves obtained for the two models under study are quite similar, practically coincident. The same behaviour is verified for the tail and lead end, represented in Appendix F, Figures F1-F2.

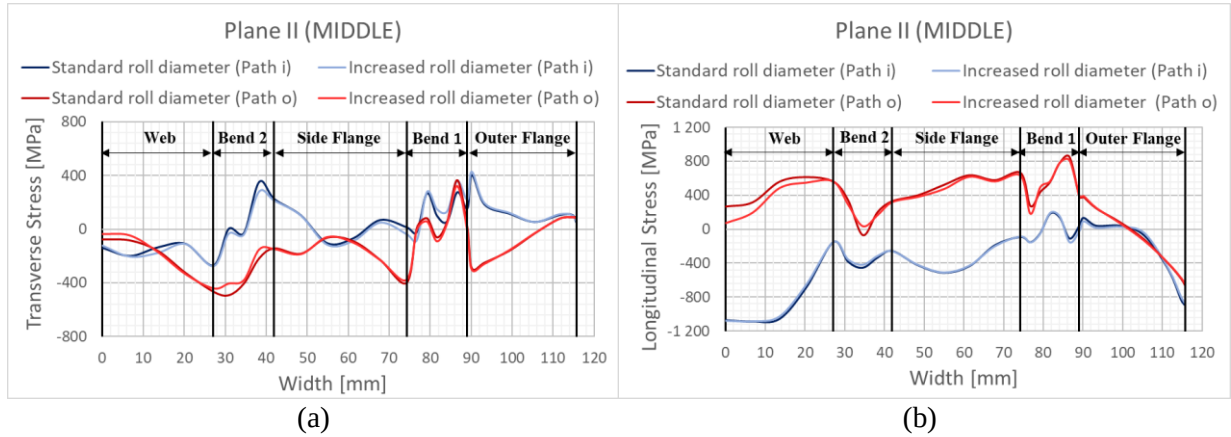


Figure 148 – (a) Transverse residual stresses across the width in plane II (Middle) for the reference model (standard roll diameter) and for the model with increased roll diameter; (b) Longitudinal residual stresses across the width in plane II (Middle) for the reference model (standard roll diameter) and for the model with increased roll diameter.

In Figure 149 and Figure 150 are illustrated, respectively, the transverse and longitudinal residual stresses across the thickness of the part for both models under study, considering the plane II (middle).

Once again it is verified that the curves obtained for the two models are quite similar, both in terms of distribution and in terms of magnitude. The same is observed for the curves of the graphs obtained for plane I (tail end) and plane III (lead end), represented in Appendix F, Figures F3-F6.

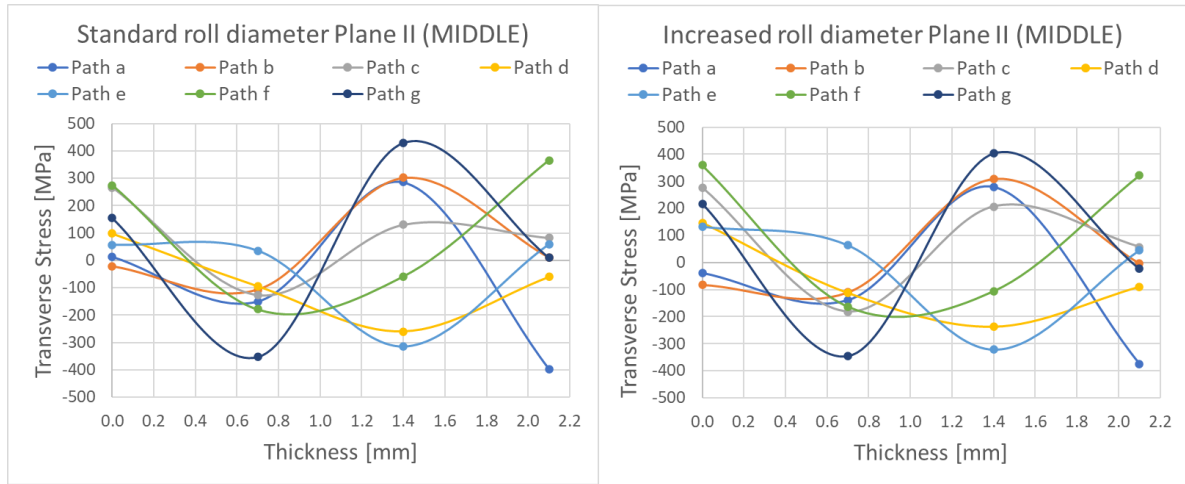


Figure 149 – (a) Transverse residual stresses across the thickness in plane II (middle), for the model with standard roll diameter (reference model); (b) Transverse residual stresses across the thickness in plane II (middle), for the model with increased roll diameter.

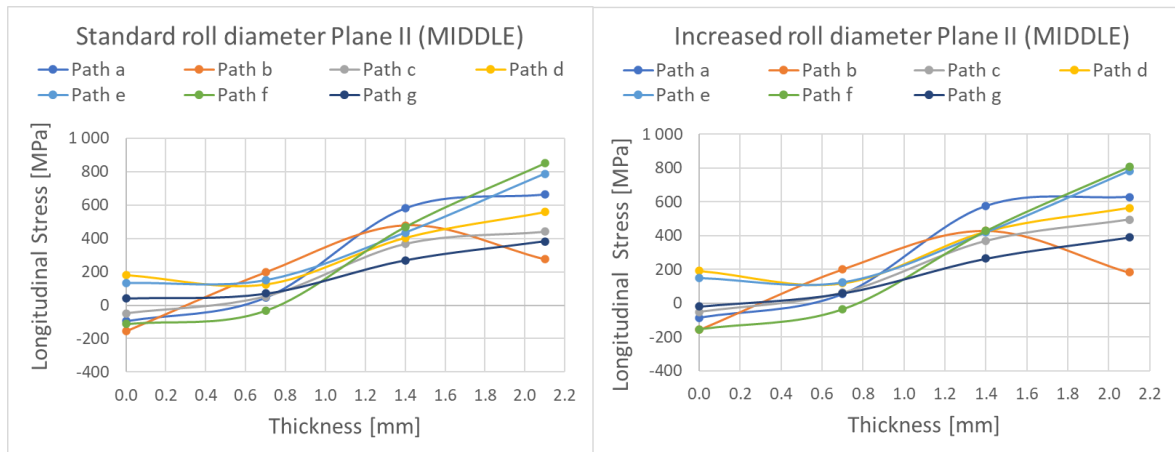


Figure 150 – (a) Longitudinal residual stresses across the thickness for the model with standard roll diameter (reference model), considering plane II (middle); (b) Longitudinal residual stresses across the thickness for the model with increased roll diameter, considering plane II (middle).

According to Paralikas et al. (2009), the distribution of the longitudinal and transverse strains in the final profile produced is affected by alternating the roll diameter. However, for the profile under study, no significant differences were found in these values.

Furthermore, according to Zhu et al. (1996), as the roll diameter becomes larger, the roll restriction becomes flatter and therefore the peak longitudinal strain becomes smaller. Also, in a study conducted by Paralikas et al. (2009), was revealed that the smaller the diameter of the rolls the greater the accumulation of longitudinal plastic strain at the strip edge, i.e, by increasing the diameter of the rolls the residual longitudinal strain is reduced. However, is also mentioned that increasing the roll diameter is a costly means of achieving a reduction in the peak longitudinal strain.

Analysing the graph of Figure 151(b), it can be seen that there is actually a reduction in the peaks of the longitudinal edge strain with increasing roll diameters, when compared to the reference model Figure 151(a).

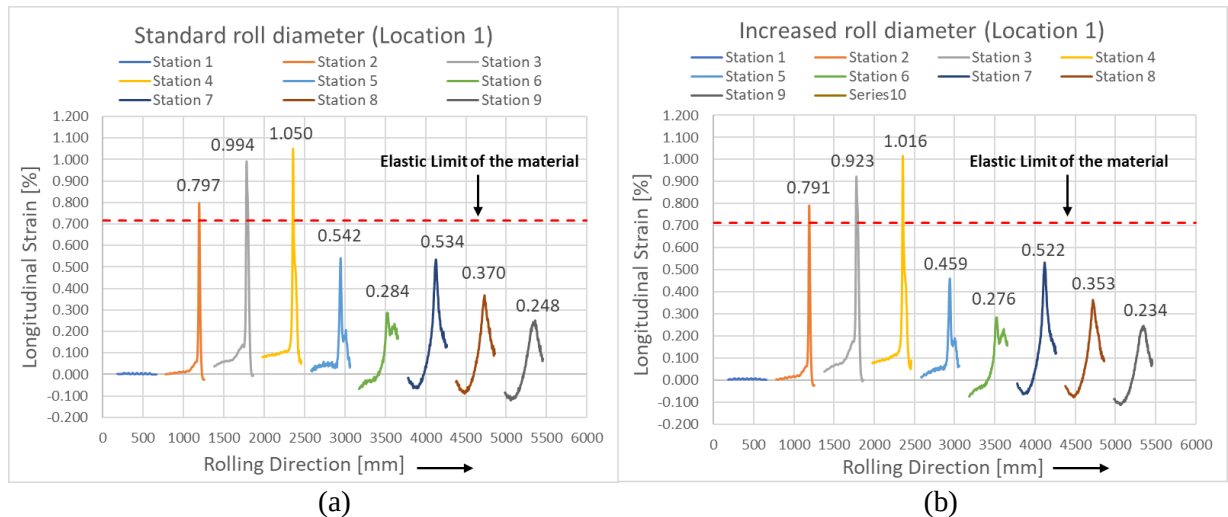


Figure 151 – Longitudinal edge strain results: (a) model with standard roll diameter; (b) model with increased roll diameter.

Regarding the springback values obtained for the two models (Figure 152), it can be seen that increasing the diameter of the rolls leads to higher springback values for both bends and for the three planes under study, except for bend 1 of plane III where the values obtained were equal. The biggest difference between the springback angles occurred for bend 2 of plane III where there was an increase of 1.7° relative to the reference model. Another noticeable aspect is that the springback angles increased much more significantly for bends 2 than for bends 1, where the values obtained were quite similar.

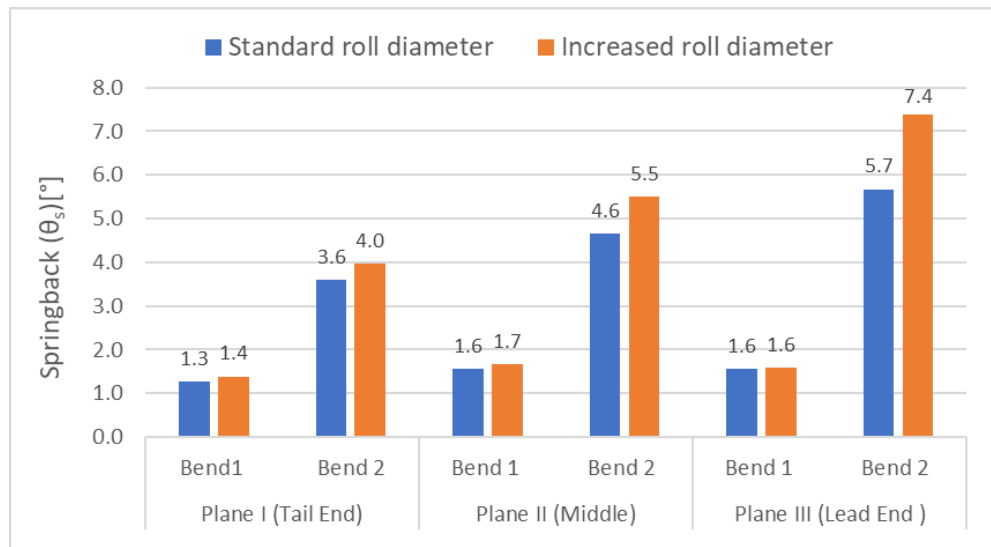


Figure 152 – Comparison between the model with standard roll diameter and the model with increased roll diameter, considering the springback angles (θ_s) [°] obtained for the two bends and three planes under study.

In turn, as can be seen in Figure 153, the end flare angles obtained were slightly lower for the model with increased roll diameter, when compared with the reference model (standard roll diameter). The biggest difference between these values occurred for bend 1 of plane III (lead end), where there was a reduction of 0.6° with a 40mm increase in the diameter of the bottom rolls.

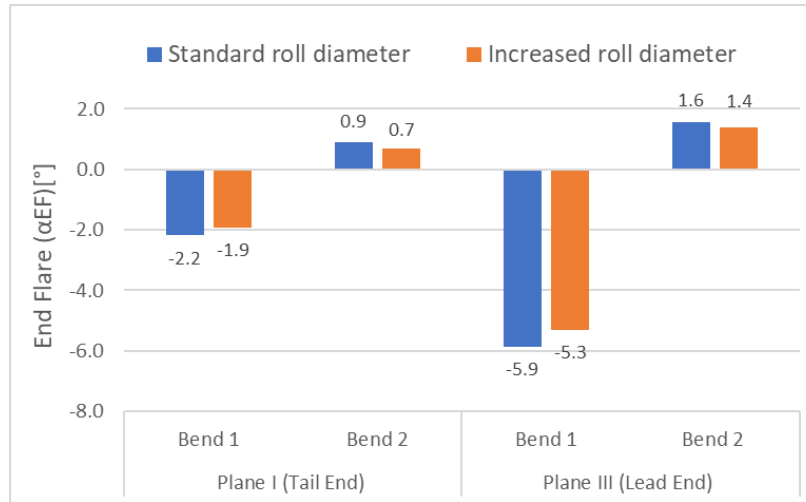


Figure 153 – Comparison between the model with standard roll diameter and the model with increased roll diameter, considering the end flare angles (α_{EF}) [°] obtained for the two bends and two planes under study.

Regarding the twist angles obtained for the two models, it was observed that these values were practically insignificant (around 0) (Table 15).

Table 15 – Twist angles (γ_T) [°] obtained from the model with standard roll diameter (reference) and the model with increased roll diameter.

Twist(γ_T) [°]	Standard Roll Diameter	Increased Roll Diameter
	0.1	-0.1

By analysing the vertical displacement of the part along the roll forming direction for the model with standard rolls, it can be seen that from station 4 the part acquires a sharp downward movement before entering each of the stations (Figure 154). The model with increased roll diameter, also acquires a downward movement at the moment just before entry into most of the stations. However, this downward movement is much less pronounced than that observed for the model with standard rolls. This fact demonstrates that the contact between the sheet and the rolls is smoother for the model with the bottom roll diameter increased by 40mm.

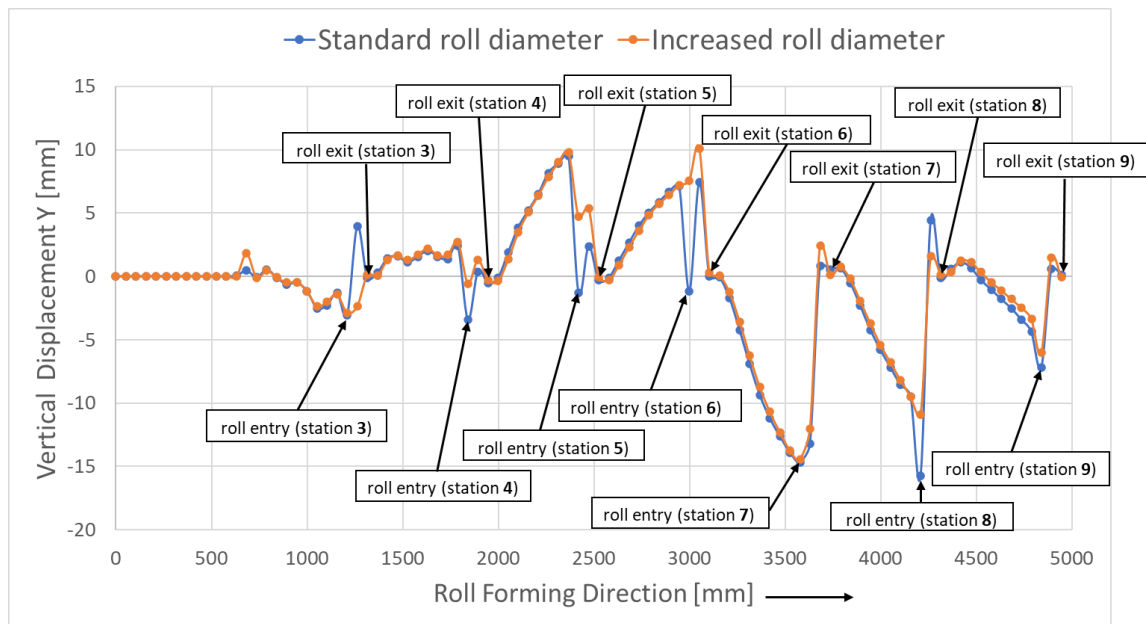


Figure 154 – Comparison of the vertical displacement along the RF process, between the model with standard roll diameter and the model with increased roll diameter.

Although increasing the roll diameter brings some advantages namely in reducing the longitudinal edge strain, reducing the end flare and providing a smoother entry into the gap between the rolls, attention must be paid to the costs associated with this increase. Furthermore, according to Paralikas et al. (2013), with the increase of the rolls diameter, the energy efficiency indicator is reduced, since the mass of the roll supports increases, thus yielding to larger requirements in the kinetic energy of the roll forming line.

5.3.6 No Friction vs Friction

Friction is described as the resistant force to a relative motion of surfaces in contact sliding against each other (X. Wang et al. 2018). As mentioned previously, simulation 1 was modelled without friction while simulation 9 was modelled with driven rolls and with a Coulomb friction coefficient of 0.2, as recommended in Xiaoli Liu et al. (2017). The friction models available in Copra® FEA RF software are presented in Figure 155.

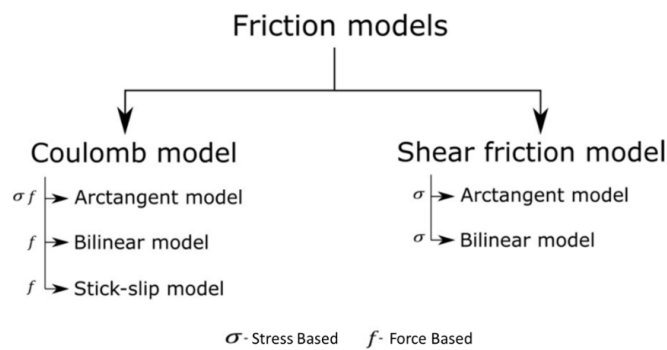


Figure 155 – Friction models available in COPRA® FEA.

In metal forming simulations, friction usually follows the Coulomb friction law or the constant shear friction law. For the Coulomb friction law, the frictional stress is proportional to the normal stress or force. In turn, for the constant shear friction law the frictional stress corresponds to a certain fraction of the shear yield stress of the material. However, the constant shear friction law neglects the effects of normal stress on the frictional stress. As such, since the frictional stress is related to the normal stress, the Coulomb friction law or its variants describe the real frictional behaviour better than the constant shear friction law (Joun et al. 2009). Thus, for the friction model performed, the Coulomb friction law was considered. Within this law, the software allows the use of three different numerical implementations, as represented in Figure 156. For the simulations performed the Bilinear model was used.

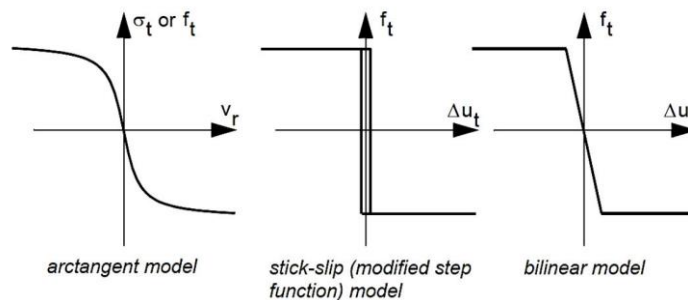


Figure 156 – Friction numerical models available in COPRA® FEA RF.

The definition of a model with driven rolls (considering friction) implies that the rolls remain fixed in space while the strips move forward along the stations due to the frictional force. In RF process, friction is the factor responsible for transmitting the driving power from the rotating rolls to the sheet. Therefore, the implementation of driven and non-driven rolls is performed in

Copra RF software through the selection of motorized axes. Coproget's roll forming line has a motor for each station. Rolls on driven axis rotate by a pre-defined rotational speed and rolls on non-driven axis rotate freely by the frictional force as applied by the moving sheet. Therefore, the speed of the strip in the rolling direction is defined by the balance of all driving and braking friction forces of the rolls on the driven and non-driven axis (data M 2020). For the first 10 stations of Coproget's RF line all the bottom rolls are driven. However, the top rolls may or may not be driven, depending on the station, as shown in Figure 157 and in Table 16. The stations that have the top rolls driven are stations that require a stronger pull of the sheet.

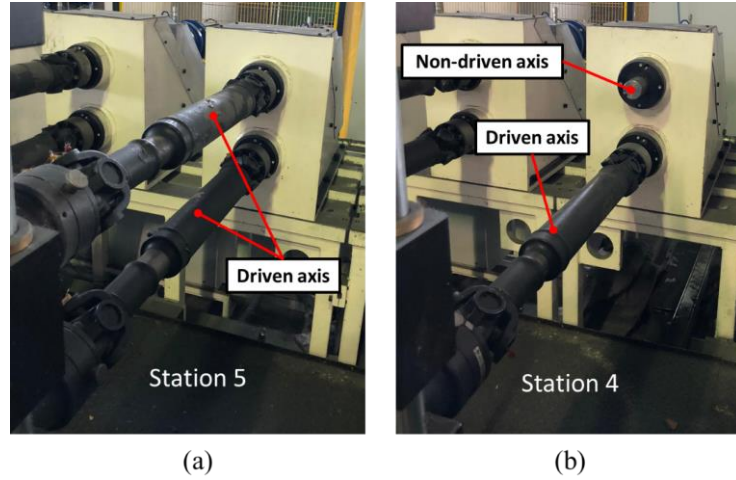


Figure 157 – (a) Station5: the top and bottom rolls are driven; (b) Station4: The bottom roll is driven and the top roll is not driven.

Furthermore, to create a model with driven rolls, Copra RF software also requests the ratio between the driving diameters of the top and bottom rolls, the rotational speed in revolutions per minute of each of the rolls and the friction coefficient.

Knowing that normally the Coproget roll forming line works at a speed of 10 m/min ($\cong 0.1667$ m/s) and knowing the driving diameters of the top and bottom rolls (Table 16), the angular velocity for each of the driven rolls was calculated (equation 5.5).

$$\omega = \frac{2V}{D} \quad (5.5)$$

Where,

- ω is the angular velocity of each roll in rad/s;
- V is the linear speed of the Coproget roll forming line in m/s;
- D is the driving diameter of each of the rolls in m;

In turn, based on the values obtained for the angular velocity and through equation 5.6 the rotational speed in revolutions per minute (RPM) was calculated for each of the driven rolls.

$$RPM = \frac{30 \omega}{\pi} \quad (5.6)$$

Where,

- RPM is the rotational speed in revolutions per minute of each of the rolls;
- ω is the angular velocity of each roll in rad/s;
- D is the diameter of each of the rolls in m;

Table 16 – Driven and non-driven rolls for the first ten stations of Coproget's roll forming line.

Station	Rolls	Driven	Driving Diameter [m]	Angular velocity ω [Rad/s]	Rotational speed in revolutions per minute [RPM]
0	Top	No	0.186	1.790	17.095
	Bottom	Driven	0.259	1.283	12.252
1	Top	No	0.186	1.787	17.067
	Bottom	Driven	0.260	1.280	12.228
2	Top	No	0.186	1.784	17.041
	Bottom	Driven	0.260	1.279	12.214
3	Top	No	0.187	1.779	16.996
	Bottom	Driven	0.261	1.275	12.181
4	Top	No	0.187	1.776	16.962
	Bottom	Driven	0.261	1.274	12.170
5	Top	Driven	0.187	1.777	16.971
	Bottom	Driven	0.261	1.273	12.163
6	Top	No	0.188	1.774	16.943
	Bottom	Driven	0.261	1.272	12.156
7	Top	No	0.187	1.775	16.951
	Bottom	Driven	0.262	1.272	12.149
8	Top	Driven	0.187	1.774	16.941
	Bottom	Driven	0.262	1.271	12.142
9	Top	Driven	0.188	1.773	16.931
	Bottom	Driven	0.262	1.270	12.135

In the simulation of the model with friction, it was verified that the sheet stopped at the exit of the last station (station 9) (Figure 158). This problem occurred due to the fact that the type of model used for this simulation has been little tested by Data M so far, since it uses pre-cut sheet and driven rolls simultaneously (model little requested by customers).

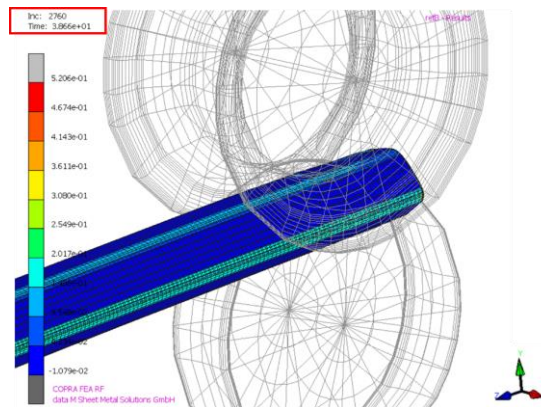


Figure 158 – End of simulation without the part completely coming out of the rolls (Total equivalent plastic strain results).

In a first attempt, the number of steps and the loadcase time were increased proportionally in order to maintain a constant time step of 0.014s, (obtained for the first simulation with this model). With an increase in the number of steps it was expected that the strip would completely exit the last station. However, this did not happen. In order to overcome this problem, an additional station (station 10) was added, with rolls exactly the same as station 9. Then, the contact bodies on the top and bottom roll of the added station (station 10) were removed, so

that it became invisible during the simulation and therefore had no influence on it (Figure 159). After performing this second attempt, it was verified that the sheet was able to get out of the rolls.

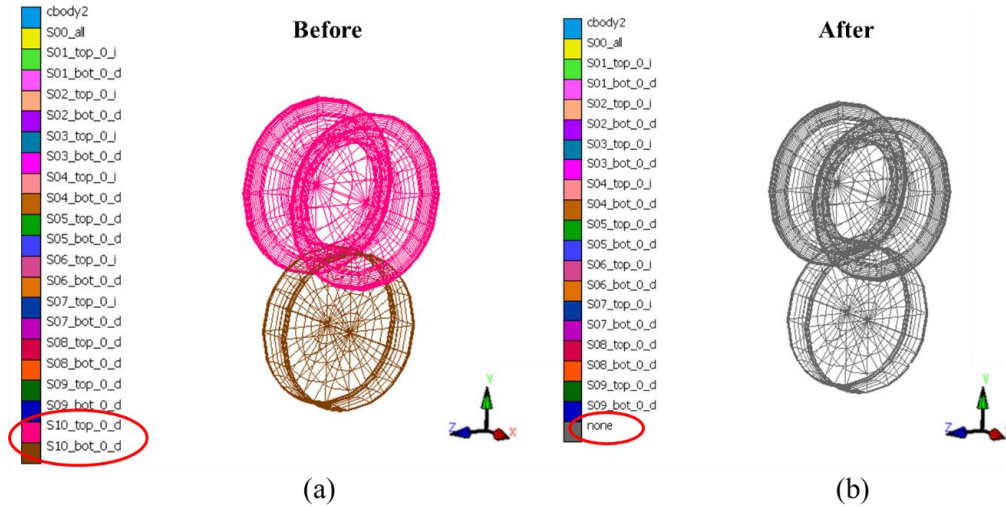


Figure 159 – Removing contact bodies from the station 10: (a) before removal; (b) after removal.

In Figure 160(a) and Figure 160(b), are represented respectively the transverse and longitudinal residual stresses along the width of the part, obtained for the model with friction and for the model without friction.

Analysing the transverse residual stresses (Figure 160(a)) for the outer (path o) and inner (path i) surfaces of plane II (middle), it can be seen that the curves obtained for the two models are quite similar, both in magnitude and distribution, except for bend 1 where the values for the model with friction were higher. In this bend 1, the model with friction reached maximum values of 241 MPa for the inner surface and 365 MPa for the outer surface, while the model without friction reached 702 MPa for the inner surface and 648 MPa for the outer surface. The results obtained for plane I (tail end) and plane III (lead end) are shown in Appendix G, Figures G1-G2. For these two planes the same behaviour was verified as for plane II, observing only a greater dispersion of the results for the web in plane I (tail end).

In turn, for the graph of longitudinal residual stresses across the width (Figure 160(b)), it is verified that the curves obtained for the two models are quite identical, observing only slight differences in the bends, with the model without friction reaching slightly higher values considering the outer surface (path o) and the model with friction reaching higher values considering the internal surface (path i).

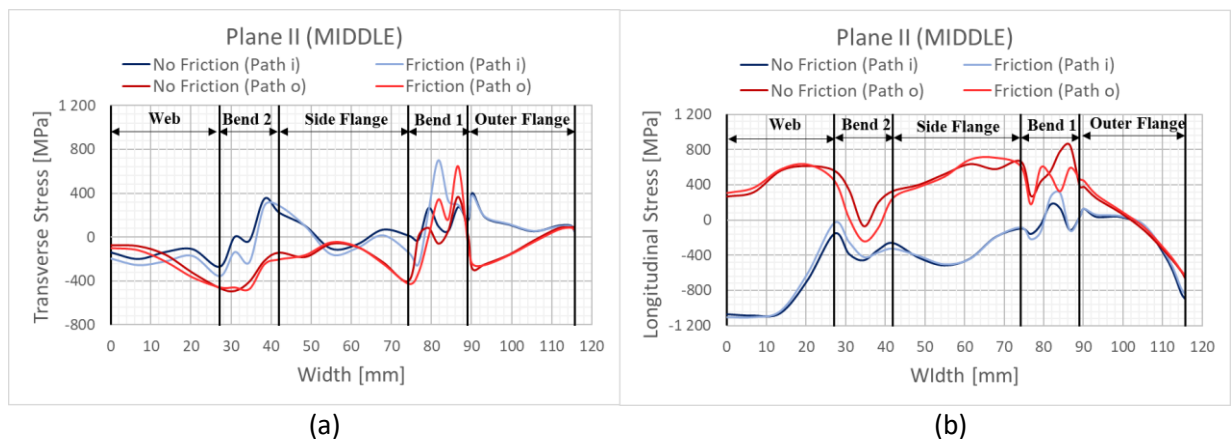


Figure 160 – (a) Transverse residual stresses across the width in plane II (Middle) for the reference model (no friction) and for the model with friction; (b) Longitudinal residual stresses across the width in plane II (Middle) for the reference model (no friction) and for the model with friction.

Figure 161 presents the transverse residual stresses across the thickness obtained from the reference model (no friction) (Figure 161 (a)), as well as from the model with friction (Figure 161 (b)), considering the plane II (middle). As can be observed, for the transverse residual stresses through the thickness, the models present differences in terms of distribution but are similar in terms of magnitude since the transverse stress values vary between -400MPa and 400MPa for both models. This behaviour is also observed for the graphs corresponding to the lead and tail end present in Appendix G, Figures G3-G4.

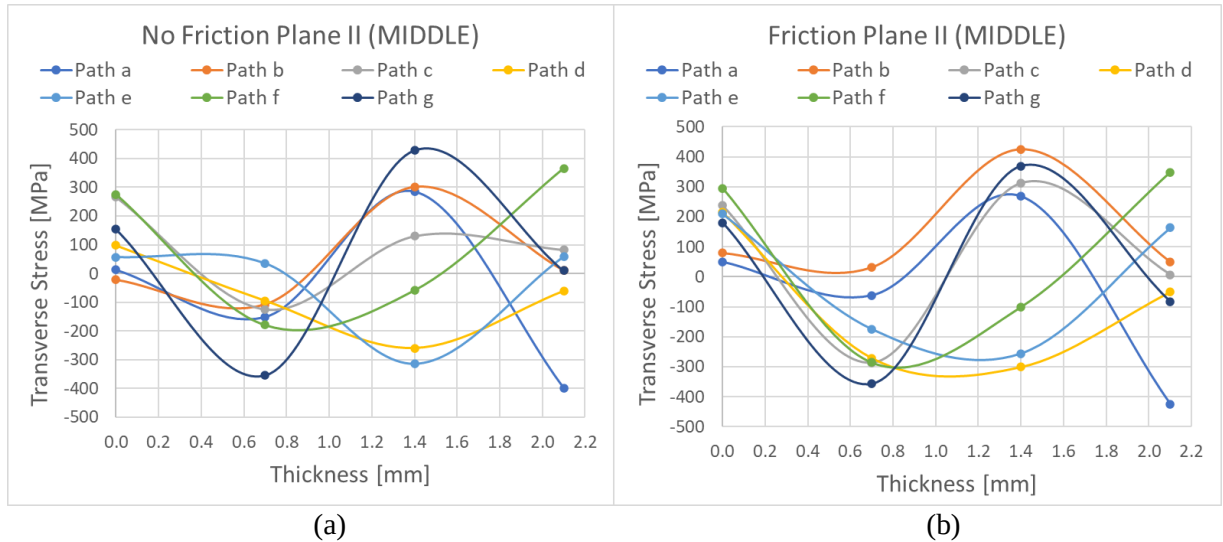


Figure 161 – (a) Transverse residual stresses across the thickness in plane II (middle), for the model without friction (reference model); (b) Transverse residual stresses across the thickness in plane II (middle), for the model with friction.

Regarding the longitudinal stresses across the thickness, for the model without friction (Figure 162(a)), and for the model with friction (Figure 162(b)), it can be observed that the curves obtained for the plane II (middle) are quite identical for both models, both in terms of distribution and magnitude. This similarity is also noticeable for the curves obtained for the plane I (tail end) and for the plane III (lead end), represented in Appendix G, Figures G5-G6.

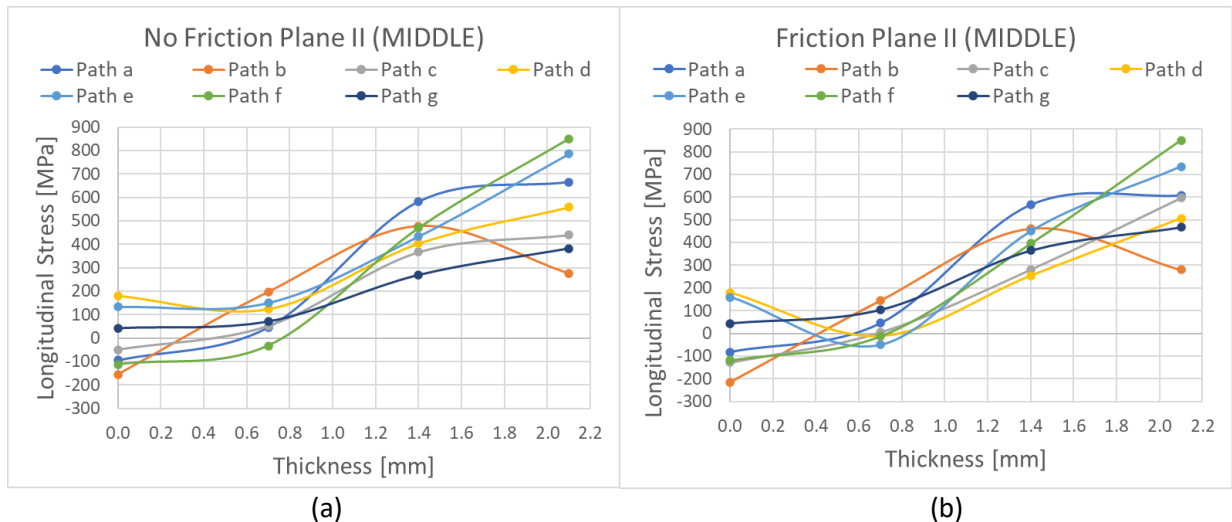


Figure 162 – (a) Longitudinal residual stresses across the thickness for the model without friction (reference model), considering plane II (middle); (b) Longitudinal residual stresses across the thickness for the model with friction, considering plane II (middle).

A study conducted by Bui and Ponhot (2008) in which two models were analysed, one with a friction coefficient of 0.2 and other without friction, revealed that there was no variation in the springback values obtained for the two models. Another study conducted by Martins (2018), in which a model with a friction coefficient of 0.2 and a model without friction were also compared, showed that the springback values are higher for models with friction. For the profile under study, it was found that there is no logical relation between the springback angles obtained for the two models (Figure 163). For example, the springback angle obtained for the model with friction considering bend 2 and the middle plane, is 3 degrees higher than the one obtained for the model without friction. However, the springback angle obtained for the model with friction considering bend 2 and plane III (lead end) is 2 degrees lower than that obtained for the model without friction. Although there is a slight variation of the springback angles according to the bend and plane under analysis, the values obtained comparing the two models are quite similar.

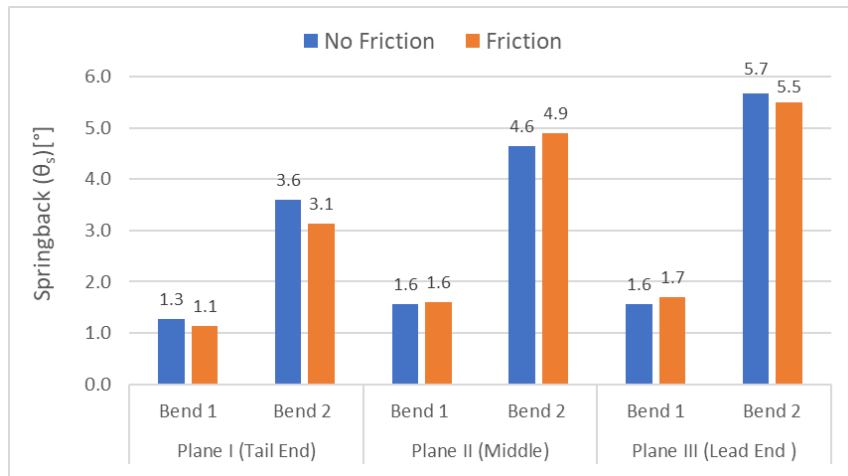


Figure 163 – Comparison between the model without friction and the model with friction, considering the springback angles (θ_s) [°] obtained for the two bends and three planes under study.

In turn, analysing the end flare values obtained for the two models, it was observed that these angles are quite similar for the two models, being slightly higher for the model with friction (Figure 164). Furthermore, it can be seen that the end flare values obtained for bend 1 of both models are quite higher than the values obtained for bend 2.

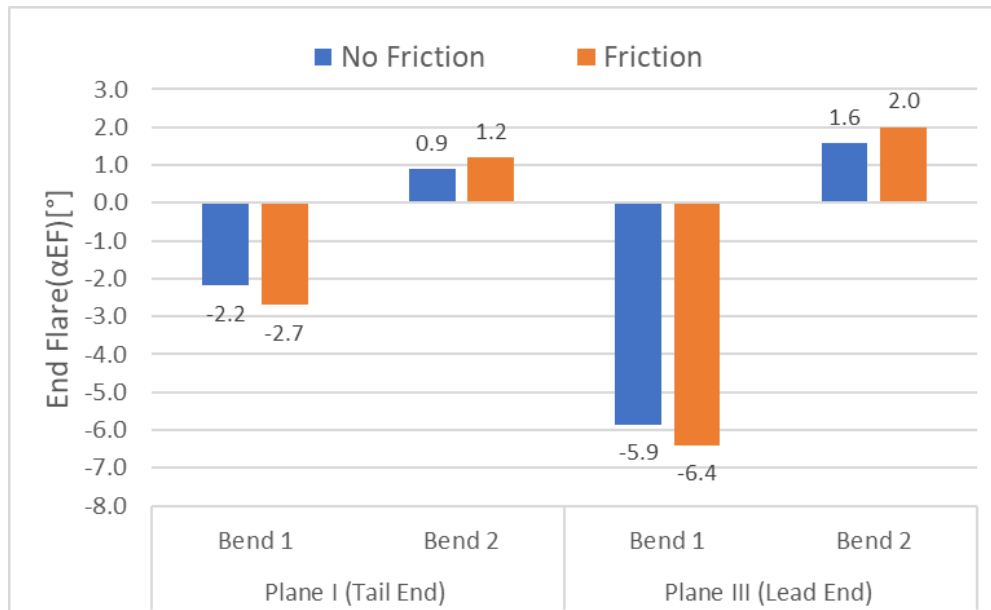


Figure 164 – Comparison between the model without friction and the model with friction, considering the end flare angles (α_{EF}) [°] obtained for the two bends and two planes under study.

Regarding twist angles, it was found that these values were practically insignificant for both models (Table 17).

Table 17 – Twist angles (γ_T) $^{\circ}$ obtained from the model without friction (reference) and the model with friction.

Twist(γ_T) $^{\circ}$	No Friction	Friction
	0.1	0.6

Analysing the cross-section geometries obtained for the two models (with and without friction) it can be observed that the cross-section geometries are practically coincident for both models considering the plane III (lead end) (Figure 165(a)). However, for planes II ((Figure 165(b)). and III (Figure 165(c)), is observed a greater difference between the cross-section geometries obtained for the two models, with this difference being much more significant for plane I (tail end).

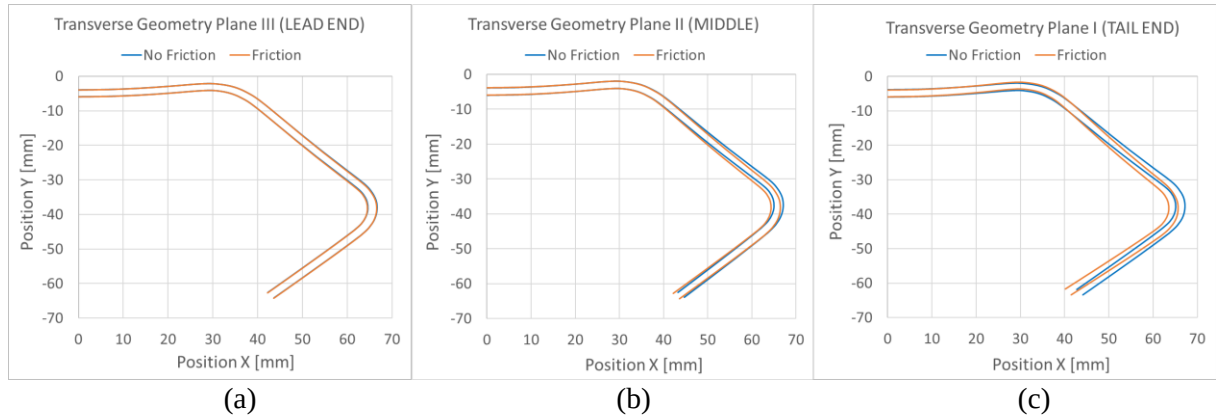


Figure 165 – Comparison between the cross-section geometries obtained for the models without friction and with friction: (a) plane III (lead end); (b) plane II (middle), plane I (tail end).

The more pronounced difference between the cross-sections of the two models for the plane I (tail end), may be due to the fact that in the model with friction, buckling (waviness) occurs at the web at the tail end. However, as can be observed in Figure 166, this fact does not happen in the experimental profile.

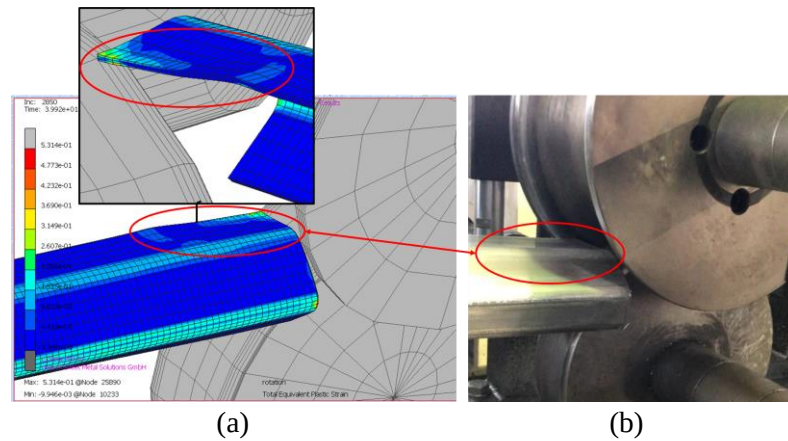


Figure 166 – Comparison of the web shape between the profile obtained from the model with friction and the experimental profile: (a) simulated profile considering friction; (b) experimental profile.

In the present process, friction at tool sheet interfaces appears to be mainly used to transmit the driving power from the rotating rolls to the sheet, rather than as a forming action. The numerical simulation of the process supports this argument, as the prediction of the forming trajectory remains mostly identical for both models, with friction ($\mu = 0.2$) and without friction ($\mu = 0$) (Figure 167). A study conducted by (Bui and Ponthot 2008), also showed that the effect of

friction is considered negligible in the forming trajectory (vertical displacement of the part along the roll forming line).

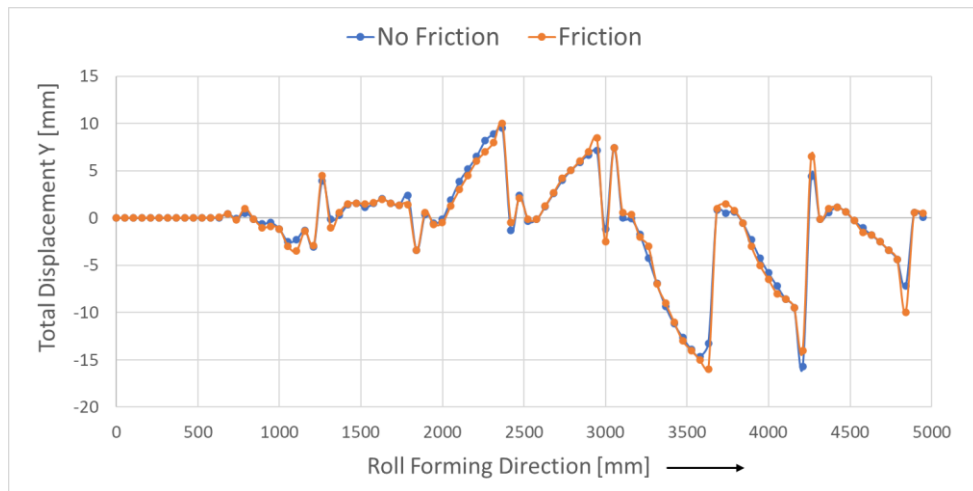


Figure 167 – Comparison of the vertical displacement along the RF process, obtained for the two models with 13 stations.

Analysing the computational time obtained for the two models (with and without friction), it can be observed that the total CPU time was much higher for the model with friction, representing an increase of 44.99 % over the model without friction. (Figure 168(a)). This increase in CPU time was mainly due to the higher complexity in the matrix calculation for the model with friction, observing an increase of 54.69% for this parameter over the model without friction (Figure 168 (b)).

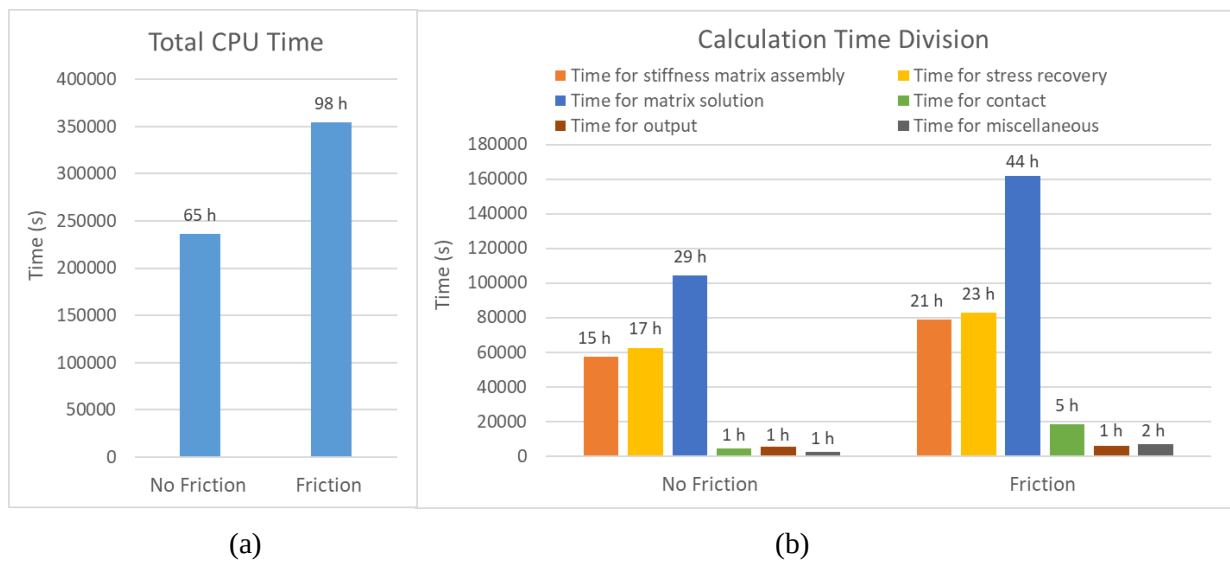


Figure 168 – Comparison of computational time between the model with friction and the model without friction: (a) Total CPU time; (b) Calculation Time Division.

As the main objective of the present study is to study mainly the formation of a profile, rather than to estimate the power required for the roll forming machine, friction can be dropped to save computational time. Furthermore, an exact measurement of the coefficient of friction between the sheet and the rolls is not a trivial task (Bui and Ponthot 2008).

5.3.7 Pre-Cut vs Final Cut

As mentioned previously, simulation 1 (reference), was modelled with pre-cut while simulation 10 was modelled with a coil value of 3.3 and cut at the end (final cut). The coil value (3.3) multiplied by the distance between stations (600mm) provides the initial sheet length ($3.3 \times 600 = 1980\text{mm}$). The strip in this model was thus meshed with 33072 elements and 49900 nodes. After the RF process, the 1980 mm strip was cut so as to obtain a rail with a length equal to that of the reference simulation (1400mm). In comparison with the reference model, for the model with final cut the strip symmetry boundary condition was maintained, as well as the Y direction boundary condition at the last three nodes at the tail end of the profile, so that the strip did not undergo rigid body motion. Furthermore, in order to simulate the continuous existence of the strip and thus replicate the use of a sheet metal coil, a z-direction boundary condition was applied on the nodes at the ends of the sheet metal (Figure 169).

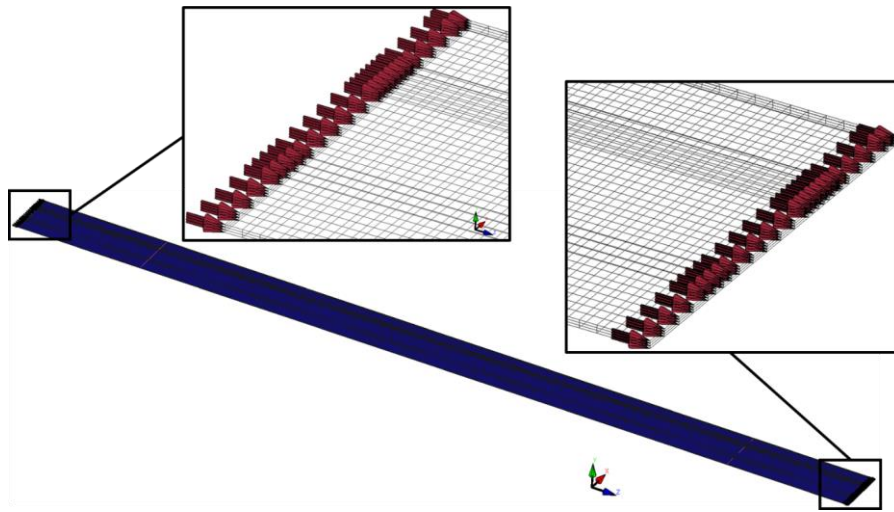


Figure 169 – Z-direction boundary condition (boundary condition applied to simulate the continuous existence of the strip).

This boundary condition allows the strip not to move in the z direction and to keep its length constant, so that the numerical simulation is as realistic as possible. Finally, a Fs boundary conditions were also applied during the increments corresponding to the free cut of the sheet, as shown in Figure 170. Therefore, both the nodes at the lead and at the tail of the sheet, were locked in all directions. In addition, the element immediately before the region where the sheet is cut was also locked, in order to avoid rigid body motion after the cut. These Fs boundary conditions are only applied when the free cut is in place (the z and y conditions are not activated).

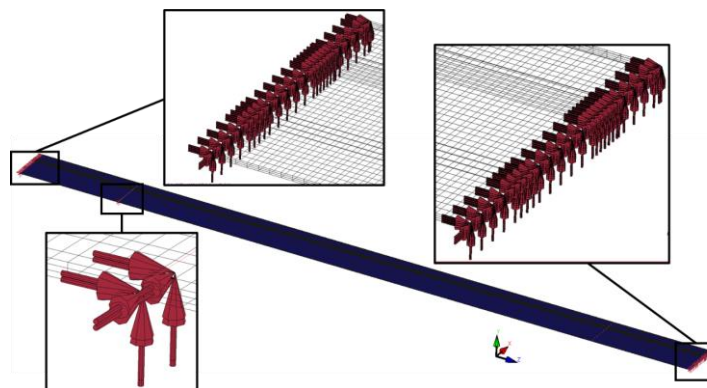


Figure 170 – Fs boundary condition to generate the free cut of the profile.

In Figure 171, the profile obtained after applying final cut can be observed. It should be noted that the cut parts undergo a huge amount of translation and that the part rises quite a bit. This happens in software due to the occurrence of the release of a high amount of residual stresses after cutting which is common in high strength materials, as seen previously.

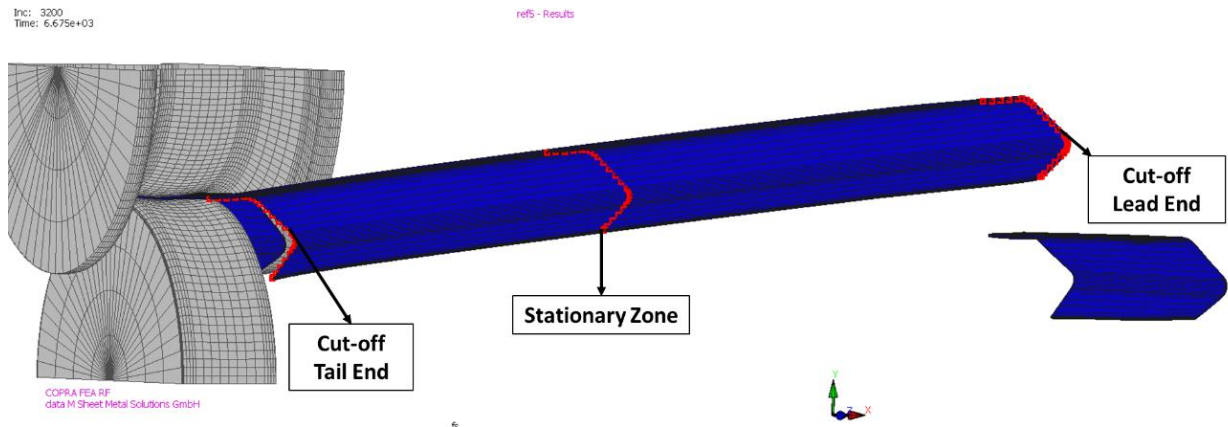


Figure 171 – Profile obtained after application of the cut at the end.

Figure 172(a) and Figure 172(b) present, respectively, the results of the transverse and longitudinal residual stresses across the inner surface (path i) and outer surface (path o) of the strip width for the pre-cut model and for the final cut model, considering plane II (middle).

As can be seen, the results obtained for the two models are quite similar, since the curves are practically coincident. The same conclusions are drawn for plane I (tail end) and for plane III (lead end) (Appendix H, Figures H1-H2).

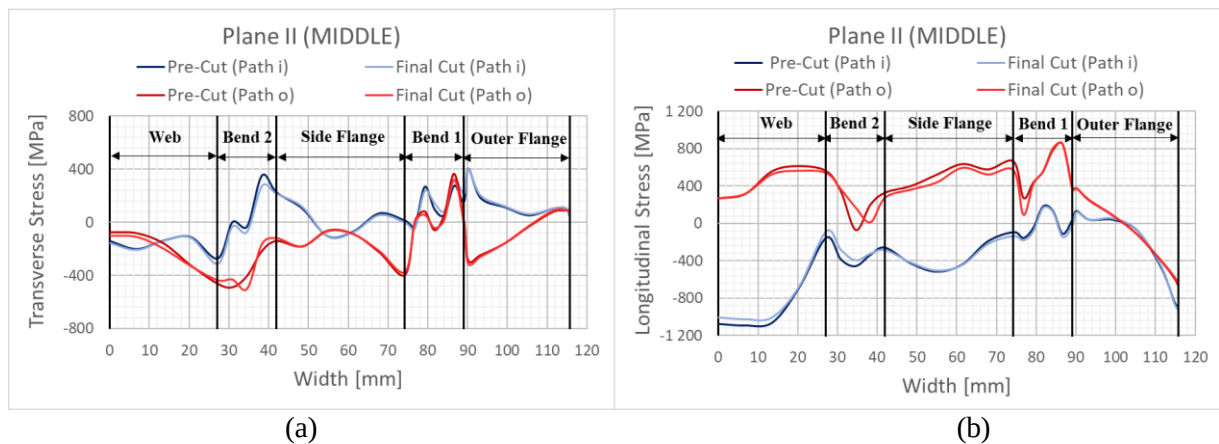


Figure 172 – (a) Transverse residual stresses across the width in plane II (Middle) for the reference model (pre-cut) and for the model with final cut; (b) Longitudinal residual stresses across the width in plane II (Middle) for the reference model (pre-cut) and for the model with final cut.

In Figure 173 and Figure 174 are represented respectively, the results for the transversal and longitudinal residual stresses across the thickness obtained for the pre-cut model (reference model) and for the model with cut at the end (final cut).

Analysing the results, it is verified that the curves for both transverse residual stresses and longitudinal residual stresses are quite similar for both models both in terms of distribution and magnitude. The same conclusions are drawn for the plane I (tail end) and for the pane II (Appendix H, Figures H3-H6).

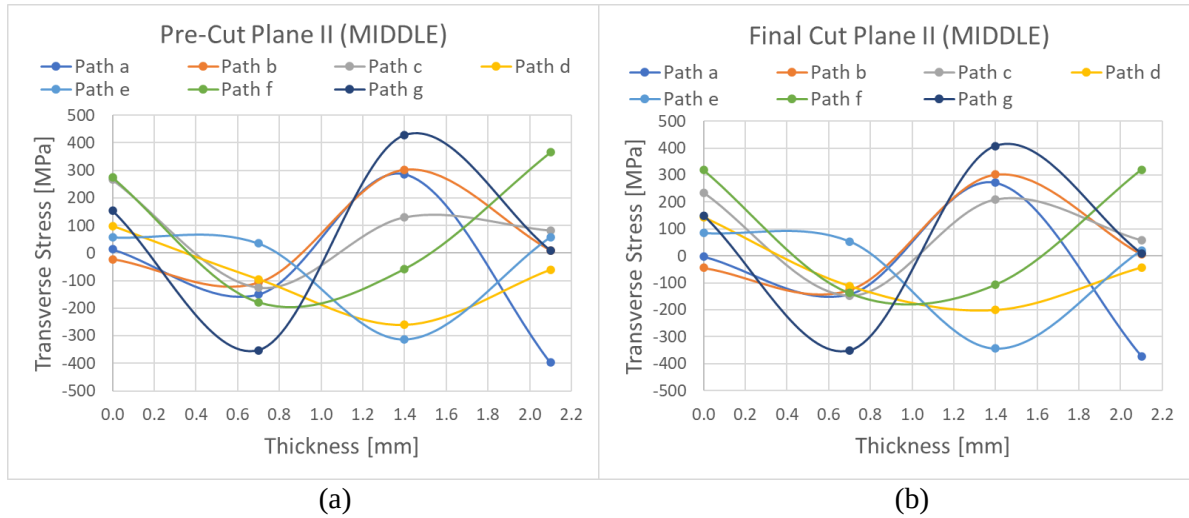


Figure 173 – (a) Transverse residual stresses across the thickness in plane II (middle), for the pre-cut model (reference model); (b) Transverse residual stresses across the thickness in plane II (middle), for the final cut model.

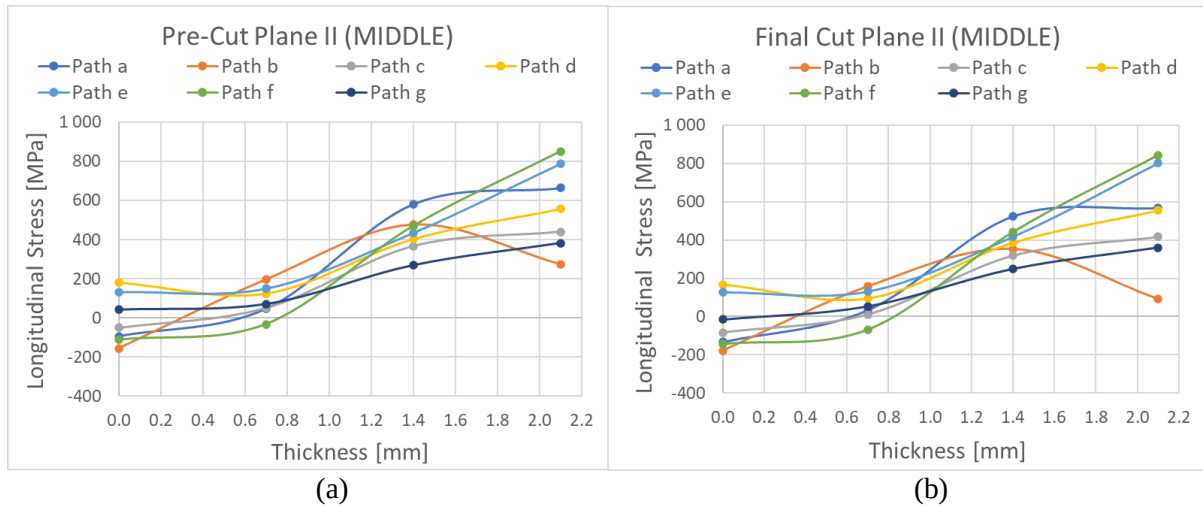


Figure 174 – (a) Longitudinal residual stresses across the thickness for the pre-cut model (reference model), considering plane II (middle); (b) Longitudinal residual stresses across the thickness for the final cut model, considering plane II (middle).

Analysing the springback values obtained for the two models under study (Figure 175), it can be seen that the model with final cut presents much higher springback values than the model with pre-cut. The only exception occurs for bend 2 of the lead end that present a reduction of 0.8 degrees in the springback value when using the model with final cut.

This may be due to the fact that the lead end is a critical area in terms of stability, since it is the area of the strip that first comes into contact with the rolls and therefore may present some distortions.

Another aspect to take into account is that the largest increase in springback value occurred for bend 2 of plane II (middle) with the use of the model with final cut.

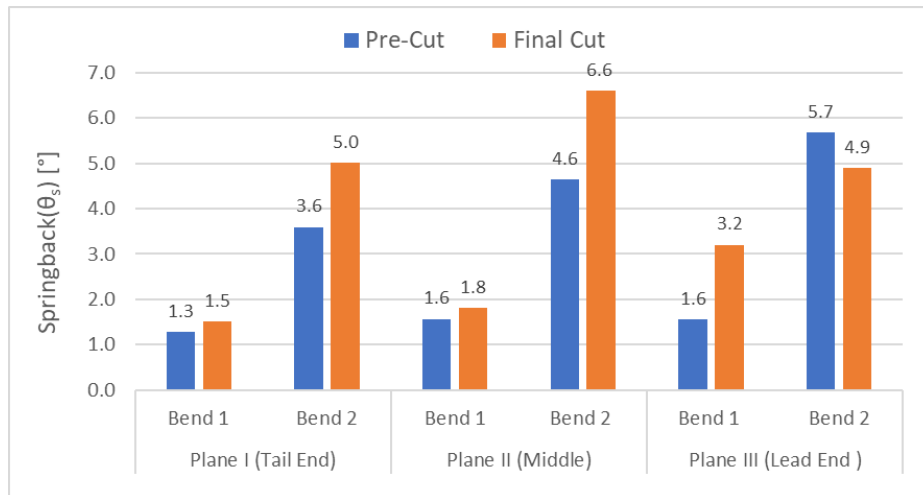


Figure 175 – Comparison between the model without pre-cut and the model with final cut, considering the springback angles (θ_s) [°] obtained for the two bends and three planes under study.

The end flare is caused by the release of internal stresses. These stresses are balanced while the section is continuous, but when the part is cut, these stresses become unbalanced (Forte 2021). As previously mentioned in section 2.4.2, when pre-cut strips are roll formed, the flare is usually higher (Halmos 2006). However, for the case of the profile under study the opposite was verified. As can be seen in the graph of Figure 176, the end flare values are much higher for the model with coil and cut at the end (final cut), especially for the bend 2 of the tail end. In this bend the springback angle was increased by 4.9° compared to the pre-cut model.

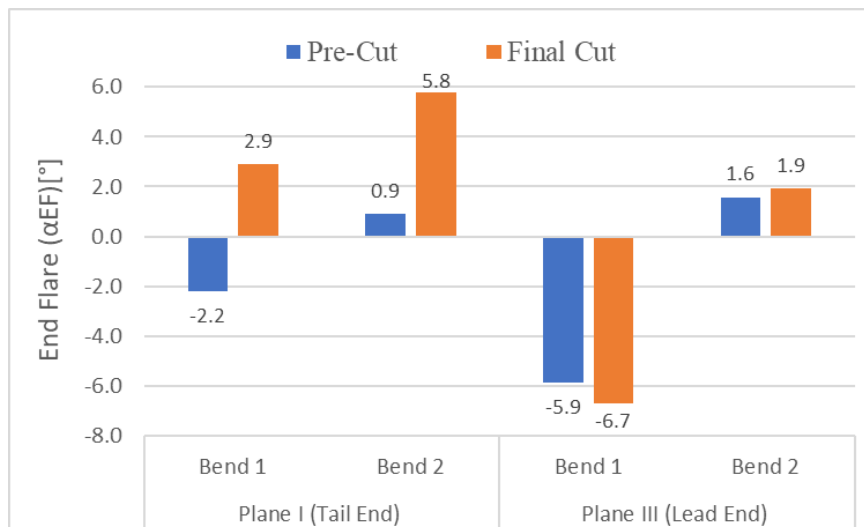


Figure 176 – Comparison between the model with pre-cut and the model final cut, considering the end flare angles (α_{EF}) [°] obtained for the two bends and two planes under study.

Regarding the twist angles obtained, there was an increase of 1.3 degrees with the use of final cut, when compared to the model with pre-cut (Table 18).

Table 18 – Twist angles (γ_T) [°] obtained from the model pre-cut (reference model) and the model with final cut.

Twist(γ_T) [°]	Pre-Cut	Final Cut
	0.1	1.4

Analyzing the final cross-section geometries of the two models obtained for the lead end, middle and tail end, it can be seen that the geometries are quite identical, almost coincident, especially for the middle plane (Figure 177). This shows that the final profile obtained by the two models is quite similar in geometric terms.

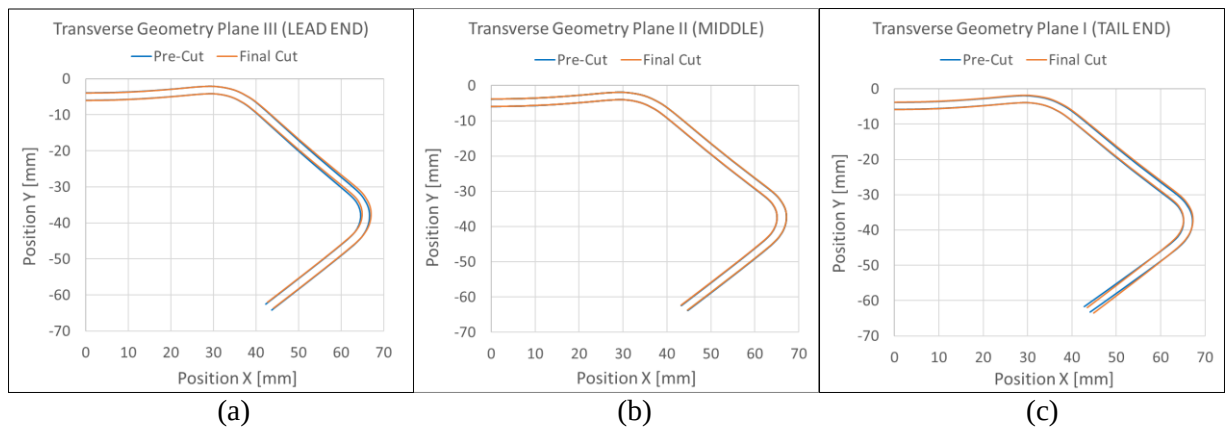


Figure 177 – Comparison between the cross-section geometries obtained for the model with pre-cut and for the model with final cut: (a) plane III (lead end); (b) plane II (middle), plane I (tail end).

Comparing the two models in terms of computation time it was found that the model with coil and cut at the end (final cut model) has the highest values of total CPU time, representing an increase of 123 % compared to the model with pre-cut, i.e, more than double (Figure 178(a)). Furthermore, as can be seen in Figure 178(b), the main factor leading to the increase in CPU time for the model with final cut is the matrix calculation time (time to matrix solution), representing an increase of 178 % over the model with pre-cut.

The reduction of computational time is obviously a great advantage for the pre-cut model. Considering that the values obtained for the residual stresses are quite identical for both simulations, as well as, the final profile geometries, the use of a model with pre-cut for the subsequent line improvement is more advantageous.

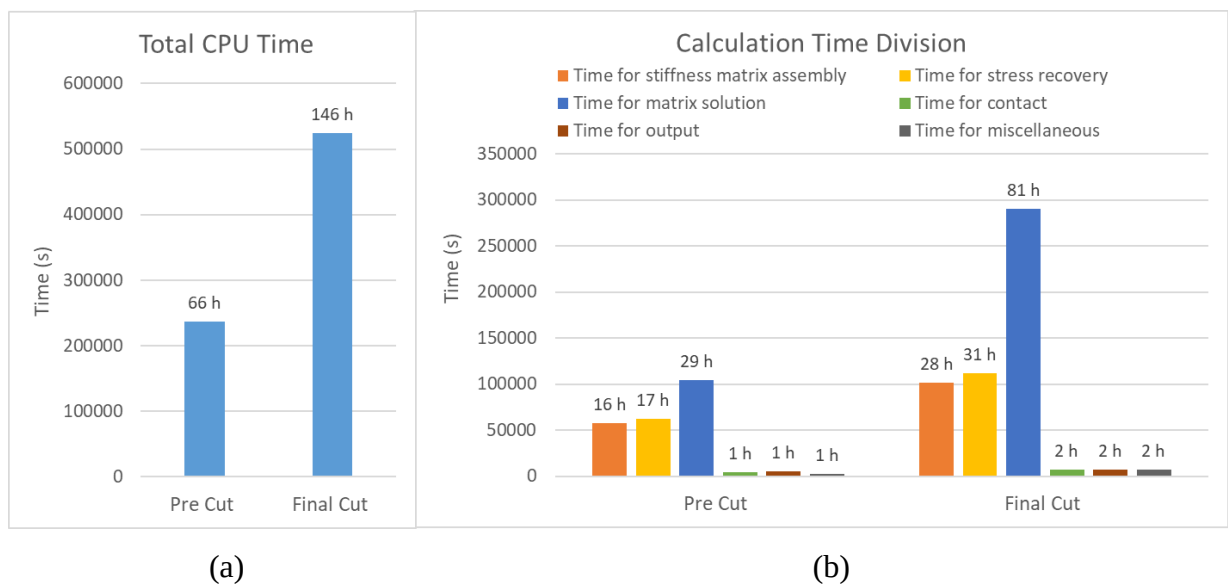


Figure 178 – Comparison of computational time between the model with pre-cut and the model with final cut: (a) Total CPU time; (b) Calculation Time Division.

5.3.8 Rigid Shafts vs Deformable Shafts

In order to investigate the inclusion of deformable tooling in roll forming simulations, two modelling concepts were compared: a simulation with rigid shafts (reference simulation) where the modelling of the rolls in the simulation was done using surfaces fixed in space and a simulation with deformable shafts where the modelling of the rolls was done using surfaces with a degree of freedom in the vertical direction. The model with deformable shafts, presents changes in the boundary conditions assigned to the rolls control nodes as represented in Figure 179. All other conditions remained the same as in the reference simulation. In the case of the simulation with rigid shafts (with both rolls fixed), both rolls have the boundary condition "bc_spring_control_xz" that blocks the movement in the x direction and controls the movement in the z direction through a table and also the boundary condition "bc_spring_control_yz" that blocks the movement in the y direction. In turn, in the case of the simulation with deformable shafts, the rolls do not have the boundary condition "bc_spring_control_yz", and instead have a linear spring link connecting the node with the ground, with a defined stiffness (Figure 179).

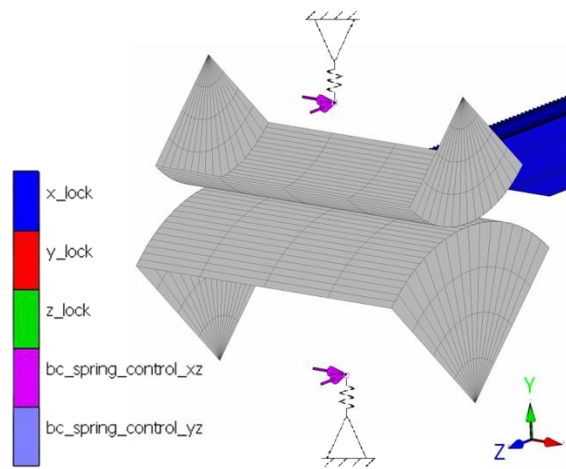


Figure 179 – Boundary conditions applied on the rolls, for the simulation with deformable shafts.

This consideration allows the movement of the rolls in the y direction due to the forming forces, while keeping the movement in the z direction defined by a table. The stiffness of the shafts is calculated automatically by the software by entering the young modulus, diameter and length of the shaft and is set to half of the actual stiffness as only half of the sheet was modelled due to symmetry (Table 19).

Table 19 – Input values for the calculation of the shaft stiffness.

Young`s modulus E [GPa]	Shaft Diameter [mm]	Shaft Length [mm]
210	60	500

Analysing the transverse residual stresses along the width of the sheet for the plane II (middle) (Figure 180(a)), it can be observed that for the inner surface (path i) the model with deformable shafts presents in general higher values of transverse residual stresses along the width of the sheet. On the other hand, for the external surface (path o), the curves for both models are relatively similar, with greater differences being observed for web and bend 1. For the case of the outer surface of the web, the model with rigid shafts is the one that presents the highest values of transverse residual stresses, reaching a maximum compressive stress of -465MPa, while the model with deformable shafts reached -377MPa. For the case of the outer surface of bend 1, the model with deformable shafts is the one that presents the highest values of transverse stresses, reaching maximum values of -231MPa (compression) and 340 MPa (tension), while the model with rigid shafts reached maximum values of -16.8MPa (compression) and 341MPa (tension). This described behaviour is also observed for plane III (lead end) and plane I (tail end) (Appendix I, Figures I1-I2).

Regarding the longitudinal residual stresses along the width for plane II (Figure 180), it was verified that there are no significant differences in the curves obtained for the two models under study. However, it can be observed that for the web and side flange, the values of the longitudinal stresses are higher for the model with rigid shafts, while for the outer surface of bend 1, the values are higher for the model with deformable shafts. For the outer flange the longitudinal residual stresses are higher for the model with deformable shafts. The same behaviour is visible for plane I (tail end) and plane III (lead end), as represented in Appendix I, Figures I1-I2.

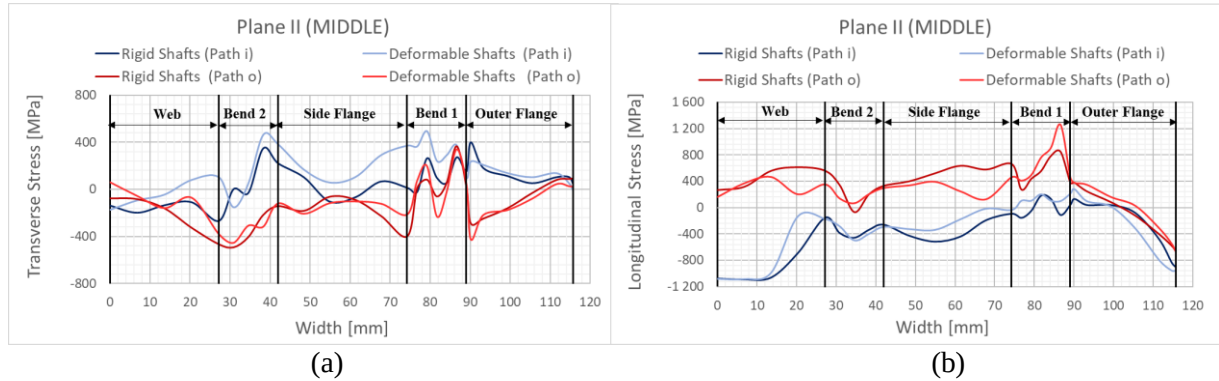


Figure 180 – (a) Transverse residual stresses across the width in plane II (middle) for the reference model (with rigid shafts) and for the model with deformable shafts; (b) Longitudinal residual stresses across the width in plane II (Middle) for the reference model (with rigid shafts) and for the model with deformable shafts.

As can be seen in Figure 181, the transverse residual stresses across the thickness for the plane II, are quite identical both in terms of magnitude and distribution for the two models under study. The main differences are for the inner surface of the bend where the model with deformable rolls reaches higher values, as is the case of the path “f” that reaches 500MPa. For the simulation with rigid shafts, the same path f presents only 300 MPa in the inner surface of the bend. The same behaviour is observed for the plane III, represented in Appendix I, Figure I3. However, for plane I, it is found that the transverse residual stresses for the inner bend surface of the model with rigid shafts are much higher than for the inner bend surface of the model with deformable shafts, as represented in Appendix I, Figure I4.

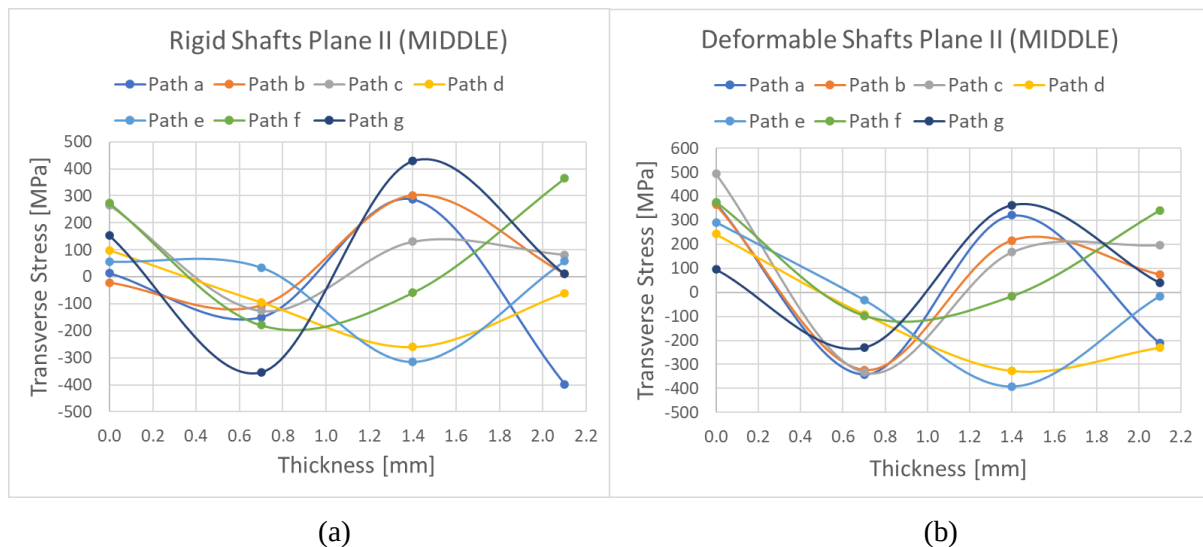


Figure 181 – (a) Transverse residual stresses across the thickness in plane II (middle), for the model with rigid shafts (reference model); (b) Transverse residual stresses across the thickness in plane II (middle), for the model with deformable shafts.

Analysing the longitudinal residual stresses across the thickness some differences between the models were observed (Figure 182). For the model with rigid shafts the inner surface of the

bend presents a greater variation of stresses (between -156MPa and 179MPa) than the model with rigid shafts (between -35 MPa and 212MPa). On the other hand, the outer surface of the bend for the model with deformable shafts presents higher values of longitudinal stresses than the model with rigid shafts. While for the model with deformable shafts the maximum value is 1254 MPa, for the model with rigid shafts it is 851 MPa. A similar behaviour as described was observed for plane I (tail end) and plane III (lead end), represented in Appendix I, Figures I5-I6.

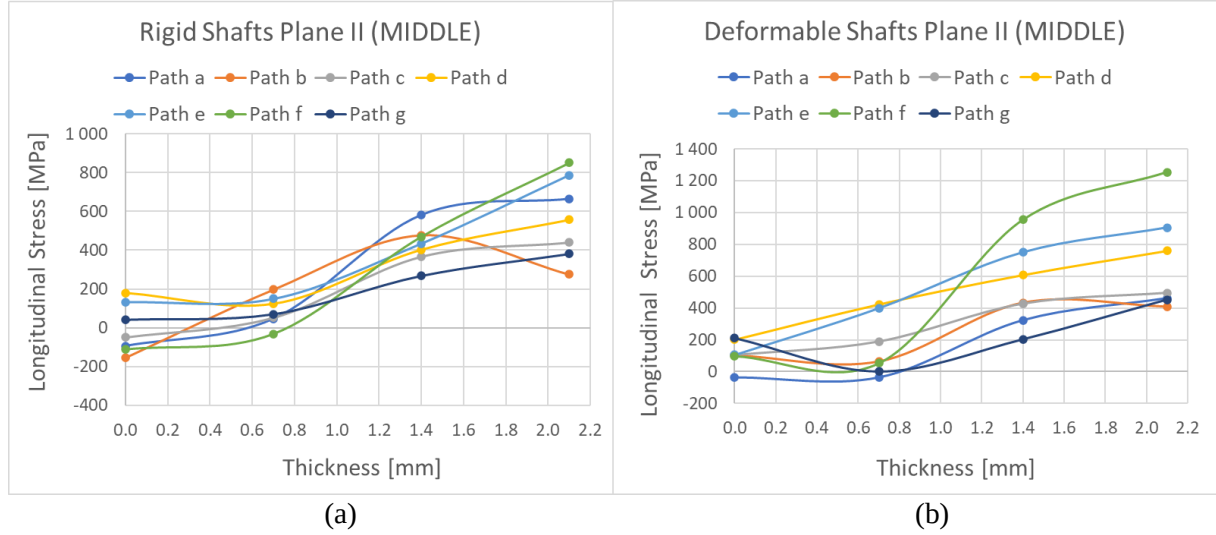


Figure 182 – (a) Longitudinal residual stresses across the thickness for the model with rigid shafts (reference model), considering plane II (middle); (b) Longitudinal residual stresses across the thickness for the model with deformable shafts, considering plane II (middle).

Figure 183 presents the longitudinal edge strain along the direction of the roll forming line for location 1. It can be observed that the peak longitudinal edge strain values are much higher for the model with deformable shafts. While the peak stress for the simulation with rigid shafts was 1.050%, for the simulation with deformable shafts it was 1.486%, which corresponds to an increase of 0.436%.

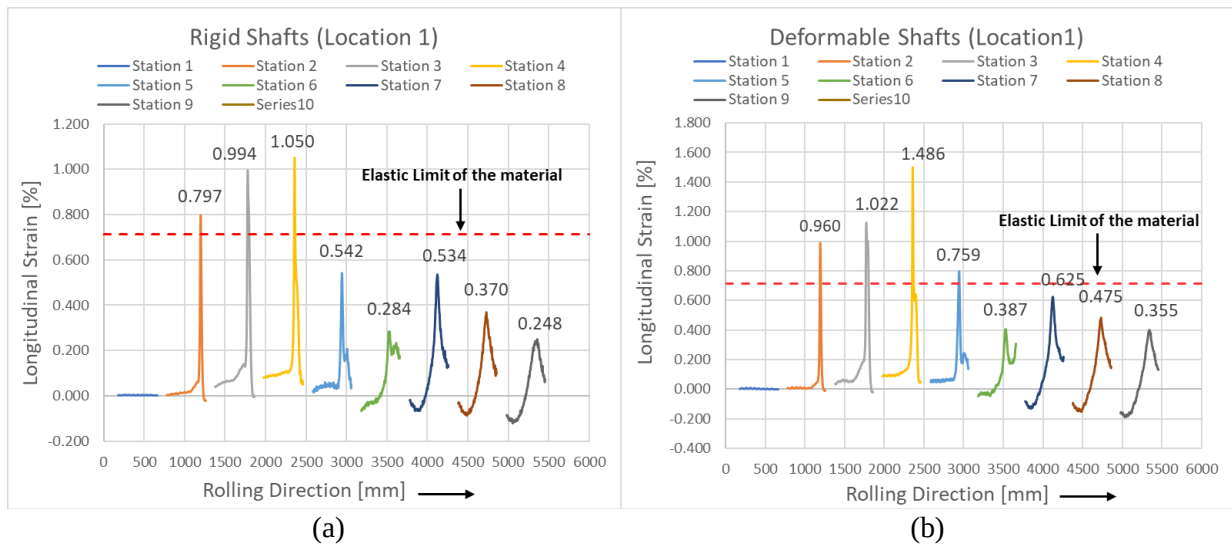


Figure 183 – Longitudinal edge strain results: (a) model with rigid shafts; (b) model with deformable shafts.

Comparing the springback values obtained for the two models, it can be seen that the model with deformable shafts presents higher springback values for both bends and for all planes under analysis (Figure 184). The largest difference between the values obtained for the two models occurred for bend 2 of the lead end where the use of deformable shafts led to an increase in springback by 2.1° relative to the model with rigid rolls. It can also be noticed that bend 2 has much higher springback angles than bend 1 for all the planes under study.

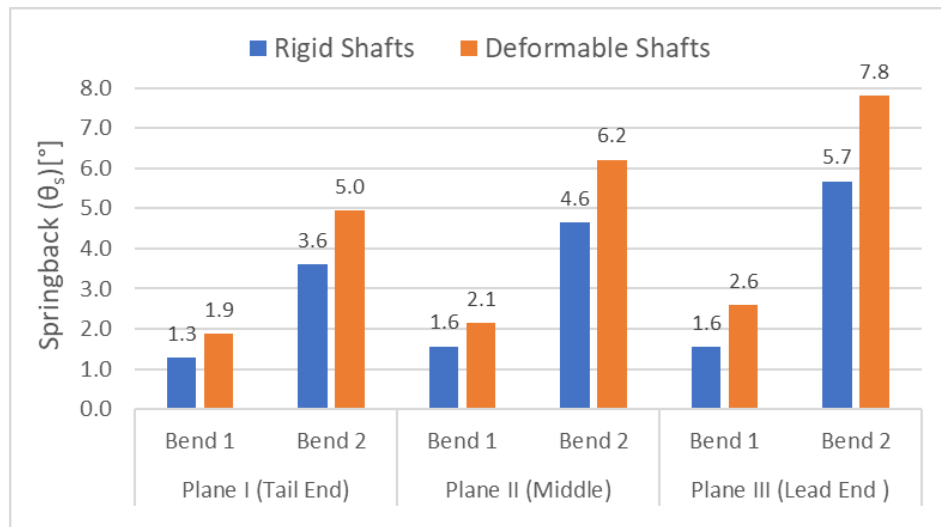


Figure 184 – Comparison between the model with rigid shafts (reference model) and the model with deformable shafts, considering the springback angles (θ_s) [°] obtained for the two bends and three planes under study.

Analysing the end flare values obtained for the two models (Figure 185), bend 1 is the one that presents the highest values, both for lead and tail end and for the two models under study. It can also be observed that for bend 1, the end flare values are higher for the model with deformable shafts, while for bend 2, the end flare values are slightly higher for the model with rigid shafts. Furthermore, it can be noted that bend 1 of the lead end is the one that presents the highest end flare values. The difference between the end flare angle obtained for the model with deformable shafts and the end flare angle obtained for the model with rigid shafts is 2.2° , and represents the largest difference between the models. It can also be noted that for both the simulation with rigid shafts and the simulation with deformable shafts, bend 1 shows flare in while bend 2 shows flare out.

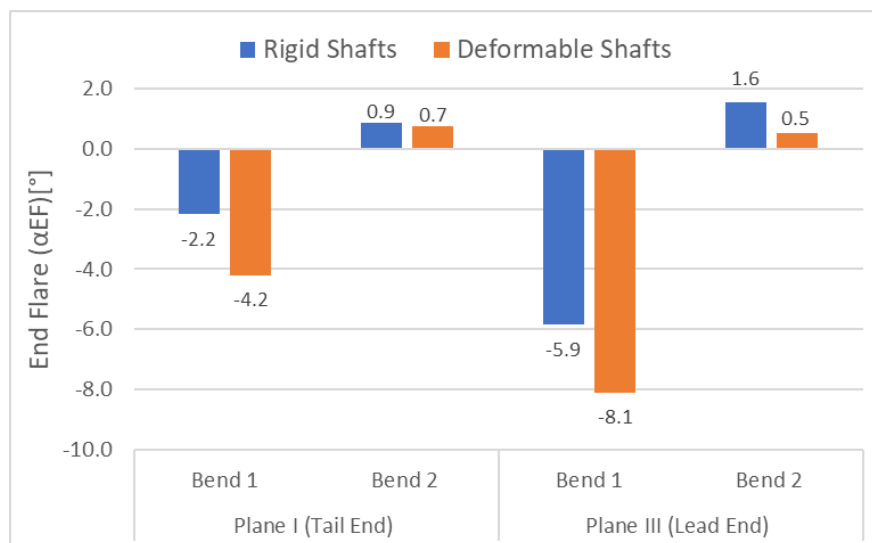


Figure 185 – Comparison between the model with rigid shafts and the model with deformable shafts, considering the end flare angles (α_{EF}) [°] obtained for the two bends and two planes under study.

Regarding the twist angles, it can be seen that for both models the twist was insignificant, close to zero (Table 20).

Table 20 – Twist angles (γ_T) [°] obtained from the model with rigid shafts (reference) and the model with deformable shafts.

Twist(γ_T) [°]	Rigid Shafts	Deformable Shafts
	0.1	0.1

Figure 186(a) illustrates the total CPU time and Figure 186(b) represents the CPU calculation time division on its components for each model. Analysing Figure 186(a), it can be seen that the simulation with deformable shafts exhibits much lower CPU time compared to the reference simulation (with rigid shafts). The simulation with deformable shafts shows a reduction in the total CPU time of about 27.76% compared to the simulation with rigid shafts.

Analysing Figure 186(b), it is verified that there is a reduction in the stiffness matrix time, which in turn leads to a reduction in the stress recovery time. Furthermore, it can be seen that the factor with the most influence on calculation time is the time for matrix solution, which is the time spent on the equation solver by the software. The time for the matrix solution was lower for the simulation with deformable shafts than for the simulation with rigid shafts. The simulation with deformable shafts led to a decrease of 22.97% in the time for matrix solution compared to the simulation with rigid shafts. However, a study performed by Ferreira (2016) showed the opposite. The simulation with deformable shafts presented a higher time for matrix calculation than the simulation with rigid shafts and consequently a higher total CPU time. In this study it is also mentioned that the use of springs adds complexity to the models, increasing the resolution time for each increment. However, the shorter time for matrix solution verified for the model with deformable shafts studied in this thesis, can be explained by the fact that the material used (Docol 1400M) is a high-strength material. Therefore, the use of springs in simulation models with this kind of material is very beneficial in terms of computing time because it allows an increase of the gap between the rolls, simplifying the material passage between the rolls (forming process) and consequently the respective matrix calculation. According to Ferreira (2016), simulations with deformable shafts also show better performance in terms of load determination.

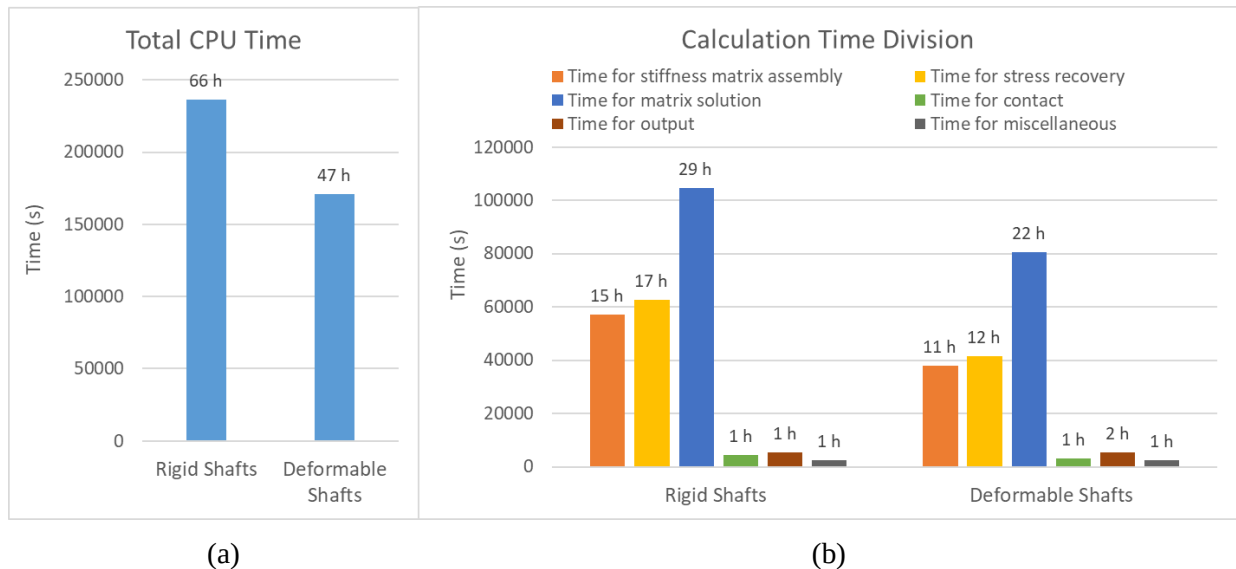


Figure 186 – Comparison of computational time between the model with rigid shafts and the model with deformable shafts: (a) Total CPU time; (b) Calculation Time Division.

Figure 187 shows the average variation of the roll gap at each of the stations for the model with deformable shafts. As can be seen, the increase in the roll gap at each of the stations is extremely high. For example, at station 4 the increase in the roll gap was greater than 1 mm, that is, there

was an increase of approximately 50% of the profile thickness. This indicates that the forming process studied in this thesis is extremely complex and that the roll design has extremely tight tolerances.

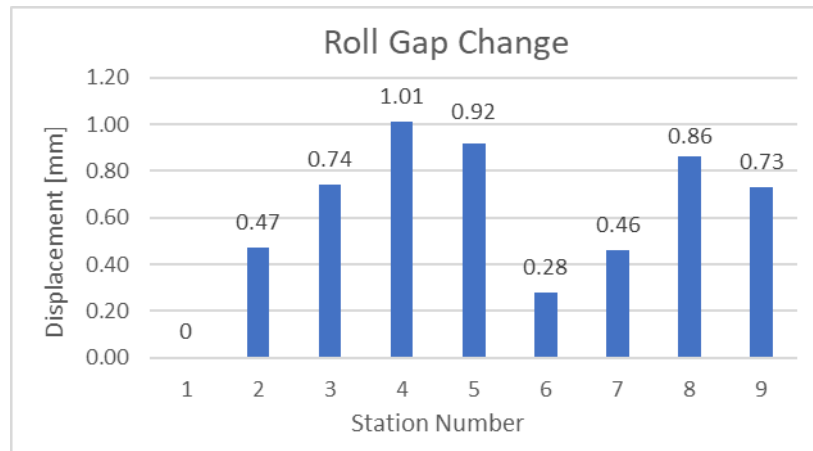


Figure 187 – Average roll gap change for the model with deformable shafts.

The complexity of the process is also evidenced in Figure 188, where the average force calculated in the y direction (top roll) during each forming stage is represented for the simulation with rigid shafts (reference simulation), as well as for the simulation with deformable shafts. Comparing the two simulations, it is verified, as expected, that the simulation with deformable shafts generates forces in the vertical direction of the top roll much lower than those observed for the simulation with rigid shafts. This is due to the fact that the forming process is highly simplified when using deformable shafts for high strength materials. As evidenced in a study by Lindgren (2009), the forming forces in the first station are significantly lower than on subsequent stations. However, no explanation for this behaviour has yet been found.

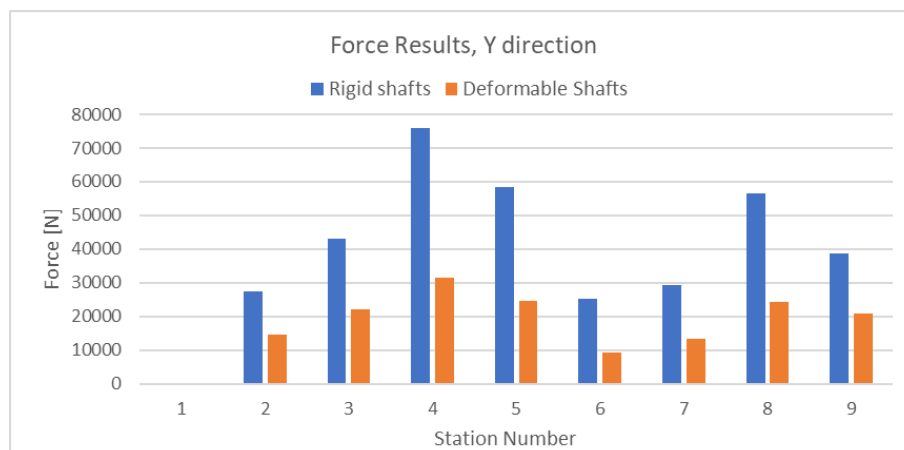


Figure 188 – Average calculated force in the y direction (top roll) during each forming step, for the model with rigid shafts and for the model with deformable shafts.

Despite the numerous advantages of using deformable shafts in terms of process simplification and consequent CPU time reduction, it is necessary to pay attention to whether the forming that the material undergoes in the simulations with this consideration is being carried out properly, i.e. in accordance with reality.

Therefore, in order to investigate whether the behaviour of the shafts during the forming for the simulation with deformable rolls was identical to that observed on the experimental line, the deflection of the shafts of the top rolls was measured up to station 9, on Coproget's roll forming

line under study. For this purpose, a dial indicator was placed on the top rolls so as to measure the vertical shaft displacement and the overall increase in the roll gap (Figure 189).

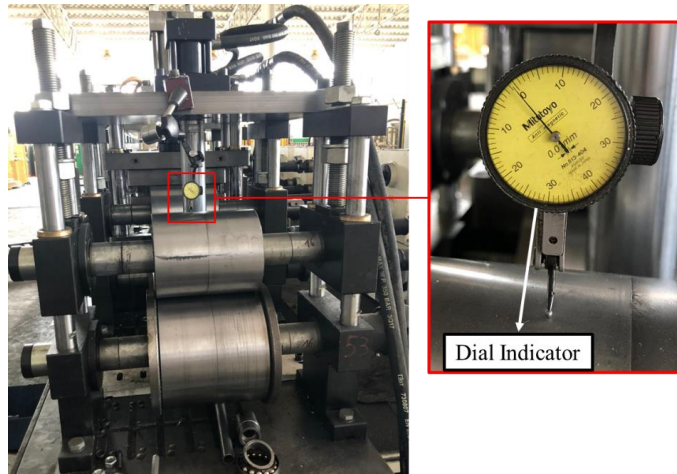


Figure 189 –Mounting position of the dial indicator on the top roll measuring the vertical displacement.

The strip was run through the rolls gap three times at each forming step (station). Therefore, three measurements were taken for each station at the time when the pointer of the indicator stabilizes and then averaged. The graph in Figure 190, allows a comparison between the average deflection values obtained for the top rolls from the simulation with deformable shafts and the average deflection values measured on Coproget's RF line for the top rolls up to station 9.

As can be observed, the deflection values of the top rolls obtained from the simulation are quite different from those measured experimentally, with the exception of station 5. These differences are more significant at the first four stations. As can be seen, the software does not consider the existence of any deflection of the top rolls at the first two stations, in contrast to what happens in the experimental line. Furthermore, stations 2 and 3 show significantly lower values of deflection for the simulation than those observed experimentally. Finally, the opposite is observed at the last stations, i.e., the deflection values obtained for the simulated top rolls are higher than those measured experimentally.

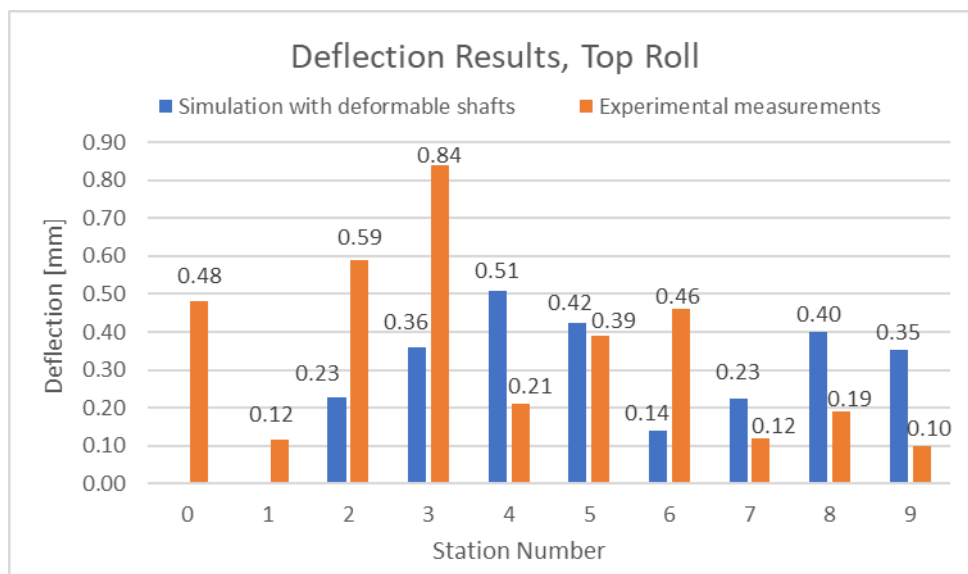


Figure 190 – Average top roll deflection values at each station calculated for the simulation with deformable shafts and average deflection values measured on the top roll at each station in the experimental line.

6 Improvement of Coproget's Roll Forming Line

In this section the attempt to obtain the C-profile under study in chapter 4 is continued, but now with some improvements implemented in the simulated line. Some of these improvements were proposed by the company Linde Opsan, a company based in Turkey, with experience in performing numerical simulations of RF processes using Copra FEA RF software. This work of improving stations requires high sensitivity and is therefore usually performed by designers who have high knowledge and experience of the RF process. After obtaining a profile similar to the one currently produced at Coproget, improvements are implemented in the simulated profile, based on the parameters studied in chapter 5 and based on the methods studied in the literature review.

6.1 Base Model

6.1.1 Concepts

Subsequently, some concepts used for the base model of the simulations performed are described:

- The forming rolls were modelled as non-deformable rigid analytical bodies while the steel strip was defined as a deformable model;
- The boundary conditions used were the same as in the base model presented in chapter 4;
- The element used was the same as the one used for chapter 4 of the base model, i.e. element type 7;
- The material of the sheet was modelled as an elastic-plastic material with isotropic hardening, using the Swift's law, as explained in chapter 4.
- Driven rolls were not used, that is, the frictional force between the rolls and the sheet was not considered, in order to reduce the computational time of the simulations performed. Furthermore, the results obtained from the parametric study showed that the profiles obtained from models with and without friction have very similar geometries and forming trajectories;
- Deformable shafts were not used, since the deflection of the top roll obtained for the simulations with deformable shafts is quite different from that observed in the experimental process. More experimental tests using load cells to measure the forming forces and strain gauges to measure the deflection of the components, for example, will be necessary to draw more accurate conclusions;
- A pre-cut sheet with 1400mm length was used for the simulations performed in order to save computational time. From the parametric study it was also concluded that the models with pre-cut and final cut are quite identical in terms of residual stresses and geometry results and therefore it pays off to opt for the one that requires less computational time (pre-cut). Furthermore, cutting AHSS at the end of the process is extremely difficult. It could be half cut at the beginning of the process and then half cut at the end, but the line would have to be longer and there is not enough room in the factory;
- The distance between main stations remained at 600mm and the distance between main and secondary stations remained at 300mm, since it is impossible to increase these distances on Coproget's current line;
- The sheet was simulated without symmetry since the process is not symmetric from station 13 onwards;
- Five side bars were used, the same as in the last simulation described in section 4.2.2;

- The roll gap used at each station was 0 mm, based on a parallel study conducted at the Coproget company by Melo (2022).

The “flat strip supporting rolls” option was used in Copra2FEA. This option ensures the vertical position of the strip entrance and stabilizes the simulation during entry into the first station (data M 2020). A chamfer of 15x20 mm was added to the lead end of the part (Figure 191). The use of chamfers allows a smoother entry of the strip into the gap between the rolls, not only in practical terms but also in simulation terms, avoiding numerical problems.



Figure 191 – Chamfer used for the base model.

6.1.2 Roll Design

In terms of roll design, Linde Opsan company provided some recommendations that were implemented in the design of the base model of the rolls of Coproget's roll RF line, namely:

- Increase the outer radius of the roll bends, including at the top curvature, so that this radius is not coincident with the outer radius of the bends (Figure 192).
- Decrease the width of the bottom roll so that the distance between the side of the bottom roll and the edge of the sheet is at least 4 mm. For example, in the station 8 design (Figure 192), the distance between the width of the bottom roll was changed from 2.79 mm to 4 mm, in order to correct the lateral edge contact problems mentioned in section 4.2.2 and existing in both the experimental and simulated line. This reduction of the roll width was only possible in some stations since it could cause some instability in forming due to the reduction of the contact area of the top bends of the part with the bottom roll.
- Place the “roll shoulders inward”, so that the sheet does not come out between the side gap between the rolls during simulation (Figure 193). This is a common practice in roll forming simulation, when working with high strength steels.

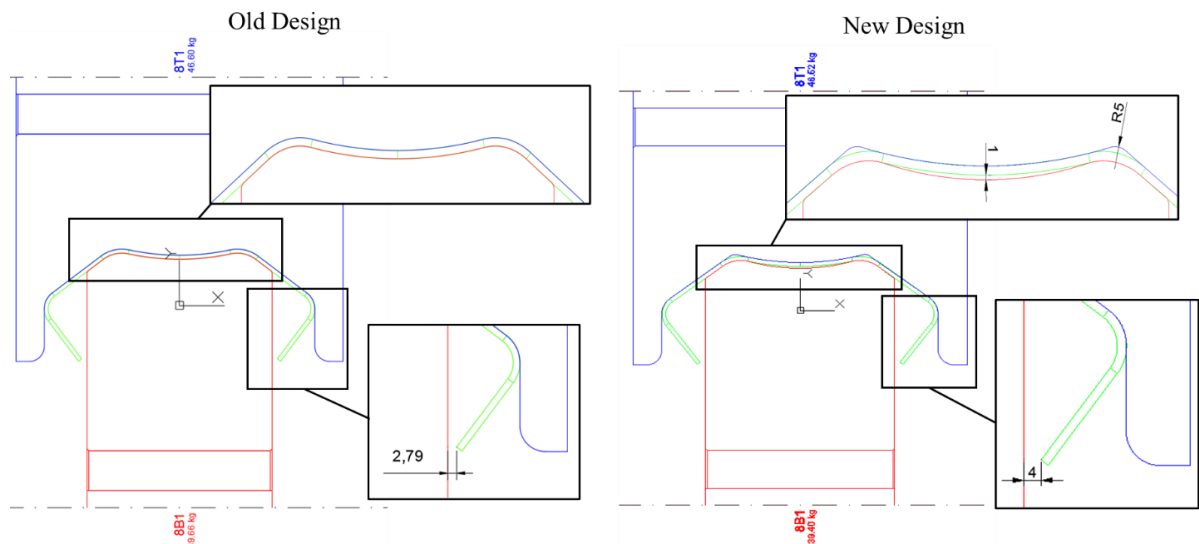


Figure 192 – Roll design modification at station 8.

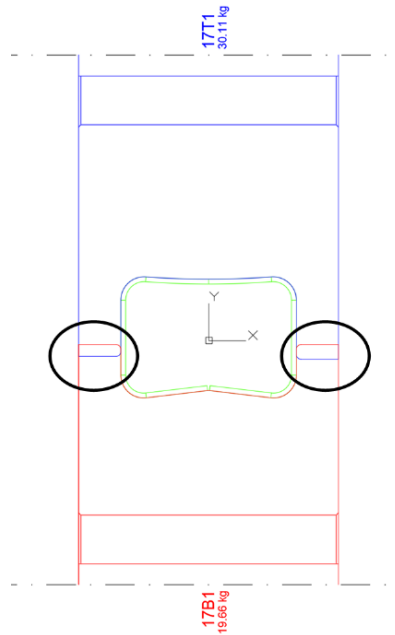


Figure 193 – Placing the rolls' “shoulders” inward.

In order to validate the influence of the design recommendations proposed by Linde Opsan, a comparison was made between the reference simulation studied in the previous chapter and a new simulation whose only difference is the design of the rolls (with the implementation of Linde Opsan's recommendations).

The results of the springback values obtained for their simulations are shown in Figure 194. As it can be seen, the new roll design allowed a slight reduction of the springback angle for both bends and for all planes under study.

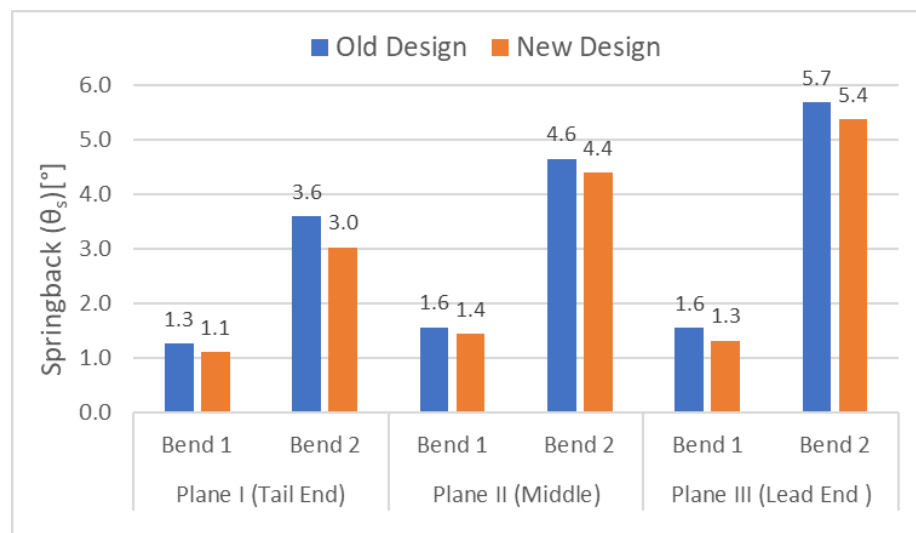


Figure 194 – Comparison between the model with the old design (reference model) and the model with the new design, considering the springback angles (θ_s) [°] obtained for the two bends and three planes under study.

The end flare values for the two simulations under study are represented in Figure 195. As it can be observed, there was also a slight reduction in the end flare values, although the end flare value for bend 2 of the tail end was slightly higher for the simulation with the new roll design. However, for bend 1 of tail end a large reduction of end flare, about 1.6° , was observed.

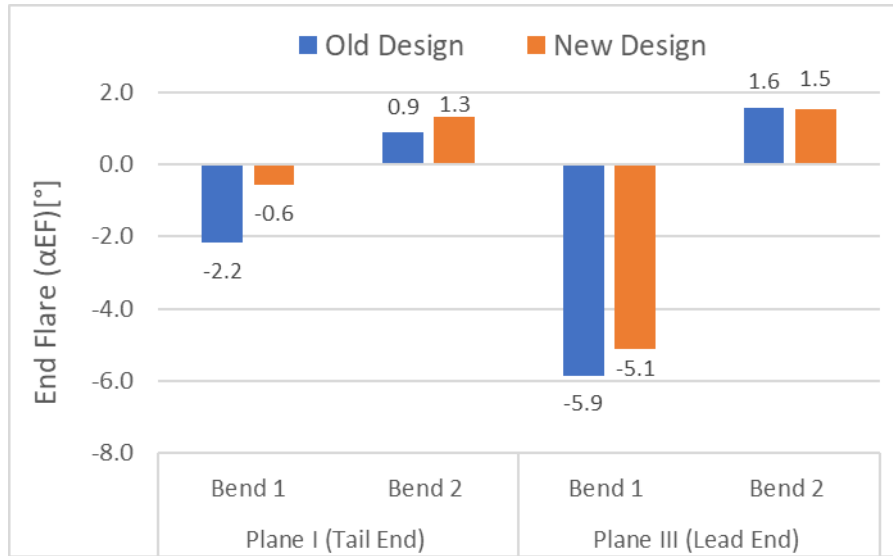


Figure 195 – Comparison between the model with old design and the model with new design, considering the end flare angles (α_{EF}) [°] obtained for the two bends and two planes under study.

Analysing the final thickness of the part (Figure 196), it can be seen that the areas where the greatest thickness reduction occurs is in the bends since it is in these areas that the forming takes place. Furthermore, it can be observed by the areas surrounded in red that for the model with the new design the thickness reduction was not as accentuated as the one verified for the model with the old design, making the part less fragile in these areas.

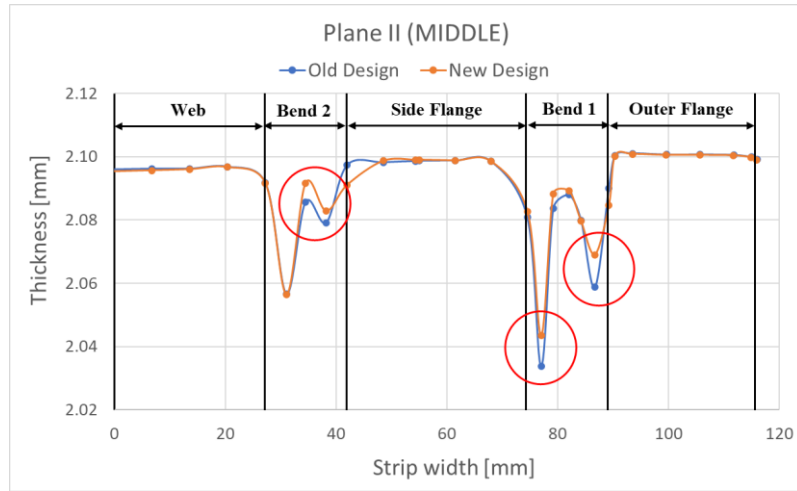


Figure 196 – Thickness of the strip across the width for the models with old and new design considering the plane II (middle).

6.1.3 Mesh definition

The mesh used for the process improvement simulations is shown in Figure 197. This mesh was chosen taking into account a parallel study performed at Coproget regarding a mesh sensitivity analysis, conducted by Melo (2022). In addition, the mesh selection was also performed taking into consideration the intermediate refinement mesh under study in section 4.2.2, which uses six elements along the web.

As seen previously, the six elements along the web allow to ensure a good compromise between computational time and reduction of the penetration problem. Furthermore, as can be observed in Figure 197, 5 elements were used across the width for the bends as advised by the company Opsan.

Another advice followed was the use of square elements instead of rectangular elements. In addition, only 1 element in thickness was chosen based on a parallel study performed in the company by Melo(2022) that showed that 1 element in thickness was enough to get accurate results. Also, according to Forte (2021), 1 element in thickness is enough to get geometrically accurate results.

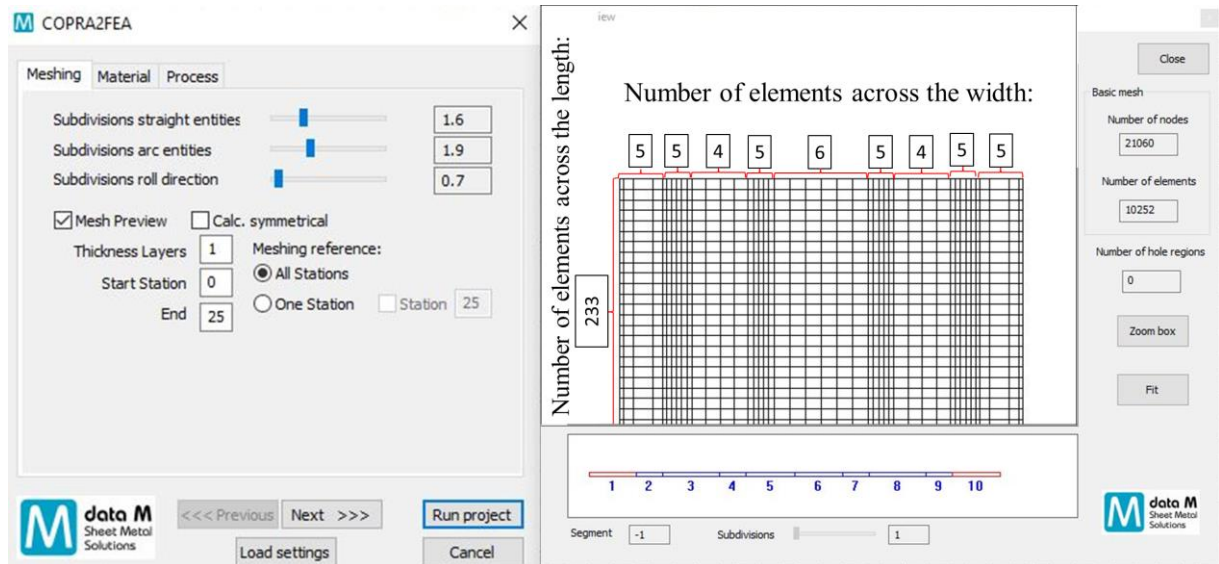


Figure 197 – Mesh parameters of the base model.

6.2 Issues and Solutions

In this section several illustrations are presented regarding the cross-section shape of the part at the moment of entry and at the moment immediately before the entry of the part into the gap between the rolls of the roll forming line stations. Figure 198 represents the legend of these same figures and highlights the different sections under analysis.

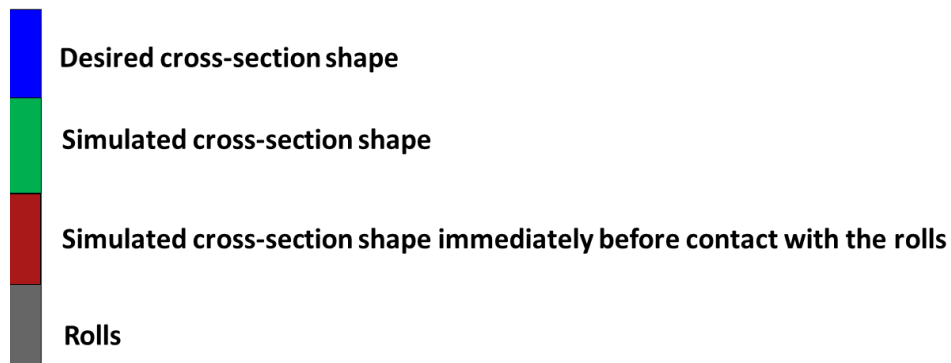


Figure 198 – Legend with the different sections under analysis.

As verified in section 4.2.2, the first stations where forming problems were observed were stations 10 and 11, as the profile cross-section was far from the desired shape (roll contour).

Therefore, some modifications were made to the rolls in those stations in order to improve the process. These modifications are surrounded in red in Figure 199(b) for the case of station 10 and in Figure 200(b) for the case of station 11.

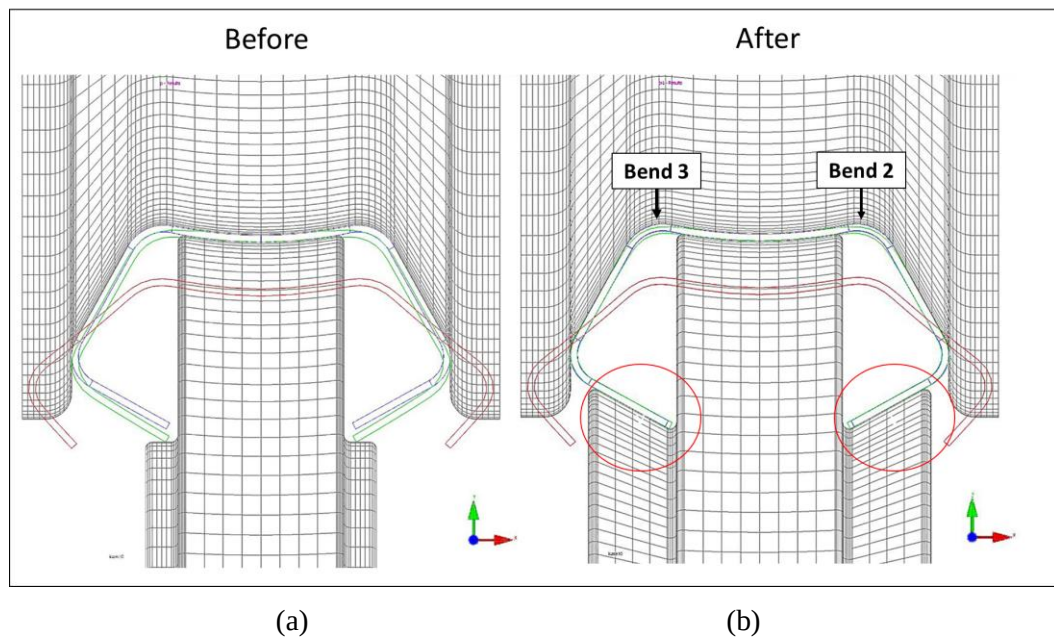
Station 10

Figure 199 – (a) Station 10 before modifications; (b) Station 10 after bottom roll modifications (surrounded in red).

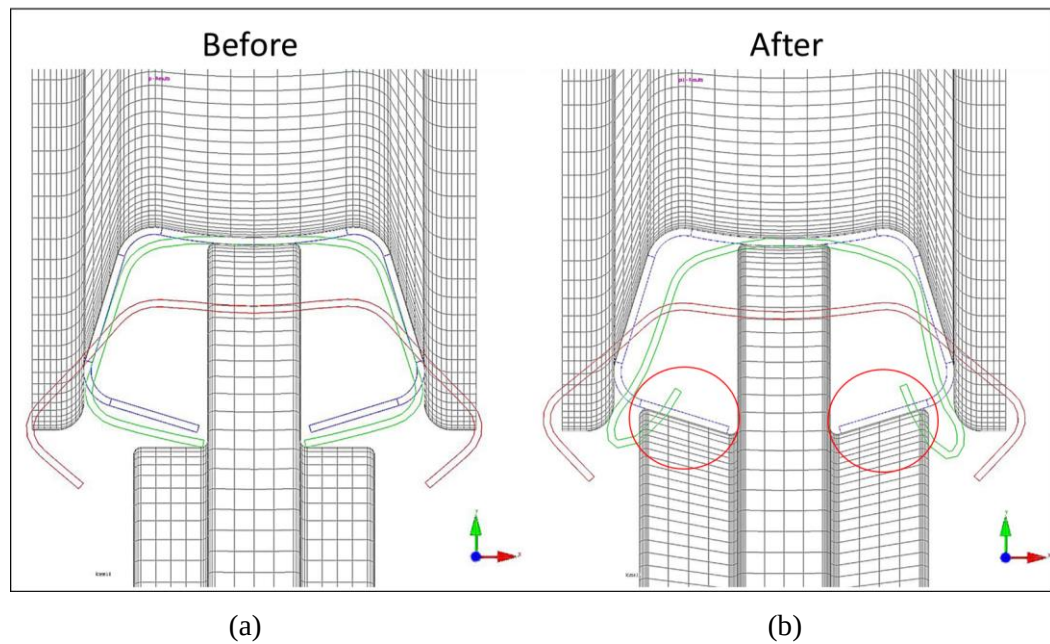
Station 11

Figure 200 – (a) Station 11 before modifications; (b) Station 11 after bottom roll modifications (surrounded in red)

For the case of station 10, there was a significant improvement as the profile cross-section clearly approached the desired cross-section (flower cross-section). As can be seen in Figure 199(b), bends 2 and 3 are much closer to the intended ones (roll contour). However, for the case of station 11 there was a collision of the sheet with the rolls, that led to the distortion of the sheet (Figure 200(b)). This collision problem is due to the fact that the cross-section of the part just before the contact between the rolls is very open due to the springback effect, even exceeding the width of the rolls (springback angles reach about 10°). Therefore, it was subsequently decided to keep the modification made on the bottom roll of station 10 and remove the modification made on station 11 (original shape). However, with this consideration it was

found that the simulated cross section of station 10 remained with good geometric results, however, the simulated cross section of station 11 presented again the same forming problems evidenced previously.

Observing again Figure 200(b), it can be observed that the part before it collides with the rolls is in a very low position on the y-axis, due to the downward movement between station 10 and 11. Comparing the position of the simulated part for the moment immediately before contact with the rolls at station 11 (Figure 201(a)), with that observed for the experimental part (Figure 201 (b)), it was found that the simulated part is in a much lower position on the y-axis than the experimental part, at the moment immediately before contact with the rolls.

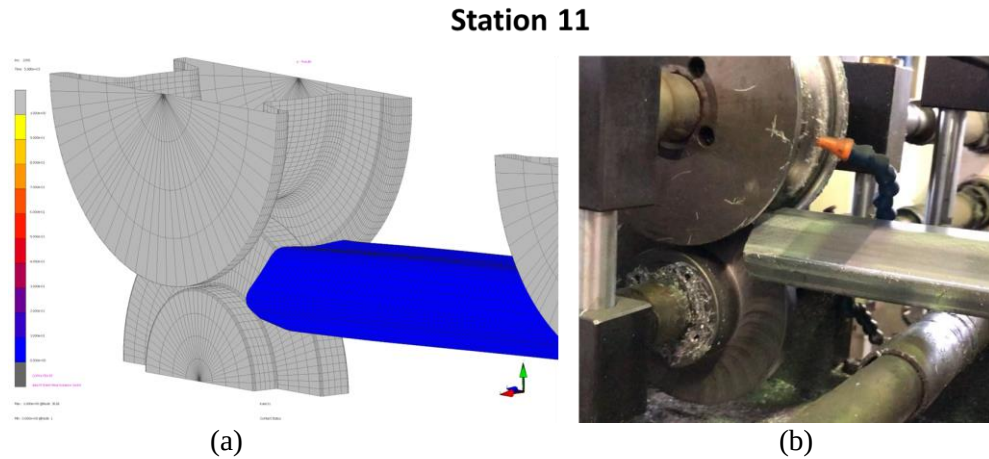


Figure 201 – Position of the part at the moment just before contact with the rolls of station 11: (a) simulated profile (contact status results); (b) experimental profile.

Therefore, in order to solve this problem and approximate the behaviour of the simulated profile to that observed for the experimental profile, a y-lock boundary condition was introduced between stations 10 and 11, so that the part would not acquire a downward movement so sharp (Figure 202). This boundary condition was applied at the lead end for the first three nodes in the middle of the bottom surface of the part to contain the displacement of these three nodes in the Y direction. Furthermore, this boundary condition only becomes active at the moment immediately after these three nodes pass through the station 10 roll plane.

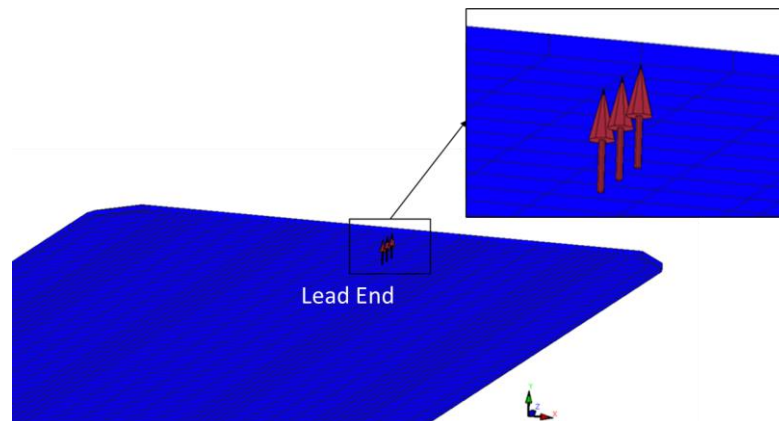


Figure 202 – Application of the y-lock boundary condition to prevent a sharp downward movement of the part.

Figure 203 shows the cross-sections obtained for station 11 before and after the implementation of the y-lock boundary condition. As can be seen, there is no longer the collision problem between the strip and the roll. In addition, a substantial improvement in the shape of the simulated cross-section was verified (quite close to the desired one) compared to the one previously observed in Figure 200, especially in bends 2 and 3.

Station 11

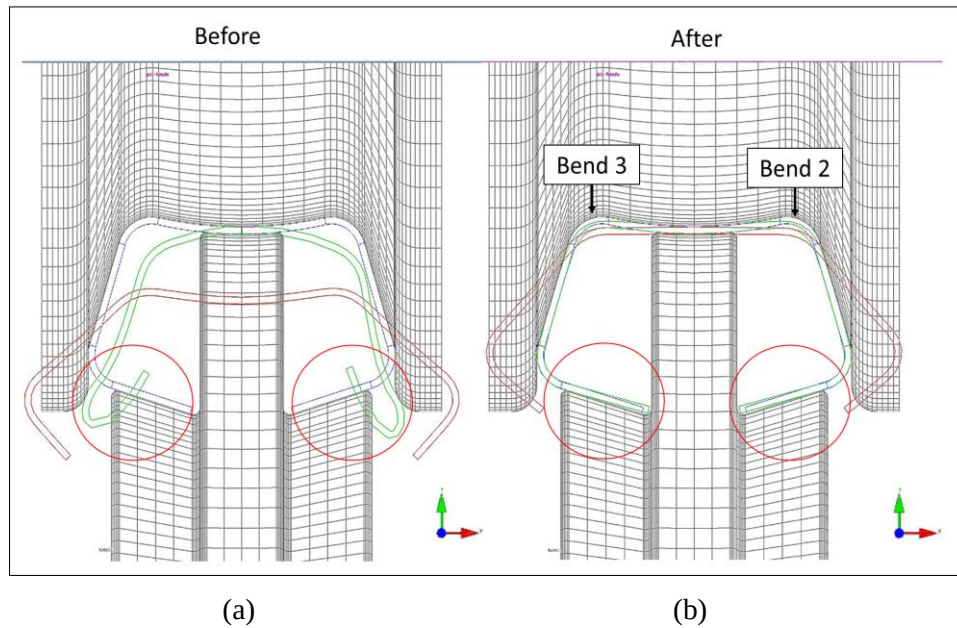


Figure 203 – (a) Profile cross-sections obtained before applying the y-lock boundary condition during the sheet path between station 10 and 11; (b) Profile cross-sections obtained after applying the y-lock boundary condition during the sheet path between station 10 and 11.

The following problem that appeared during the simulations of Coproget's roll forming line occurred at station 13. As can be seen in Figure 205(a), the outer flanges of the simulated profile have a significantly higher slope than the flanges of the desired cross-section (flower cross-section). Once again, as can be seen in Figure 204, the position of the profile in the y-axis just before the rolls enter is considerably lower than that observed experimentally.

Station 13

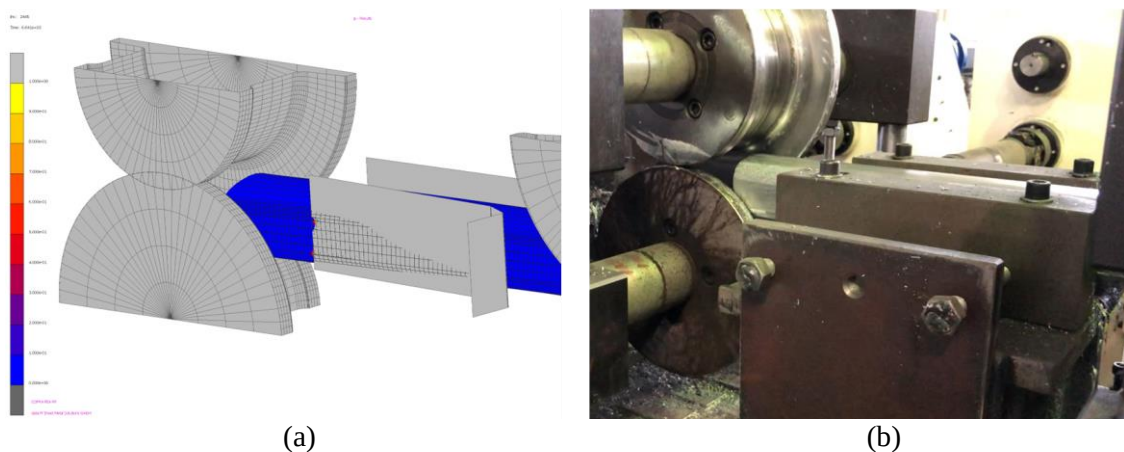


Figure 204– Position of the part at the moment of entry into the gap between the rolls at station 11: (a) simulated profile (contact status results); (b) experimental profile.

In order to approximate the entry position of the part on the rolls with that observed experimentally, it was decided to extend the y-lock boundary condition previously activated between stations 10 and 11 to station 13. After extending the y-lock boundary condition to station 13, it was found that the simulated profile cross-section became quite close to the intended profile cross-section (Figure 205(b)). In addition, it can also be observed that the steep inclination of the outer flanges previously observed no longer exists.

Station 13

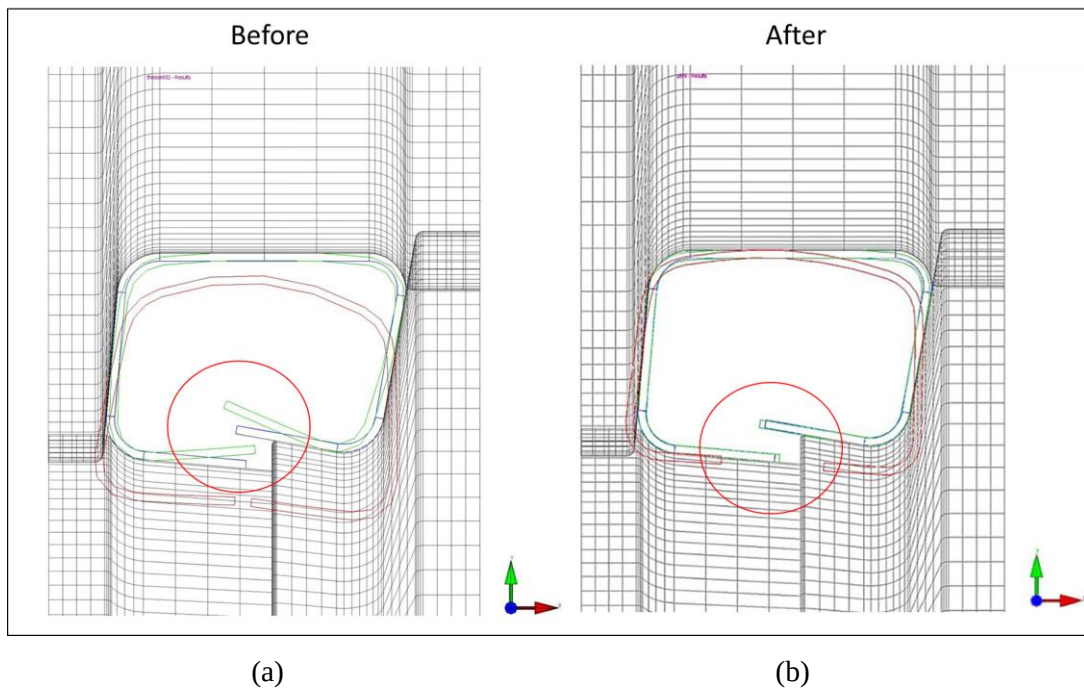


Figure 205 – (a) Cross sections obtained before the extension of the y-lock boundary condition to station 13; (b) Cross sections obtained after the extension of the y-lock boundary condition to station 13.

After station 13, the following problem in the line occurred at station 17. As can be seen in Figure 206, at this station there are minor contact problems between the outer flange edges. These contact problems are almost impossible to eliminate completely due to the existing proximity between the two flange edges during the entire process. Furthermore, this contact between the flange edges also occurs on Coproget's experimental line and therefore no changes were made at this station.

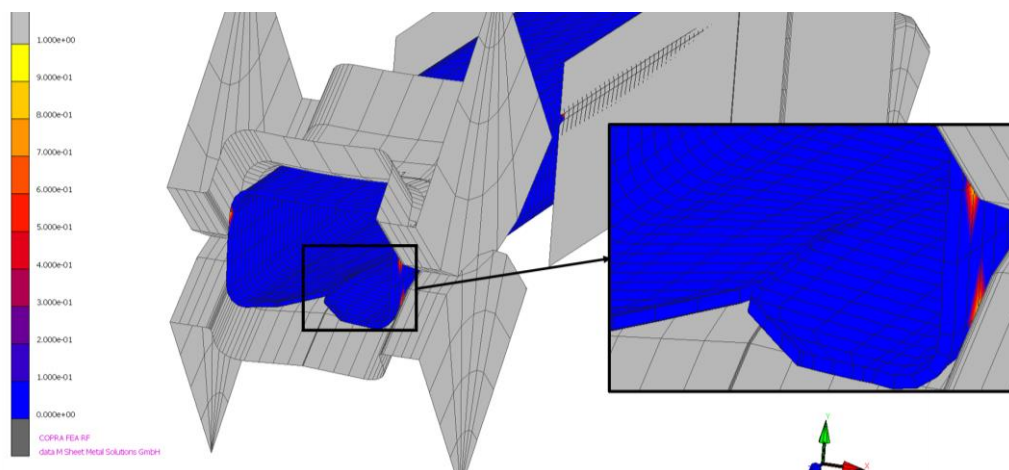


Figure 206 – Contact problems between the outer flange edges at station 17 (contact status results).

Subsequently, another problem was detected at station 19. As can be seen in Figure 207 (a), at this station a collision was observed between the corner of bend 4 of the strip and the "shoulder" of the bottom roll, which led to a high deformation of the strip in this area. In order to solve this problem, the inner diameter of the bottom roller "shoulder" where the contact was observed, was increased to 15 mm as shown in Figure 207 (b).

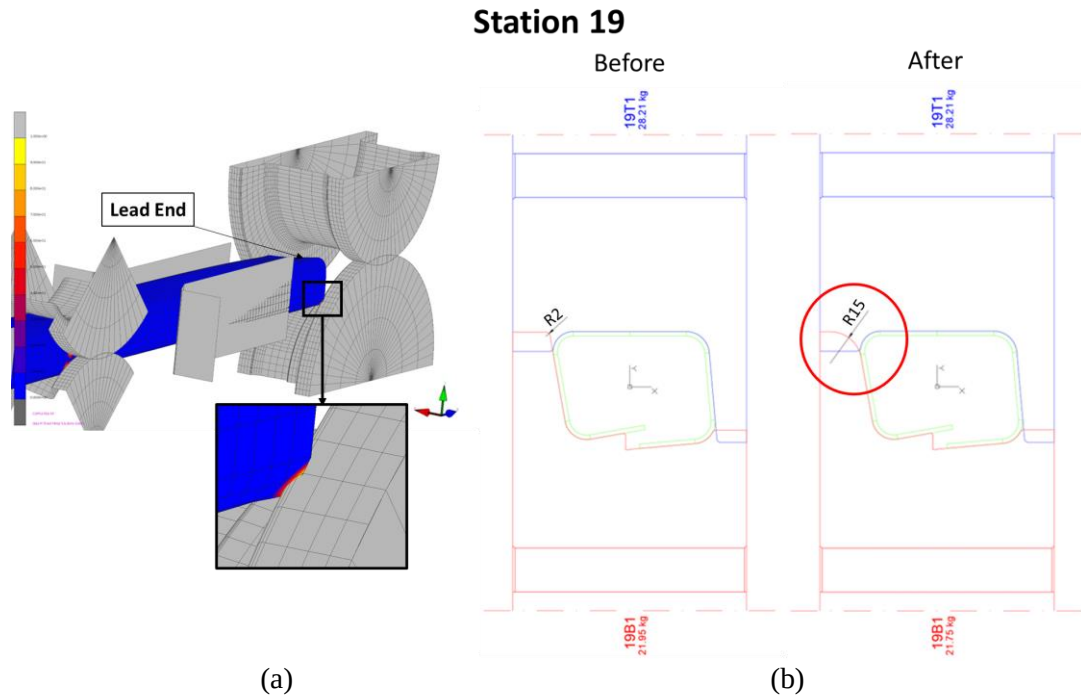


Figure 207 – (a) Collision between the corner of bend 4 of the strip and the "shoulder" of the bottom roll at station 19 (contact status results); (b) Increase by 15 mm the inner diameter of the "shoulder" of the bottom roll where the contact was observed (front view).

As can be seen in Figure 208, it was verified that after increasing the inner radius of the bottom roll "shoulder", the collision problem no longer existed and consequently the high deformation existing at the corner of bend 4 was eliminated.

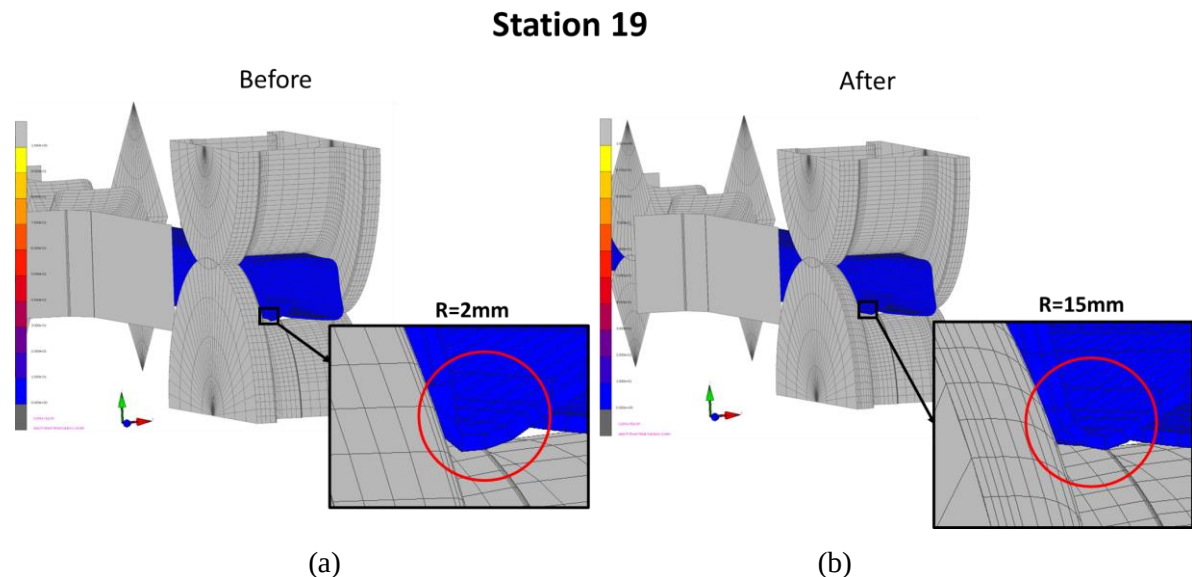


Figure 208 – (a) Excessive deformation of the corner of bend 4 to an inner bottom roll "shoulder" radius of 2mm (contact status results); (b) Elimination of excessive bend deformation by increasing the inner radius of the bottom roll "shoulder" to 15mm (contact status results).

However, it was observed that the simulated cross section geometry of the station 19 had the outer flanges too high compared to the ideal section geometry, as shown in Figure 209 (c). In order to solve this problem, it was decided to increase the angles of the station 17 roll between the side flanges and the outer flanges by 15° , as represented in Figure 209 (a) and in Figure 209 (b). This implied an increase of 1.18 mm for the internal radius of bends 1 and 4 of the profile

for this station. With the implementation of this modification in station 17, the outer flange problem was solved and the simulated cross section became very similar to the desired cross section (flower cross-section), as can be seen in Figure 209 (d).

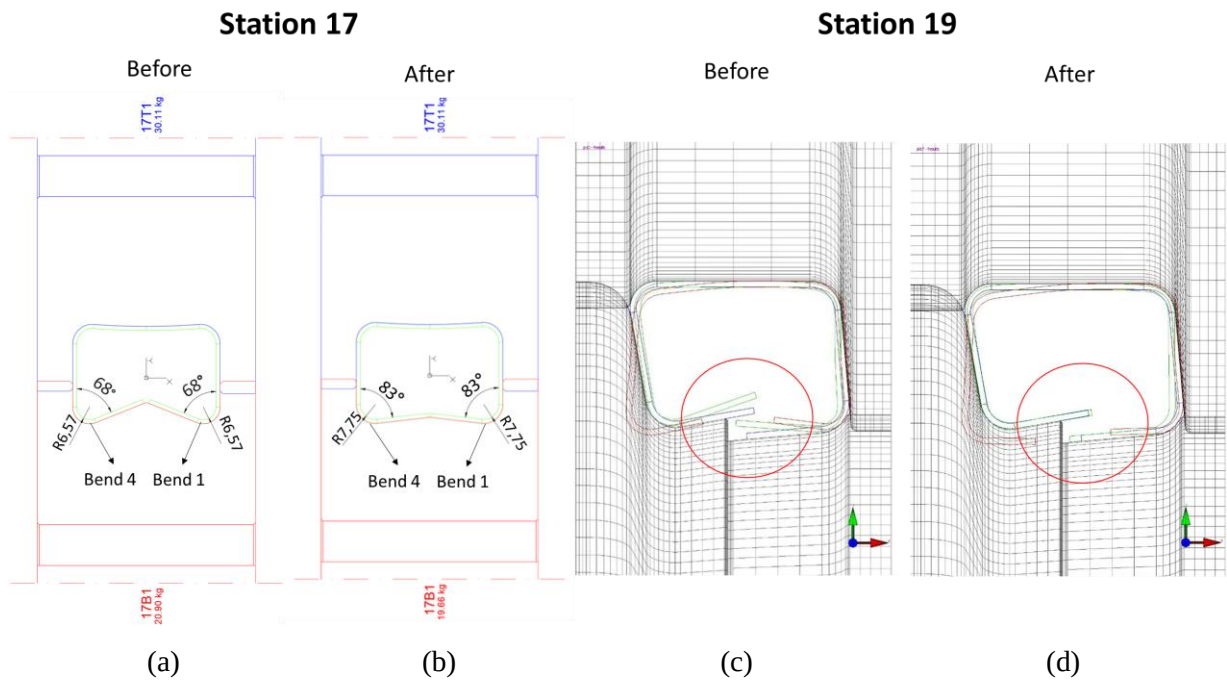


Figure 209 – (a) Original rolls of station 17; (b) Increase angles between side flanges and outer flanges by 15° for the bottom roll of station 17; (c) Outer flanges of station 19 too high compared to the desired cross-section geometry; (d) simulated profile cross-section for station 19 quite identical to the desired cross section (flower cross-section).

Subsequently, it was also verified that there was another collision problem of the strip with the rolls at station 23, as shown in Figure 210(a). In order to solve this problem, the internal radius of the rollers' "shoulders" was increased 8 mm as shown in Figure 210(c) and in Figure 210(d). After implementing this modification, it was found that, the contact problem no longer existed and the strip was able to pass through the gap between the rolls, as depicted in Figure 210 (b).

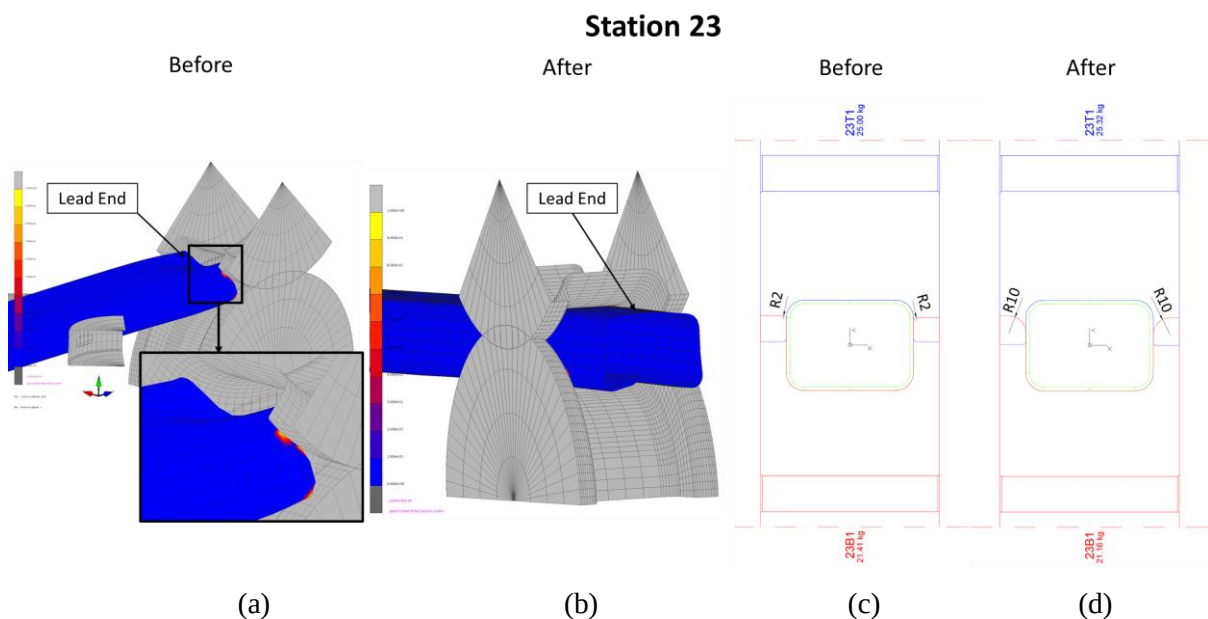


Figure 210 – (a) Collision problem at station 23(contact status results); (b) Collision problem solved (contact status results); (c) internal radius of the roll "shoulders" of 2 mm; (d) internal radius of the roll "shoulders" of 10 mm;

However, once again it was observed that the simulated cross-section geometry of station 23 had the outer flanges too high compared to the ideal section geometry as shown in Figure 211 (c).

Therefore, as was done for station 17, it was decided to also increase the roll angles of station 21 between the side flanges and the outer flanges by 15° as shown in Figure 211 (a) and Figure 211 (b), to see if this modification had a positive effect on station 23. This consideration implied again an increase of 1.18 mm to the inner radius of bends 1 and 4 of the profile for this station.

As can be seen Figure 211 (d), the modifications made at station 21, allowed a better approximation of the simulated cross-section of station 23 with the intended cross-section of station 23, as the outer flanges now perfectly follow the roll contour.

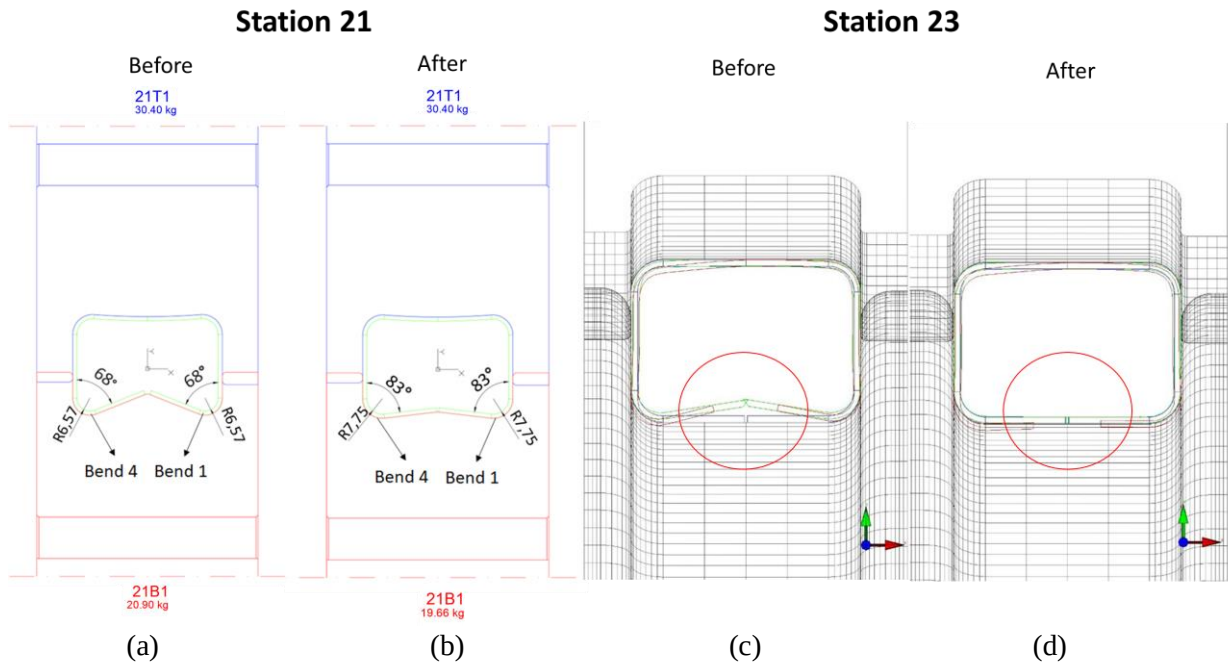


Figure 211 – (a) Original rolls of station 21; (b) Increase angles between side flanges and outer flanges by 15° for the bottom roll of station 21; (c) Outer flanges of station 23 too high compared to the desired cross-section geometry; (d) simulated profile cross-section for station 23, quite identical to the desired cross section (flower cross-section).

Finally, as can be seen in Figure 212 (a), at station 25 there were again collision problems between the strip and the bottom roll. In order to eliminate this problem, the radius of the inner “shoulders” of the bottom roll was increased again 8mm, as represented in Figure 212 (c) and Figure 212 (d).

After implementing this modification, it was found that the collision problem no longer existed and the strip was able to pass through the gap between the rolls without any problem until the end of the simulation Figure 212 (b).

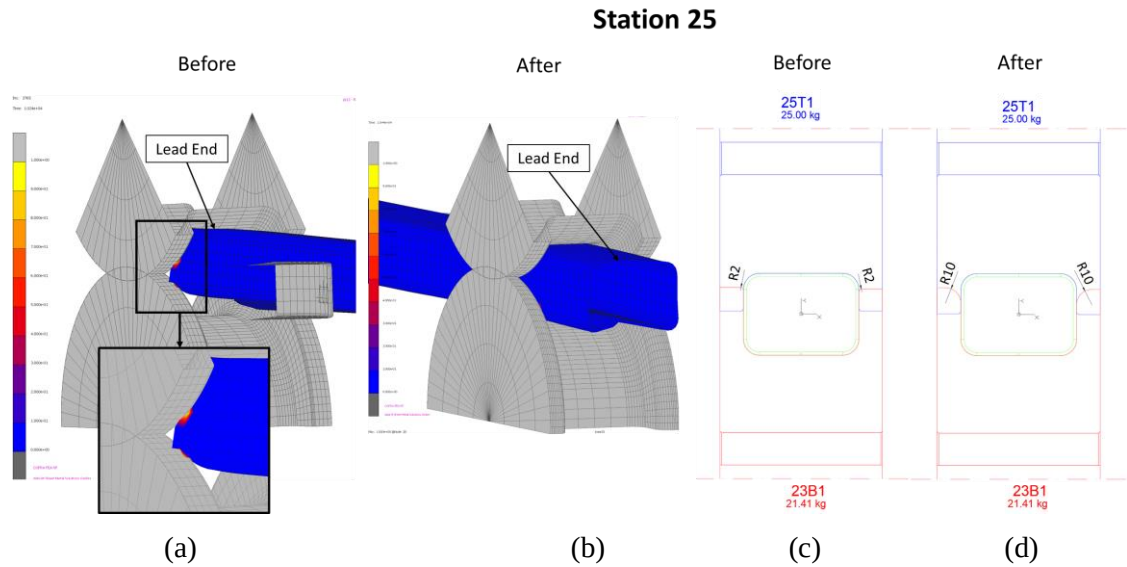


Figure 212 – (a) Collision problem at station 25(contact status results) ;(b) Collision problem solved (contact status results); (c) internal radius of the roll "shoulders" of 2 mm; (d) internal radius of the roll "shoulders" of 10 mm;

Once a part was obtained, a new simulation was run but with a pre-cut length of 2345 mm, that is, with the same length of the parts produced in Coproget's RF process. This consideration was made in order to allow the measurement of the springback, end flare and twist angles of the simulated part and their comparison with the experimental measurements previously made for the experimental part (see section 3.4). Figure 213 (a) shows the final part 1 (first final part), obtained with a pre-cut length of 2345 mm, while Figure 213 (b) shows the cross-section of the plane located at the mid-length of this part. In Figure 213 (a) it is possible to clearly observe the end flare effect at the ends of the part, while in Figure 213(b), it is possible to observe the springback effect mainly at bends 1 and 4.

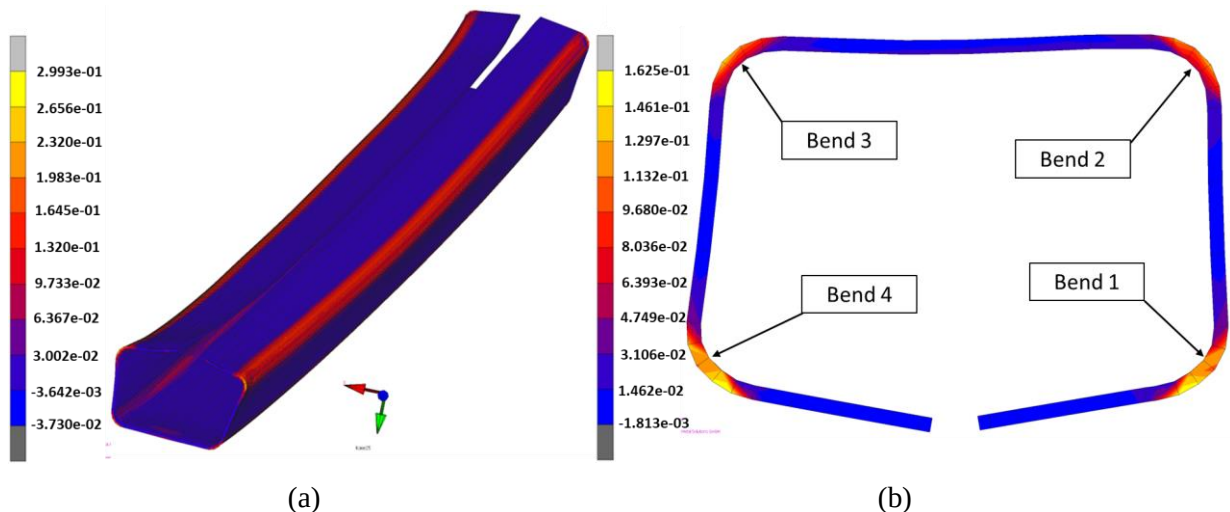


Figure 213 – (a) Final Part 1 (total equivalent plastic strain results); (b) Cross-section at the mid-length of the part (total equivalent plastic strain results).

Figure 214(a) and Figure 214(b) show, respectively, the profile final angles and end flare angles obtained for the simulation "final part 1" and its comparison with experimentally measured values. These defects were measured for the simulation as described in section 3.4. The values shown in the graph regarding the profile final angles correspond to the arithmetic mean of the measurements taken for six planes of the part.

Analysing the values obtained for profile final angles (Figure 214(a)), it can be seen that the simulated part ("Final Part 1") shows better results than the experimental part for bends 2 and 3. However, for bends 1 and 4 their values are much higher than experimentally measured and therefore the part need to be improved in these areas. In turn, analysing the values obtained for the end flare, it is verified that the simulated part always presents higher values of end flare than the experimental part except for the bend 2 of the tail end. Therefore, this defect needs to be improved in general.

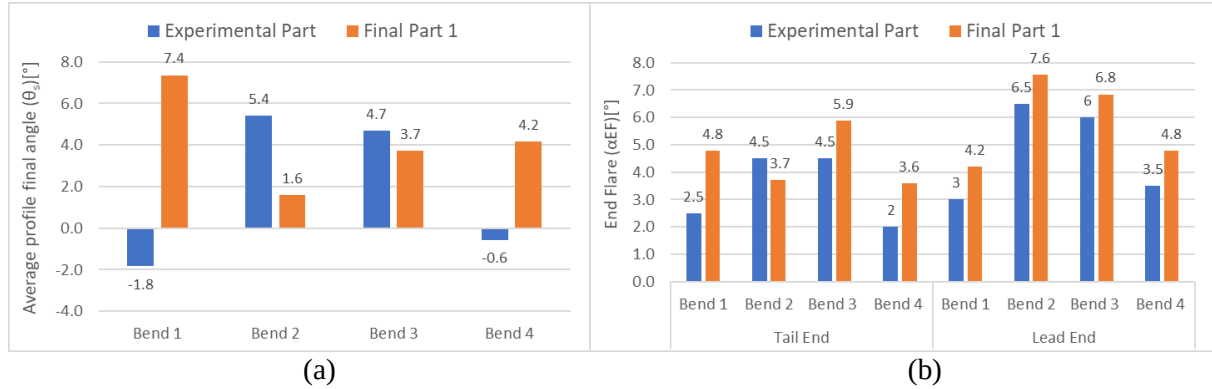


Figure 214 – (a) Comparison of the average profile final angles obtained for the experimental part and the simulated part ("final part 1") for the four bends under study; (b) Comparison of the end flare angles obtained for the experimental part and the simulated part ("final part 1") for the four bends of the lead and tail end.

6.2.1 Reduction of defects in the beam

In this subsection some modifications performed on the simulated roll forming line are presented in order to reduce the defects observed in the "final part 1" simulation. As previously verified, the average springback angles obtained for bends 1 and 4 of the simulated part were much higher than those observed for the experimental part. Also, the values of the end flare angle were high for these bends, compared to the experimental part. Therefore, in order to reduce these defects, modifications were made in the stations with more influence on these bends. As can be observed in Figure 215 (a), for station 13, the angle between the web and side flange of the bend 3 was changed from 95° to 90°. The same procedure was performed for the angle of bend 2 relative to station 19, as can be seen in Figure 215 (b).

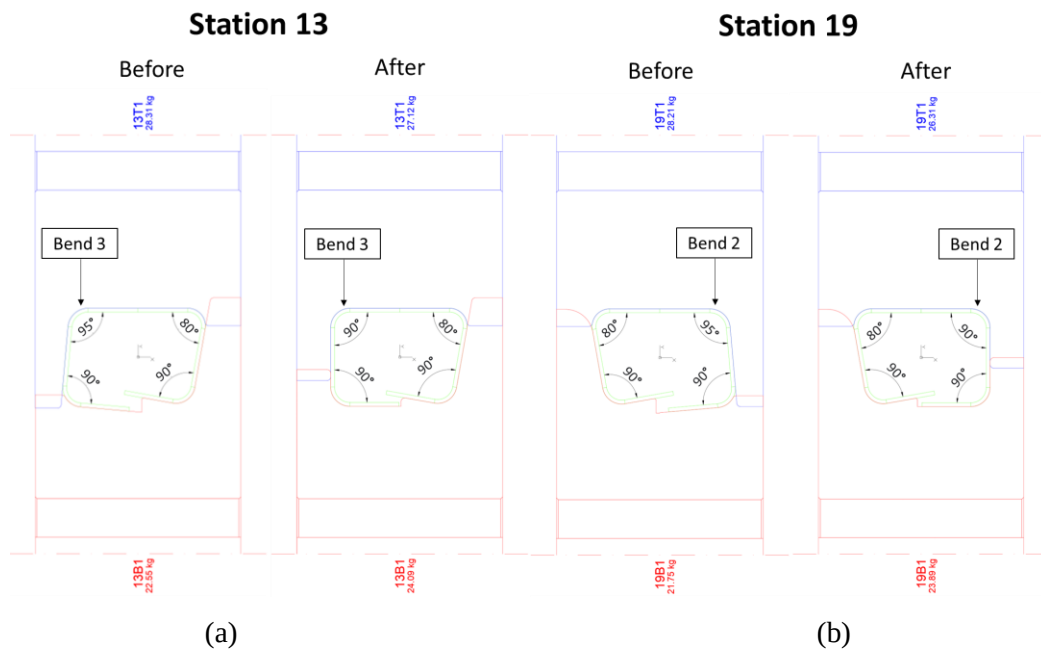


Figure 215 – (a) Reduction of the angle at bend 3 of station 13, from 95° to 90°; (b) Reduction of the angle at bend 2 of station 19, from 95° to 90°.

After performing these modifications, it was observed for example, a better fit of the lateral flange of the profile with the roll, as evidenced in the areas surrounded in red in Figure 216(a) e Figure 216(b).

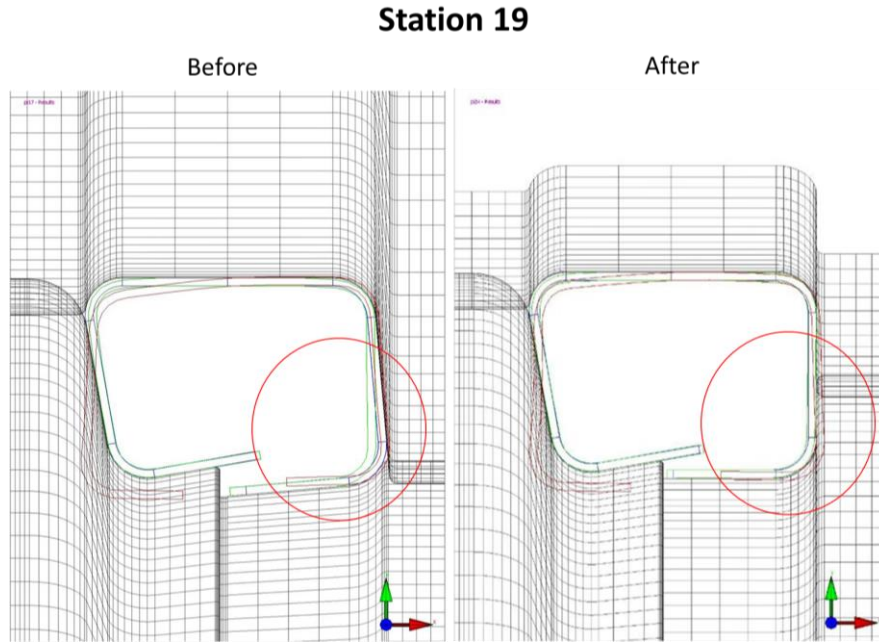


Figure 216 – (a) Before changing the angle in bend 2 of station 19; (b) After changing the angle in bend 2 of station 19.

Another station with a major influence on bends 1 and 4 is station 21 (Figure 217). As was proven by the parametric study (see section 5.3.3), increasing the number of stations makes the bending process more gradual and therefore defects like end-flare are reduced. Since the end flare values obtained for the simulation "Final Part 1", were higher for most of the bends than those obtained for the experimental part, a new station was added after station 21 (station 22) at a distance of 600 mm and with a reduction of 10° in the angles formed between the side flanges and the outer flanges (bend 1 and bend 4), in order to create the overbending effect. This modification implied a decrease of 0.83 mm for the internal radius of bend 1 and 4 of the profile for station 22.

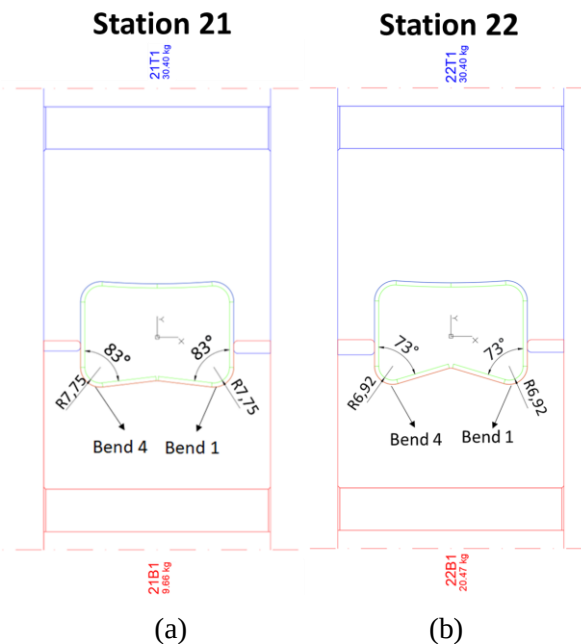


Figure 217 – (a) Original Station 21; (b) New station added after station 21 with 10° less in the angles formed between the side flanges and the outer flanges.

However, the collision of the part with the newly added station (station22) was observed (Figure 218).

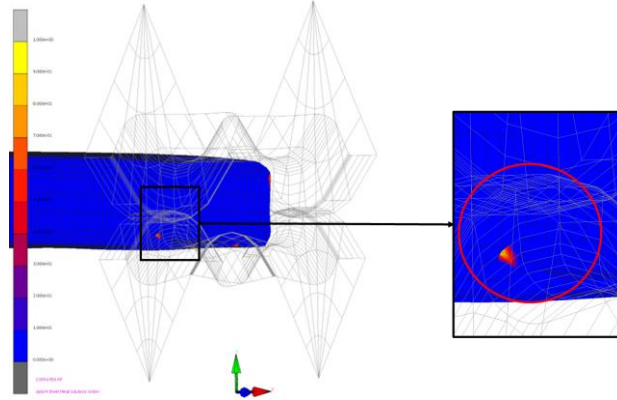


Figure 218 – Collision of the part with the newly added station (station22).

Therefore, new side bars were added between station 21 and the new added station (station22), located 300 mm away from each of these main stations. Sidebars have been added instead of side rolls, since the latter are difficult to use with pre-cut strip (not continuous). This difficulty is due to the fact that the material used is a high strength material and therefore successive contacts of the strip edge with the side rolls can knock them off their axis. In addition, side rolls are more expensive and are only useful with coil (continuous). After placing the new side bar, it was found that the part reached the end of the simulation without any problem.

In order to further reduce the end flare, a countermeasure was also used to reduce this defect described in the literature as the "lowering and elevating" method (see section 2.4.2). Thus, the rolls at station 25 (penultimate station) were lowered 0.5mm with the intention of the part lowering and raising again at the last station, reducing the end flare defect.

Figure 219 (a) shows the final profile obtained from all these changes and with a pre-cut length of 2345 mm (actual length of the part), while Figure 219(b) shows the cross-section of the plane located at the middle of the part length. Compared with the profile previously shown in Figure 213(a), it can be seen that for the profile obtained in this simulation although the existence of end flare at the ends is notorious, it can be seen that the external flanges are much closer to each other. This aspect is quite important, as it makes welding the part much easier. On the other hand, Figure 219 (b) shows a clear reduction of the springback angle for bends 1 and 4, when compared with the springback angles of the profile represented in Figure 213(b).

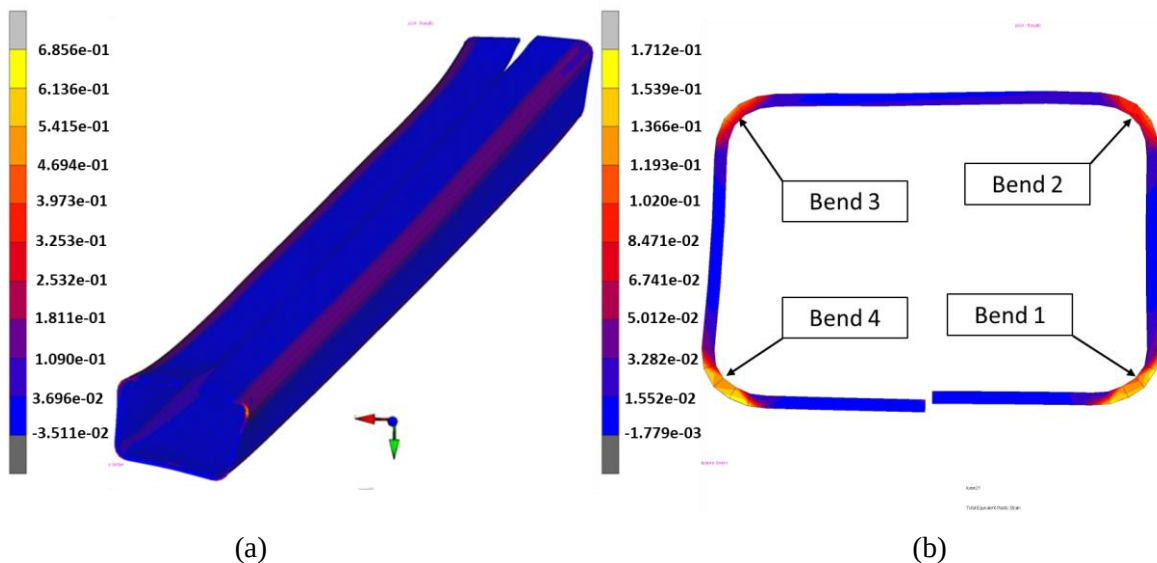


Figure 219 – (a) Final Part 2 (total equivalent plastic strain results); (b) Cross-section at the mid-length of the part (total equivalent plastic strain results).

Once this final part was obtained, new measurements of the end flare, the profile final angles and twist angles were taken. Figure 220 shows the profile final angles values obtained for the experimental part, Final Part 1 (simulation), and Final Part 2 (simulation). In turn, Table 21 shows the percentage change in profile final angles values for Final Part 2 compared to the Experimental Part and Final Part1.

Analysing both Figure 220 and Table 21, it can be seen that the Final Part 2 was the one that presented in a general way lower profile final angle values. Its values were higher only for bend 3 when compared to Final Part 1 or for bend 4 when compared to the Experimental Part. For all other cases the profile final angle values for Final Part 2 were lower, reaching a reduction of 83.8% for the case of bend 1 compared to Final Part 1 and a reduction of 74.1% for bend 2 compared to the Experimental Part.

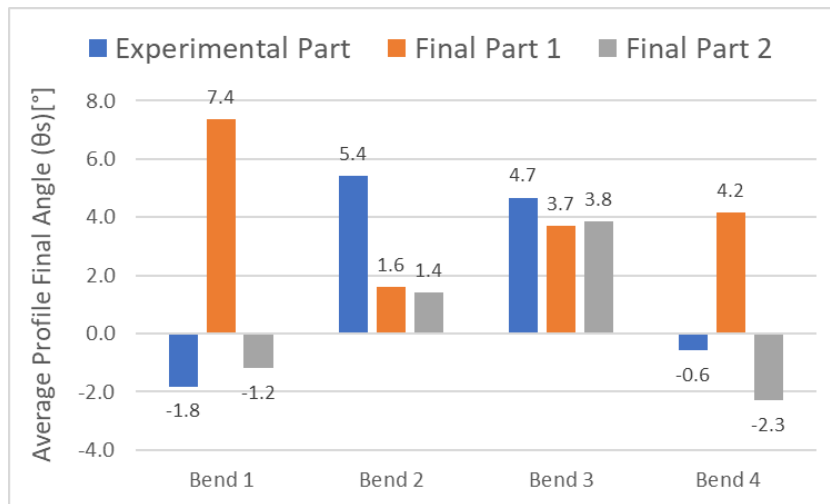


Figure 220 – Comparison of the average profile final angles obtained for the Experimental Part, the Final Part 1 (simulated part) and the Final Part 2 (simulated part), for the four bends under study.

Table 21– Percent variation of profile final angle values of “Final Part 2” compared to the “Experimental Part” and “Final Part 1” [%].

	Percent variation of profile final angle relative to Final Part 2 [%]			
	Bend 1	Bend 2	Bend 3	Bend 4
Experimental Part	-34.8	-74.1	-17.7	296
Final Part 1	-83.8	-12.0	3.5	-44.8

In turn, Figure 221 shows a comparison between the end flare values obtained for the Experimental Part, Final part 1 and Final Part 2 for the four bends of the lead and tail end. Table 22, shows the percentage of change in end flare values for Final Part 2 relative to the Experimental Part and Final Part 1.

Analysing both Figure 221 and Table 22, it can be seen that the Final Part 2 presented in general the lowest values of end flare compared to the Final Part 1 and the Experimental Part. This part only showed higher values for bend 3 of the lead end compared to the experimental part and to Final Part 1, and for Bend 4 of the tail end compared to the Experimental Part. Furthermore, it can be seen that the largest percentage reduction of the end flare occurred for bend 1 of both the tail and lead end. For the tail, a 54.4% reduction was obtained compared to the Final Part 1 and for the lead a 68.7% reduction was obtained compared also to the Final Part 1. Compared to the Experimental part there was a significant reduction for bend 4 of the lead end (56%)

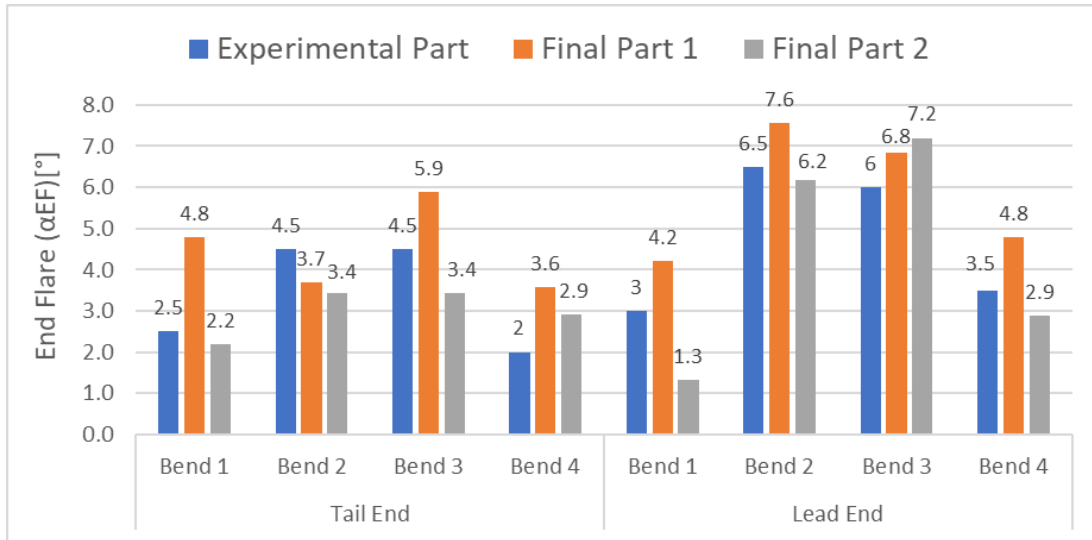


Figure 221 – Comparison of the end flare angles obtained for the Experimental Part, the Final Part 1 and the Final Part 2 and for the four bends of the lead and tail end.

Table 22 – Percent variation of end flare values of “Final Part 2” compared to the “Experimental Part” and “Final Part 1” [%].

	Percent variation of end flare relative to Final Part 2 [%]							
	Tail End				Lead End			
	Bend 1	Bend 2	Bend 3	Bend 4	Bend 1	Bend 2	Bend 3	Bend 4
Experimental Part	-12.8	-24.0	- 24.0	45.5	-56	-5.1	20	-17.4
Final Part 1	-54.4	-7.6	-41.94	-18.7	-68.7	-18.3	5.3	-39.5

Regarding the twist values taken for the experimental part and the two simulated parts (Table 23), it was found that the simulated parts have the same twist angle (8°), which is smaller than the twist angle of the experimental part (11°).

Table 23 – Twist angles (γ_T) [°] obtained from the Experimental Part, Final Part 1 and Final Part 2.

Twist(γ_T) [°]	Experimental Part	Final Part 1	Final Part 2
	11	8	8

7 Conclusions and Future Work

7.1 Conclusion

Roll forming is a continuous process, widely used in the automotive industry, which uses a continuous bending operation to convert flat metal strips into a final profile by passing it through a series of rotating rolls. Each set of rolls performs incremental bends in the strip to produce the desired cross-section of the profile.

The following thesis arises from Coproget S.R.L's need to simulate, evaluate and optimise its roll forming line for the production of C-section beams. These C-section beams make up the rear bumpers of a commercial van model produced by the multinational car manufacturing company Stellantis and are made of an AHSS (Advanced High Strength Steel), the Docol1400M. This material is extremely difficult to deform as it has high springback angles as a result of its high strength. Therefore, the effect of springback and the defects visible in the part, namely end flare and twist, need to be redressed.

Chapter 1 provided the reader with the context, objectives and challenges of the work developed during this dissertation.

The literature review performed in chapter 2 allowed a better understanding of the basic concepts of the roll forming process, the most common types of deformations and defects resulting from it, the finite element method and the residual stresses. Several investigations found in the literature were reported during this dissertation to provide a comparison and a better understanding of the results obtained. The main conclusions drawn in chapters 3, 4, 5 and 6 are presented as follows:

Chapter 3

After performing the experimental measurements of the visible defects on the part, it was found that the part suffers high springback after being released from the action of the rollers, giving rise to defects such as end flare and twist. The waviness on the outside flanges is also visible but is not significant. The worst results of springback measurements occurred for bend 2 and 3, corresponding to the bend between the side flange and the web of the profile. End flare values were high for all bends of the profile. However, it was observed that the lead end bends presented significantly higher values than those observed for the tail end. Another aspect highlighted was the fact that the profile presented flare out at both ends, which is common when working with AHSS. Regarding the twist, it was verified that the part presents a twist of 11 degrees. After an analysis of the line it was verified that the present process in the company is not very fluid and noisy and therefore needs improvements.

Chapter 4

The modelling of Coproget's previous process (with 16 stations) as well as the process under study during this thesis (with 25 stations) is presented, in order to understand the past problems of the line and thus combat the present problems. In the simulations performed for the Coproget process with 16 stations, contact problems were observed between the outer flanges due to successive overbends at stations 13 and 14. Waviness was also observed on the side flanges and twist as was the case in the experimental profile. During the attempt to model the actual Coproget roll forming process (25 stations), it was verified that it would be quite difficult to replicate the line, due to the numerous manual adjustments that were performed on it. Thus, the need arose to make manual adjustments also on the simulated line in order to obtain a profile. The adjustment of the side bars allowed a simulated profile to be obtained, but with a shape far from the experimental profile, due to the forming problems existing along the line. Therefore, it was concluded that in order to obtain a simulated profile identical to the experimental one, it would be necessary to analyse and correct the differences between the profiles at each forming stage. Between station 5 and 11 of the process there was a propensity for lateral edge contact

to occur on both the experimental and simulated line. Up to station 9, the process was found to be well simulated (the experimental profile was identical to the simulated profile and no forming problems were observed). At stations 10 and 11 penetration problems were observed which decreased with increasing mesh refinement. However, there was no improvement in the forming with decreasing penetration. Despite this forming problem, the geometry of the simulated profile was identical to the experimental one at stations 10 and 11. Station 13 presented forming problems not observed in the experimental line that did not improve with mesh refinement. This fact led to the conclusion that it would be useless to try to replicate the experimental profile and that, therefore, the process should be improved starting from station 9, since the profile was well simulated until this station. For this purpose, it was verified that it would also be necessary to carry out a parametric study, for a better understanding of the parameters to be used in this improvement.

Chapter 5

In this chapter, a parametric study was carried out for the first 10 stations of the process (0-9), through which the influence of the number of stations, the radius/thickness ratio of the profile, the diameter of the rolls, the use of friction, the type of part cut and the use of deformable shafts, on the final profile obtained, was analysed. The implementation of different materials in the process was also studied. For the reference simulation it was found that, after the part was released from the action of the rolls, the most plasticised areas were the bends. In addition, a maximum peak longitudinal edge strain of 1.050% was observed for station 4, so this was the critical station.

Comparing three different materials used in the company for the production of profiles through the roll forming process, it was found that the higher the yield strength of the material, the higher the residual stresses present in the part. In turn, it was observed that the end flare values were much higher for the lower strength material, compared to the higher strength materials, which is contradictory to the literature. It was also found that bend 1 presented "flare in" and bend 2 "flare out" for both lead and tail for the three materials studied. For most stations, the peaks of longitudinal edge strain were higher for the materials with higher yield strength. The material with lower yield strength was the one that presented more edge wave on the outer flanges, as this defect occurs when the edge elongation exceeds the elastic limit. The materials with higher yield strength presented higher springback values. The twist angles obtained for the three materials were practically insignificant (near 0). Furthermore, it was also found that the vertical displacement of the sheet during the process is more stable for lower strength materials than for higher strength materials.

Regarding the number of stations, it was found that the bends of the part were the areas of the profile that presented a more irregular distribution of the transverse and longitudinal residual stresses. The increase in the number of stations led to a large increase in the transverse residual stresses in the bend between the side flange and the outer flange (bend 1). For the outer flange, there were no significant differences in residual stresses with increasing number of stations. Regarding the longitudinal stresses along the width of the strip, there were also no significant differences with the increase in the number of stations. In turn, it was observed that the transverse residual stresses, obtained for the inner surface of the bend 1, increased with the increase in the number of stations. For the longitudinal residual stresses along the thickness of the part, no significant differences in terms of distribution and magnitude were observed with the increase in the number of stations. With the increase in the number of stations, the peaks longitudinal edge strain decreased as the bending applied was more gradual, leading to a reduction in strains. On the other hand, with the use of two equal stations in a row, there was a large reduction in the peak longitudinal edge strain between the two stations. However, for the station immediately afterwards a significant increase in peak longitudinal edge strain to a value identical to the reference model was observed. With the increase in the number of stations, there was also a reduction in the end flare values obtained for all the bends of the part. Comparing

the end flare angles obtained for the model with 13 non-incremented stations, with those obtained for the model with 13 incremented stations, it was found that, for the latter, the end flare values are lower since the bending is more gradual. A large increase in springback was also observed with the reduction of the bending angle for the two bends and three planes under study. Comparing the two models with 13 stations it was found that there is a tendency for the model with 13 stations incremented to have higher springback values than the model with 13 stations not incremented. The greatest discrepancy in springback values was found for bend 2. It was also found that, although the model with 10 stations has fewer forming steps, it has greater plastic strains in the bend zone than the models with 13 stations. Comparing the two models with 13 stations, it was found that the model with 13 stations incremented is the one that presents lower values of plastic strains in the bend zone and is the one that presents higher springback values. The differences between the equivalent plastic strain values obtained for the three models was more pronounced for outer bend 2. This difference is even more evident when comparing the model with 13 stations incremented with the other two models, since the latter present much higher values of equivalent plastic strain. The opposite happens in relation to the springback values. Therefore, it was concluded that the higher the equivalent plastic strain in the bending zone, the lower are the springback values. In relation to the twist angle, there was a slight increase with the increment in the number of stations, although not significant. It was also observed that, in the model with 13 incremented stations the profile has a more abrupt vertical displacement than the model with 13 non-incremented stations along the RF line.

Comparing the reference model with the model with thickness reduction, it was verified that for bend 1 the values of the transverse residual stresses are higher for the model with thickness reduction. Regarding the longitudinal residual stresses along the profile thickness, it was verified that, for the model with thickness reduction these values are lower than for the reference model for the web and side flange areas. The results obtained for the longitudinal residual stresses for the outer flange were quite identical for the reference model and for the model with reduced thickness. Regarding the longitudinal residual stresses along the thickness of the part obtained for the model with the increased internal bending radius, no significant differences were observed compared to the reference model. This similarity is also verified for the transverse residual stresses along the thickness in terms of magnitude, although there is a greater uniformity of them for the model with increased internal bending radius. In turn, it was also found that the profile with the increased radius has much higher peak longitudinal edge strain values than the reference model. The opposite happens for the profile with thickness reduction. Furthermore, it was found that the springback values increase with the increase of the bending radius and with the reduction of the profile thickness. The end flare values also increased with the increase of the radius/thickness ratio, being more significant for the bend 1 of the lead end. The model with increased internal bend radius was the one that presented the highest twist value, being this value insignificant for the other two models.

The residual stresses observed for the model with the bottom roll diameter increased by 40mm, were quite similar to those of the reference model. It was also observed a reduction of the peaks longitudinal edge strain with the increase of the rollers' diameter. In turn, it was found that increasing the roll diameter leads to higher springback values, this increase being more significant for bend 2. On the opposite, it was found that increasing the roll diameter leads to lower end flare values. The twist was insignificant for both models. It was also observed that for the model with increased roll diameter, the profile shows a much less pronounced downward movement before entry into the stations, compared to the reference model, which demonstrates that entry into the rolls is smoother with increasing roll diameter.

Comparing the transverse residual stresses along the width of the profile for the model with friction, with the model without friction, it was found that there are no significant differences either in magnitude or distribution. For the longitudinal residual stresses across the width, although the curves obtained are quite identical, there are slight differences in the bends. For

the transverse residual stresses along the thickness of the part, it was found that the curves obtained for the two models differ in terms of distribution but are similar in terms of magnitude. For the longitudinal residual stresses along the thickness of the part it was found that the curves obtained for the two models are quite identical both in terms of distribution and magnitude. The springback and end flare values obtained were quite similar for both models, although the end flare values are slightly higher for the model with friction. The twist was negligible for both models. The geometries of the final profiles obtained as well as the forming trajectory were quite similar (practically coincident) for both models. The CPU time was much higher for the model with friction compared to the reference simulation (44.99% increase), mainly due to the increased matrix calculation time. As there were no significant differences between the results obtained for the two models, a model without friction was used in the improvement simulations as it requires less computational time.

The models with pre-cut and final cut proved to be quite similar both in terms of the distribution and the magnitude of the residual stresses. The final profiles obtained were also quite identical in geometric terms. The model with final cut presented much higher values of springback, end flare and twist than those obtained for the model with pre-cut. In terms of CPU time, it was verified that, the model with final cut presents much higher values compared to the model with pre-cut (123% increase). Since the geometry of the profiles is quite identical for both models, the pre-cut model was chosen to be used in the improvement simulations since it requires lower computational times and the magnitude of the defects observed in it is smaller.

The model with deformable shafts presents higher values of transverse residual stresses along the sheet width for the internal surface and similar values for the external surface, when compared with the model with rigid shafts. For the residual stresses along the width of the part and for the transverse residual stresses along the thickness of the part, no significant differences were observed between the two models. Considering the longitudinal stresses along the thickness, it was found that the model with deformable shafts presents a smaller variation of these values for the internal surface of the bend. The peaks of longitudinal edge strain were much higher for the model with deformable shafts. The springback values were also higher for the model with deformable shafts. The end flare values for bend 1 were higher for the model with deformable shafts, while for bend 2 they were higher for the model with rigid shafts. The twist was negligible. The CPU time was much lower for the model with deformable shafts compared to the model with rigid shafts (27.76% reduction) due to the simplified matrix calculation. The increase of the roller gap at each station was much higher for the model with deformable shafts. In turn, the forces in the vertical direction of the top roll for each station were much lower for the model with deformable shafts, which demonstrates the simplification of the process with the use of this model. Despite the advantages of using the model with deformable shafts, namely in terms of computational time reduction and process simplification, the results of the top roll deflection at each station measured experimentally were quite different from those obtained from the simulation, and therefore this model was not used for the improvement simulations. Therefore, it was concluded that further experimental tests on the line are necessary, using load cells to measure the forming forces and strain gauges to measure the deflection of the components, for example, in order to validate if the model with deformable shafts adequately reproduces the experimental profile.

Chapter 6

The design recommendations suggested by the company Linde Opsan, had positive effects in reducing the profile final angles and end flare. With these recommendations, the profile obtained also presented a smaller thickness reduction in the bending zones, which makes it less fragile in these zones. During the process improvement, it was found that the forming problems at stations 11 and 13 due to the inadequate downward movement of the part before entering these stations, were solved with the application of a y-lock boundary condition at the lead end. The part collision problems with the rolls at stations 19, 23 and 25 were solved by increasing

the internal radius of the roll “shoulders”. The inadequate forming at stations 19 and 23 was improved by reducing the bending angle of the outer flanges of the immediately preceding stations (stations 17 and 21). The reduction of the bending angle for bend 3 at station 13 and bend 2 at station 19 by 5 degrees, the addition of station 22 with a reduction of 10 degrees for bend 1 and 4 (relative to station 21), and the application of the literature-based “lowering and elevating” method, produced a simulated profile of much higher quality than the experimental profile. It was verified a reduction of the profile final angles in all bends except for bend 4. The end flare was reduced for all bends but for bend 4 of the tail end section and 3 of the lead end section. The twist was also reduced in 3 degrees in relation to the experimental profile.

7.2 Future Work

The work developed in this project allowed a better understanding of the behaviour of the Coproget roll forming line during the forming of the studied C-profile. Given the large amount of research work that can be done to improve the simulation of Coproget's roll forming process, as well as to reduce defects in the parts it produces, some recommendations on future work on this subject are provided as follows:

- to perform a tensile test of the material, in order to allow a better characterization of the material;
- to create an accurate model of Coproget's roll forming line through reverse engineering techniques;
- to conduct an analysis to the microstructure of the material using a non-invasive methodology such as scan electron microscopy;
- to study the use of an anisotropic plasticity model, such as Hill's criterion;
- perform a mesh sensitivity analysis for the various models studied;
- to study the impact of different elements from the Marc/Mentat library in the models under study. It would also be interesting to combine different types of elements in different areas of the sheet for the models studied;
- to use a more refined mesh for the last simulation obtained and compare the end flare, springback and twist angles with those obtained for the experimental part;
- to develop simulations with different degrees of freedom of the top and bottom rolls, e.g. including the angular displacement of the rolls in the z direction (forming direction), for example, to simulate the real shaft stiffness;
- to develop a new roll forming stand capable of reducing end flare, springback and twist defects. Some patents have already been developed regarding this subject.
- to create a new flexible 3D roll forming stand controlled by CNC that allows the production of parts with variable cross- sections. In addition, this new roll stand can be useful for reducing defects such as end flare, using the "overbending and bending back" method described in section 2.4.2, as it allows the rolls to move back and forth in a direction perpendicular to the sheet feed direction. A prototype of this roll stand started to be developed during the internship period in the company, as shown in Figure 222 . However, this prototype is at a very early stage and therefore needs a lot of research and development work before it is completed;

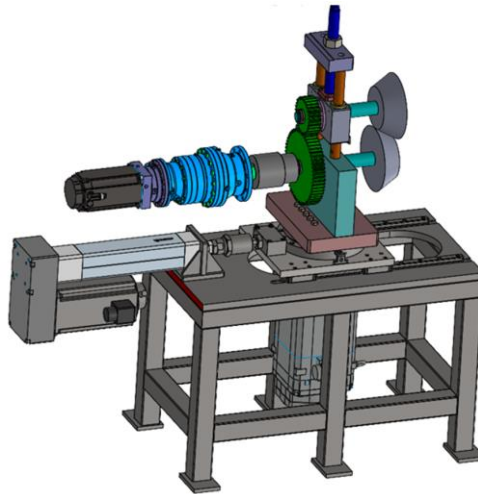


Figure 222 – Flexible 3D roll forming stand.

- to use other friction models available in COPRA® FEA and described in section 5.3.6. Compare the results obtained and draw conclusions;
- to study models with different friction coefficients to verify their influence on the geometry of the final part obtained;
- to develop a boundary condition to be used in models that combine friction with pre-cut length, so that the sheet does not stop at the last station of the process, as was the observed in section 5.3.6;
- to test a new way of roll forming rectangular tubes called CRF (circle-to-rectangular forming), since the C-profile under study in this thesis is actually a rectangular profile after being welded. A process identical to the SRF (strip to rectangular forming) was used to form the studied C-profile, in which the steel strip is formed directly along successive rolls and then is welded to form a closed rectangular section. On the other hand, in the CRF process, the steel strip is first roll formed into a circular section by successive passing through a set of rolls, then it is welded and finally it is transformed into a rectangular section steel by passing through a new set of rolls (Peng et al. 2014; Li et al. 2011). Therefore, it would be interesting to study this process and compare it with the one studied during this thesis. Figure 223(a) and Figure 223(b) show examples of flowers developed to obtain a generic rectangular section profile using the SRF and CRF processes, respectively;

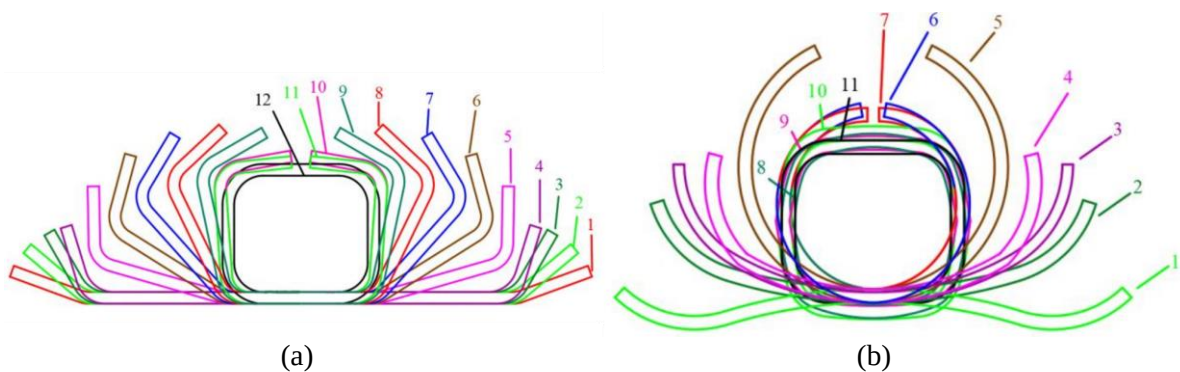


Figure 223 – (a) SRF process; (b) CRF process (F. Han et al. 2020).

- to study the roll forming of different profiles produced at Coproget. Furthermore, some flowers of profiles that will be produced in the future were developed during the internship and therefore it would be interesting to make a study about the forming of these new profiles;
- to experimentally test and validate on Coproget's roll forming line the modifications made to the simulated roll forming line, which allowed reductions in the values of springback, end flare and twist angles;
- perform experimental measurements on Coproget's roll forming line, in addition to those that have been carried out, as done in Ferreira (2016). For example, using load cells, to measure the forming force on the drive and operator-side stands, strain gauges mounted on the drive-side connecting rods, to measure the deflection of these components during forming, and dial indicators to measure the displacement of various machine components during forming to compare with the results obtained for the developed model with deformable shafts;
- to continue with the development of a new roll forming strategy initiated but not finalised during the internship in Coproget. This new strategy consists of a new roll forming line design in which the profile is roll formed symmetrically from the beginning to the end of the process. The forming steps are shown in Appendix J Figure J6 and the bending sequence is presented in Appendix J, Figure J7. One of the problems verified during the development of this new roll forming strategy occurred at station 8, since the bending radius of the profile bends increased significantly due to the high strength of the material used. As can be seen in Figure 224, bends 1 and 2 of the profile do not have enough support from the rolls at station 8 to be bent properly.

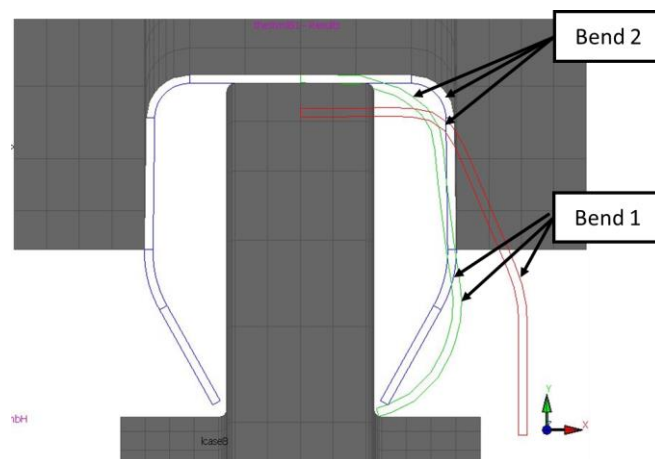


Figure 224 – New roll forming strategy.

These bending difficulties are mainly due to the impossibility of placing internal rolls on the bends that would allow a better adjustment of the bends to the top roll. An alternative studied and that could be implemented to improve the bending process would be the use of a static bar inside the profile in order to give more support in the internal bends, as represented in Figure 225.

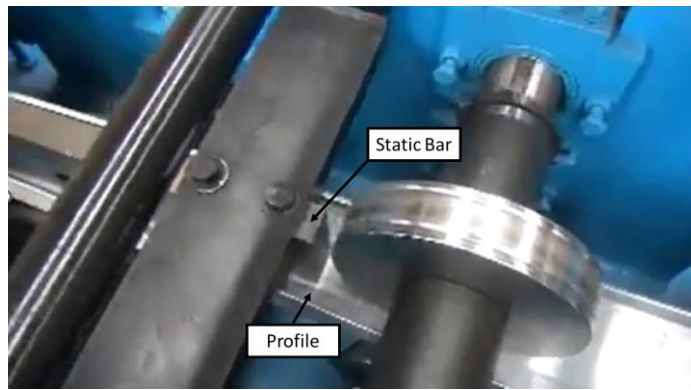


Figure 225 – Static bar inside the profile.

This strategy is widely used in the industry for lower strength materials such as aluminium. However, it is necessary to take into account that in the case of stronger materials such as the material under study during this thesis (Docol 1400 M), this process may involve a high amount of friction between the profile and the static bar and consequently lead to defects in the part. Furthermore, this process will lead to more heat generation due to the need for increased torque from the electric motors to drive the rolls. In addition, the profile in this new bending strategy presents an inverted position in relation to the one used in Coproget's roll forming process (rotated at 180°). However, this position generates a flow of lubricant that is unwanted by Coproget. The original position of the profile could be maintained, but after discussion with other company collaborators, it was concluded that the efficiency and functionality of the process could be compromised. Therefore, it would be interesting to study new solutions for a correct bending of the profile in a symmetrical way and taking into consideration the problems previously mentioned.

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APPENDIX A: Bending angles Measurements

Table 24 – Measurements of the bending angles β for the profile final angles calculation[°].

Cross-Section	Left		Right	
	Bend 1 (β_1)	Bend 2 (β_2)	Bend 3 (β_3)	Bend 4 (β_4)
1	89.0	96.0	96.0	89.0
2	88.0	95.5	94.5	88.0
3	88.0	94.0	94.0	87.5
4	88.0	94.5	94.5	88.5
5	88.0	95.5	94.0	90.5
6	88.0	97.0	95.0	93.0
Average	88.17	95.4	94.7	89.4

Table 25 – Measurements of the bending angles β for End Flare calculation [°].

Cross-Section	Left		Right	
	Bend 1 (β_1)	Bend 2 (β_2)	Bend 3 (β_3)	Bend 4 (β_4)
1 (Tail end)	89.0	101.5	99.5	91.5
2 (Middle)	86.0	95.0	93.5	88.0
3 (Lead end)	88.5	99.5	98.0	90.0
Average	87.8	98.7	97.0	89.8

Table 26 – Measurements of the angles α for End Flare calculation [°].

Cross-Section	Left		Right	
	Bend 1 (α_1)	Bend 2 (α_2)	Bend 3 (α_3)	Bend 4 (α_4)
1 (Tail end)	91.5	80.5	82.0	90.0
2 (Middle)	94.0	85.0	86.5	92.0
3 (Lead end)	91.0	78.5	80.5	88.5
Average	92.2	81.3	83.0	90.2

APPENDIX B: Material Properties

- SSAB Domex 500MC

Table 27 – Mechanical properties of SSAB Domex 500MC (SSAB 2022).

Steel Grade	Yield strength $R_{p0.2}$ (MPa)	Tensile strength R_m (MPa)	Elongation $A_{80mm}^{1)}$ Min (%)	Elongation $A_{5mm}^{2)}$ Min (%)	Min.inner bending radius for 90°
SSAB Domex 500MC	500	550-700	14	18	0.6 x t

¹⁾ A_{80} : value applies for thicknesses < 3.00 mm;

²⁾ A_5 : value applies for thicknesses $\geq$ 3.00 mm.

Table 28 – Chemical composition of SSAB Domex 500MC (SSAB 2022).

Steel Grade	C Max (%)	Si Max (%)	Mn Max (%)	P Max (%)	S Max (%)	Al Min (%)	Nb Max (%)	V Max (%)	Ti Max (%)
SSAB Domex 500MC	0.10	0.21 ¹⁾	1.60	0.025	0.010	0.015	0.09 ²⁾	0.20 ²⁾	0.15 ²⁾

¹⁾ If the material is to be hot dip galvanized, this must be specified in the order;

²⁾ The sum of Nb, V and Ti is max 0.22%.

APPENDIX C: Material Docol 1400M vs MartenSite 1500M vs Domex 500MC

- Residual stresses across the width**

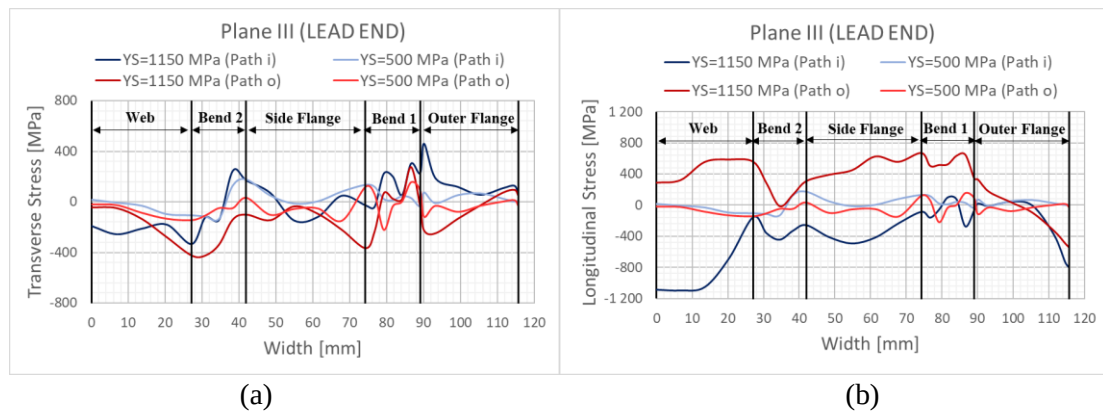


Figure 226 – (a) Transverse residual stresses across the width in plane III (lead end) for the models with YS=1150 MPa and YS=500MPa; (b) Longitudinal residual stresses across the width in plane III(lead end) for the models with YS=1150 MPa and YS=500MPa.

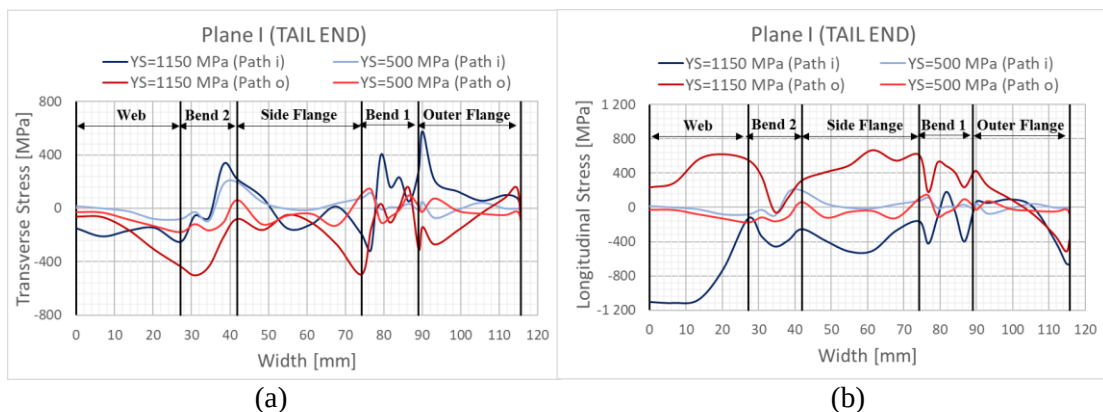


Figure 227 – (a) Transverse residual stresses across the width in plane I (tail end) for the models with YS=1150 MPa and YS=500MPa; (b) Longitudinal residual stresses across the width in plane I (tail end) for the models with YS=1150 MPa and YS=500MPa.

- Residual stresses through the thickness**

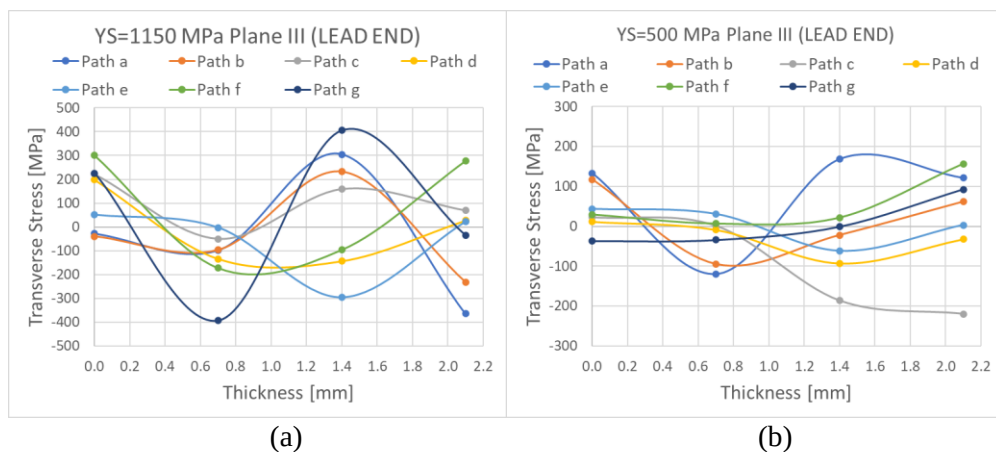


Figure 228 – (a) Transverse residual stresses across the thickness in plane III for the model with YS=1500MPa (reference model); (b) Transverse residual stresses across the thickness in plane III for the model with YS=500MPa.

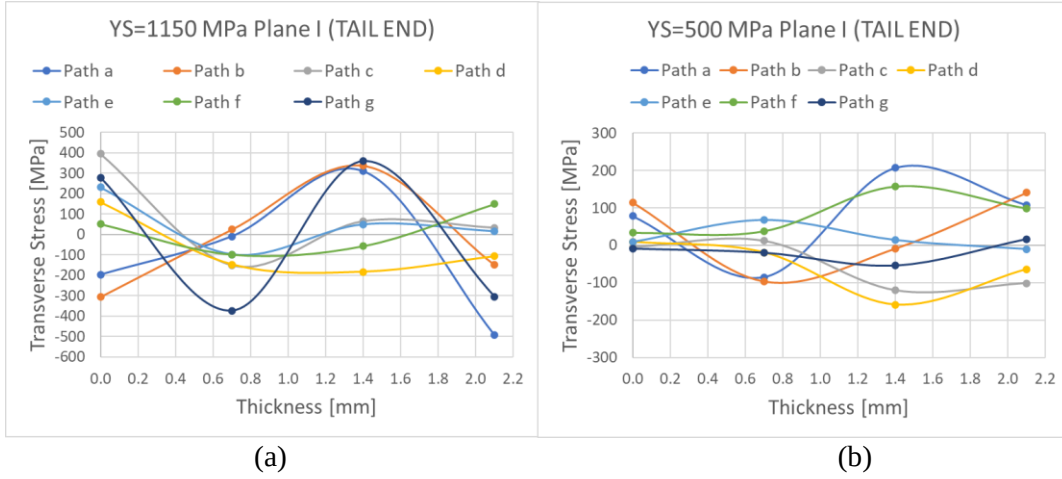


Figure 229 – (a) Transverse residual stresses across the thickness in plane I for the model with YS=1500MPa (reference model); (b) Transverse residual stresses across the thickness in plane I for the model with YS=500MPa.

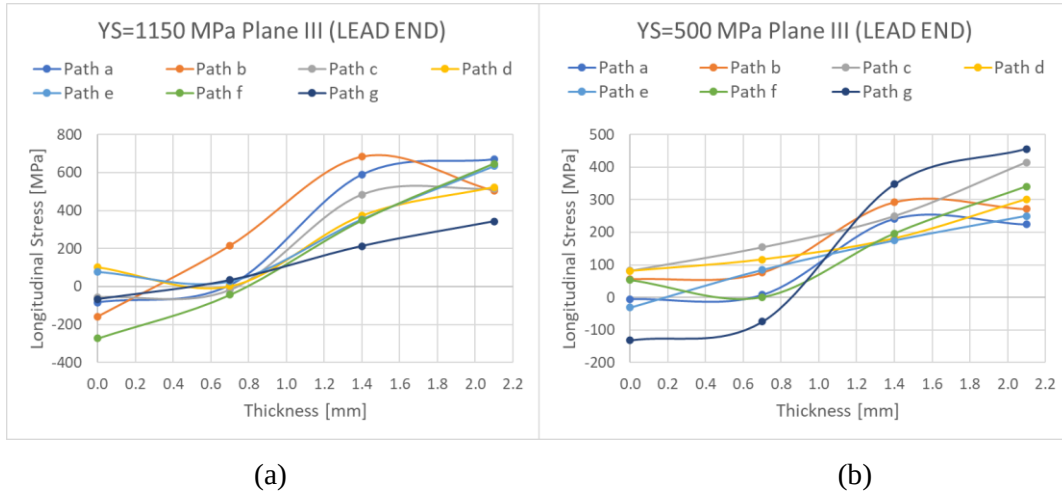


Figure 230 – (a) Longitudinal residual stresses across the thickness in plane III for the model with YS=1500MPa (reference model); (b) Longitudinal residual stresses across the thickness in plane III for the model with YS=500MPa.

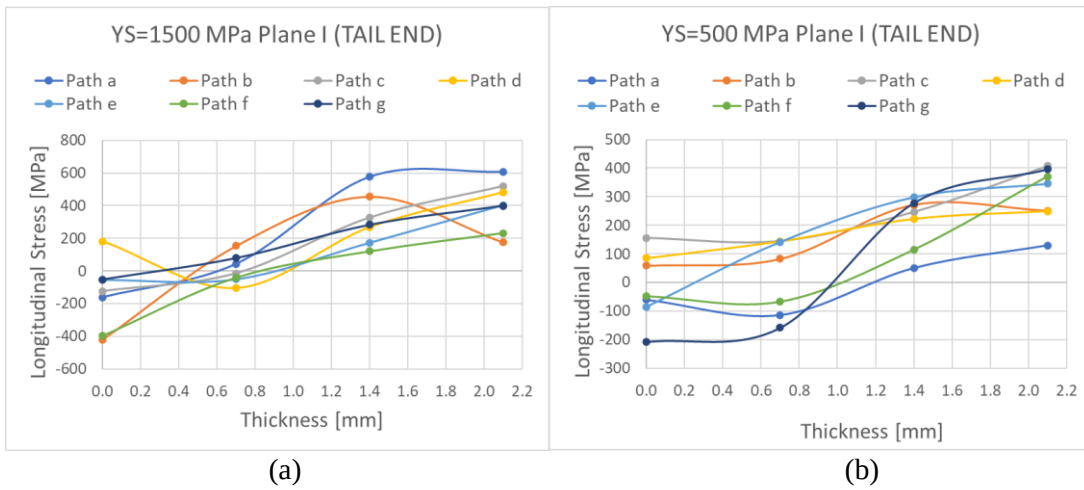


Figure 231 – (a) Longitudinal residual stresses across the thickness in plane I for the model with YS=1500MPa (reference model); (b) Longitudinal residual stresses across the thickness in plane I for the model with YS=500MPa.

APPENDIX D: 10 stations VS 13 Stations

- Residual stresses across the width**

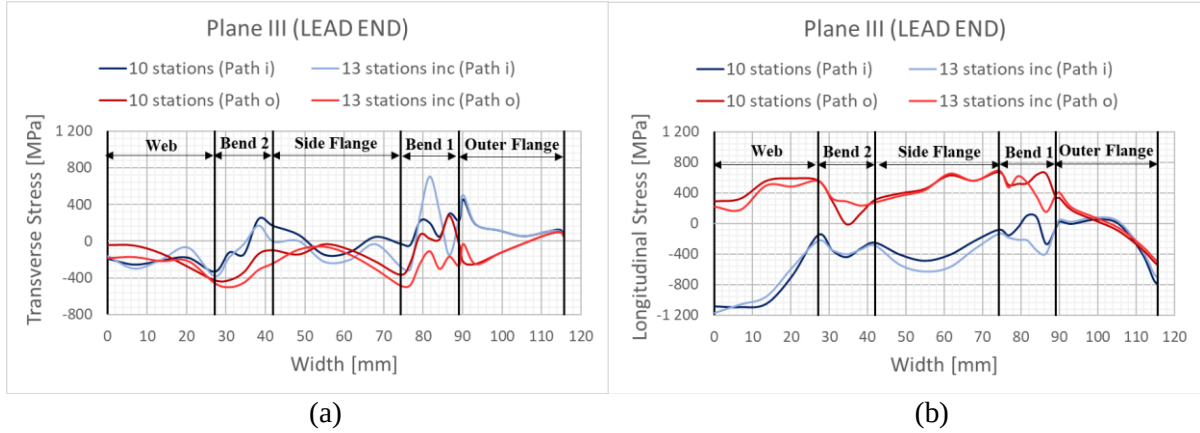


Figure 232 – (a) Transverse residual stresses across the width in plane III (lead end) for the models with 10 stations and 13 stations incremented; (b) Longitudinal residual stresses across the width in plane III (lead end) for the models with 10 stations and 13 stations incremented.

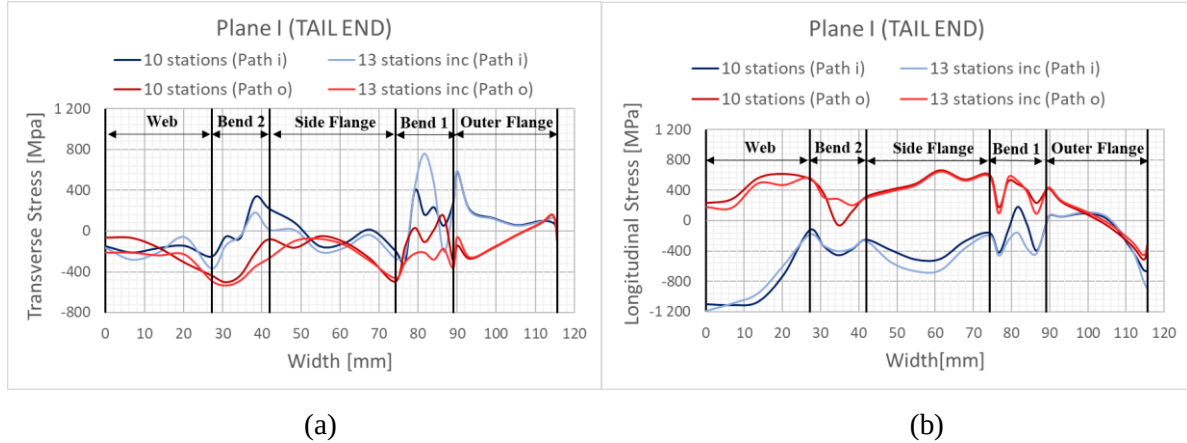


Figure 233 – (a) Transverse residual stresses across the width in plane I (tail end) for the models with 10 stations and 13 stations incremented; (b) Longitudinal residual stresses across the width in plane I (tail end) for the models with 10 stations and 13 stations incremented.

- Residual stresses through the thickness**

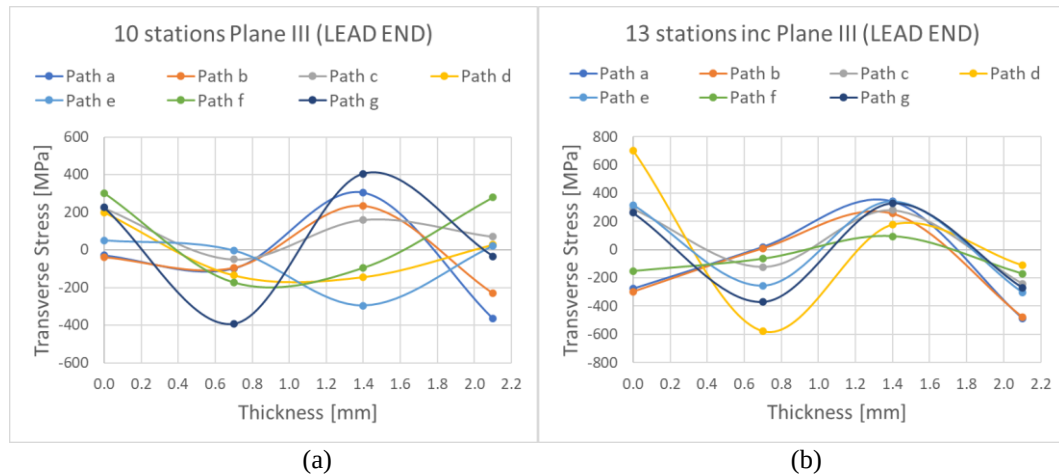


Figure 234 – (a) Transverse residual stresses across the thickness in plane III, for the model with 10 stations (reference); (b) Transverse residual stresses across the thickness in plane III for the model with 13 stations incremented.

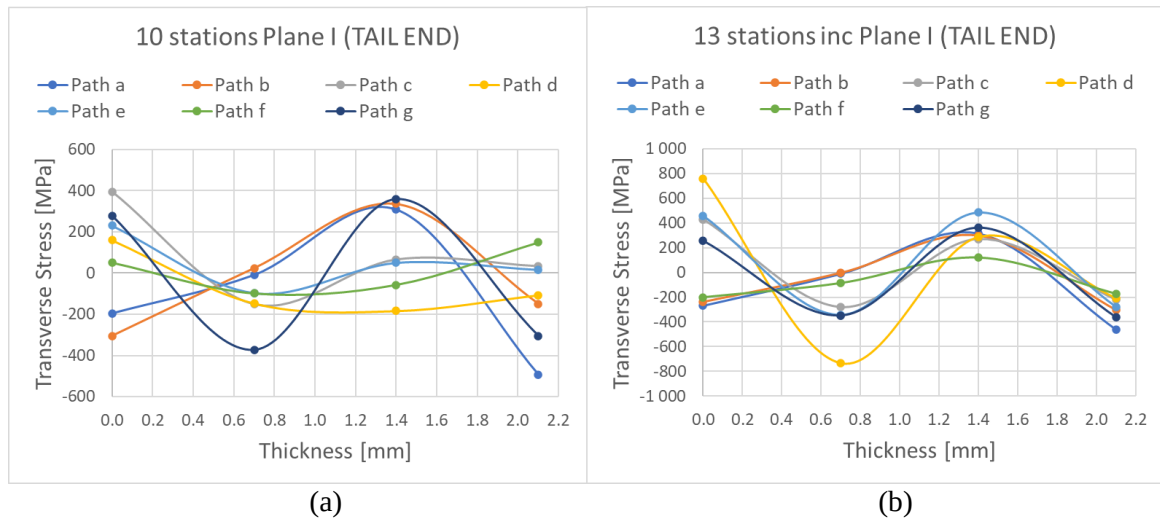


Figure 235 – (a) Transverse residual stresses across the thickness in plane I, for the model with 10 stations (reference); (b) Transverse residual stresses across the thickness in plane I for the model with 13 stations incremented.

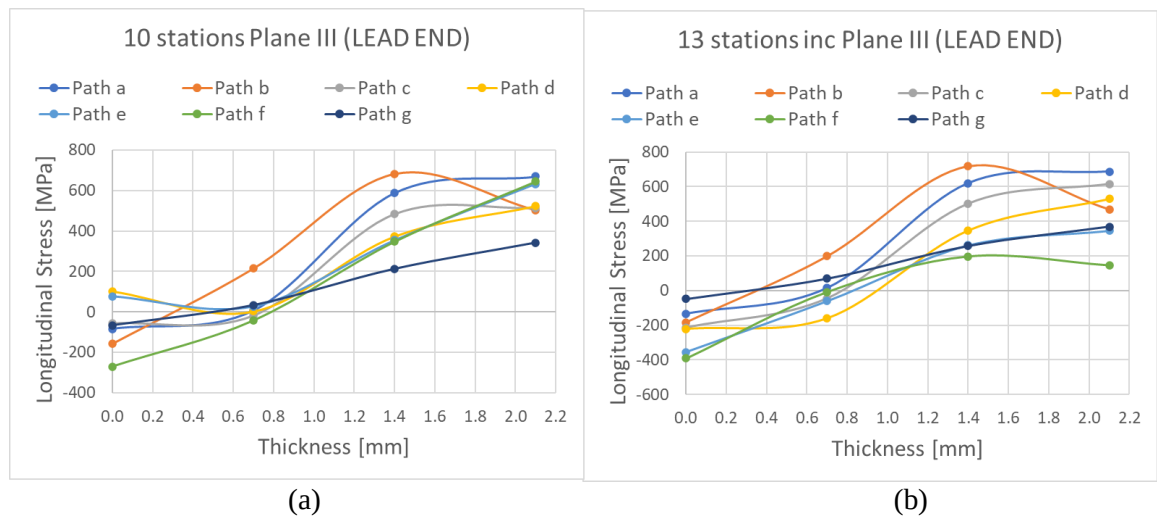


Figure 236 – (a) Longitudinal residual stresses across the thickness in plane III for the model with 10 stations (reference model); (b) Longitudinal residual stresses across the thickness in plane III for the model with 13 stations incremented.

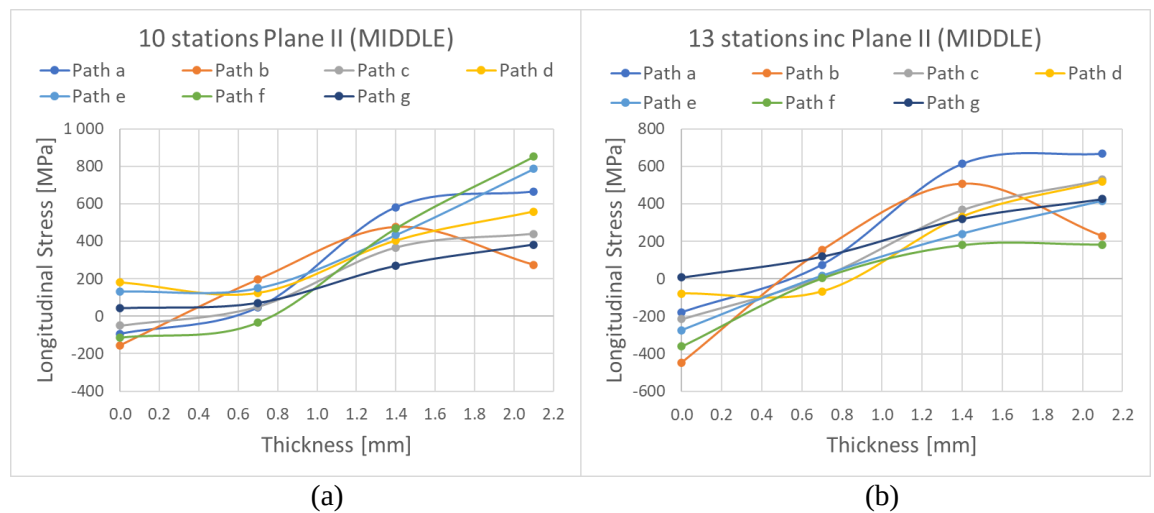


Figure 237 – (a) Longitudinal residual stresses across the thickness in plane II for the model with 10 stations (reference model); (b) Longitudinal residual stresses across the thickness in plane II for the model with 13 stations incremented.

APPENDIX E: Radius/Thickness=4 vs Radius/Thickness=8

- Residual stresses across the width

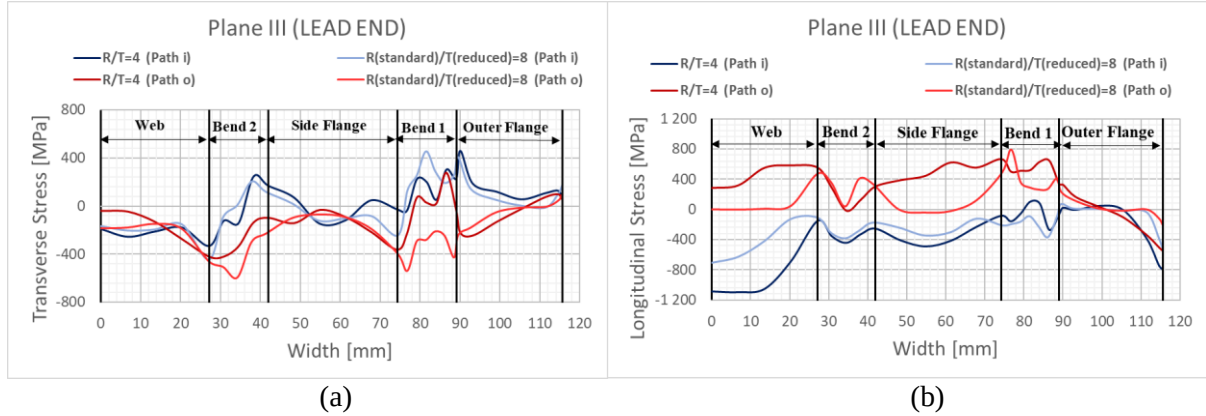


Figure 238 – (a) Transverse residual stresses across the width in plane III (lead end) for the reference model ($R/T=4$) and for the model with thickness reduction ($R(\text{standard})/T(\text{reduced})=8$); (b) Longitudinal residual stresses across the width in plane III (lead end) for the reference model ($R/T=4$) and for the model with thickness reduction ($R(\text{standard})/T(\text{reduced})=8$).

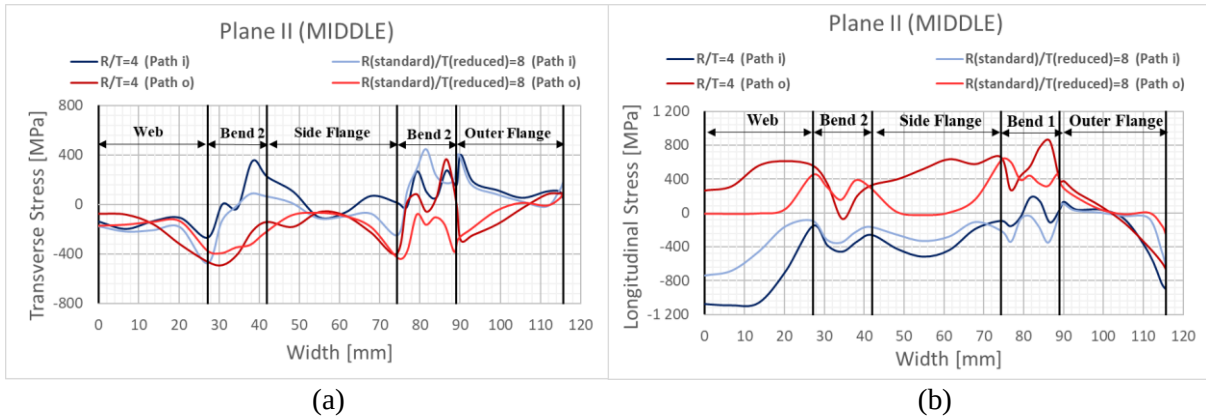


Figure 239 – (a) Transverse residual stresses across the width in plane II (middle) for the reference model ($R/T=4$) and for the model with thickness reduction ($R(\text{standard})/T(\text{reduced})=8$); (b) Longitudinal residual stresses across the width in plane II (middle) for the reference model ($R/T=4$) and for the model with thickness reduction ($R(\text{standard})/T(\text{reduced})=8$).

- Residual stresses through the thickness

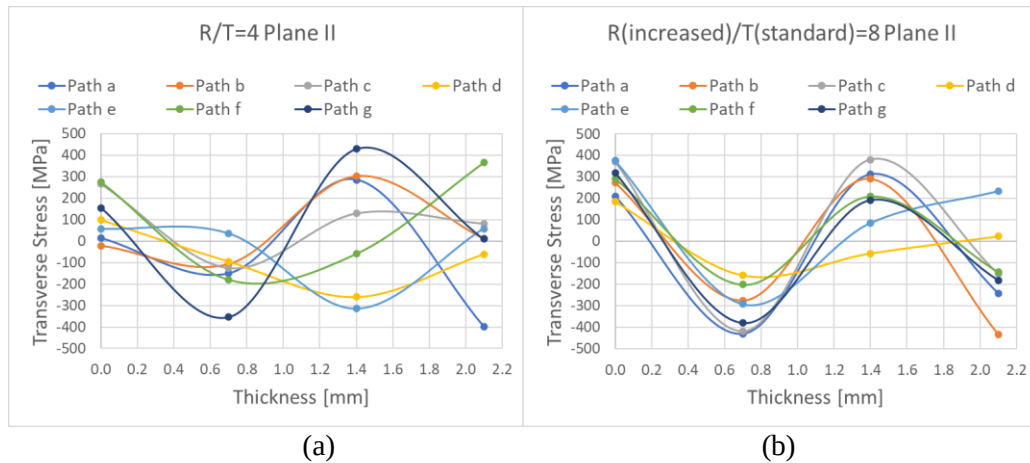


Figure 240 – (a) Transverse residual stresses across the thickness in plane II, for the model with $R/T=4$ (reference model); (b) Transverse residual stresses across the thickness in plane II, for the model with increase of the internal bending radius to double ($R(\text{increased})/T(\text{standard})=8$).

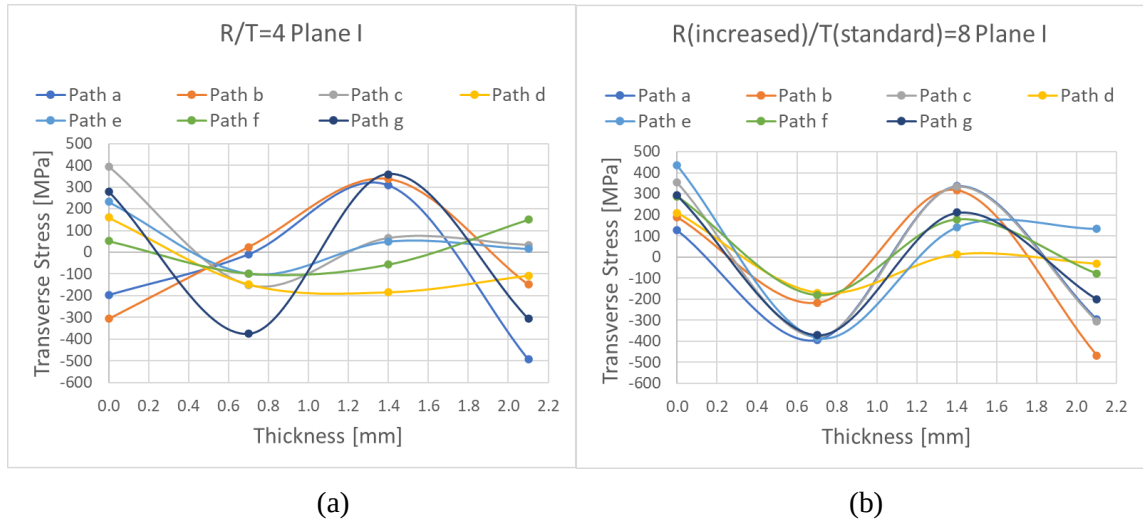


Figure 241 – (a) Transverse residual stresses across the thickness in plane I, for the model with $R/T=4$ (reference model); (b) Transverse residual stresses across the thickness in plane I, for the model with increase of the internal bending radius to double ($R(\text{increased})/T(\text{standard})=8$).

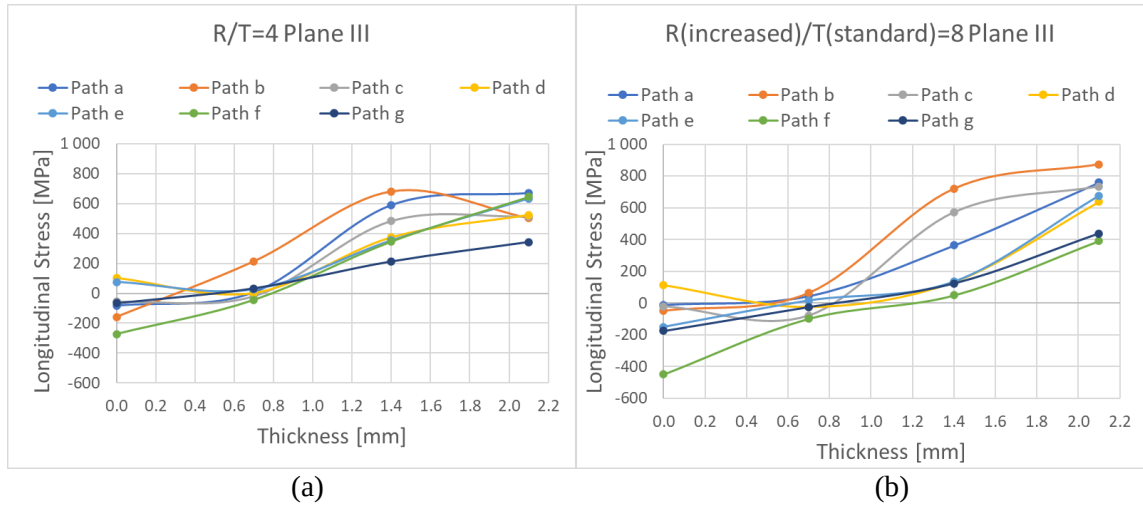


Figure 242 – (a) Longitudinal residual stresses across the thickness for the model with $R/T=4$ (reference model), considering plane III (lead end); (b) Longitudinal residual stresses across the thickness for the model with ($R(\text{increased})/T(\text{standard})=8$), considering plane III (lead end).

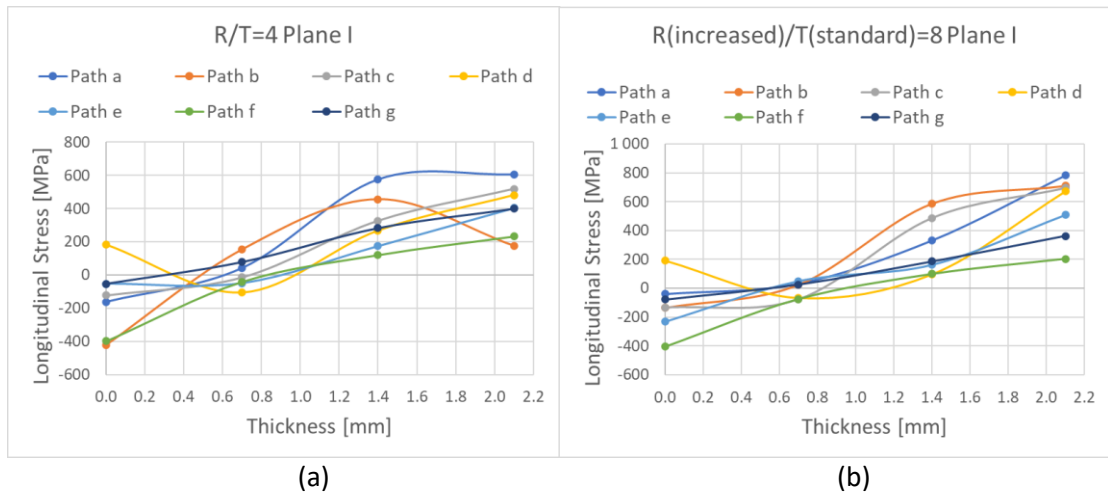


Figure 243 – (a) Longitudinal residual stresses across the thickness for the model with $R/T=4$ (reference model), considering plane I (tail end); (b) Longitudinal residual stresses across the thickness for the model with ($R(\text{increased})/T(\text{standard})=8$), considering plane I (tail end).

APPENDIX F: Standard roll diameter vs Increases roll diameter

- Residual stresses across the width**

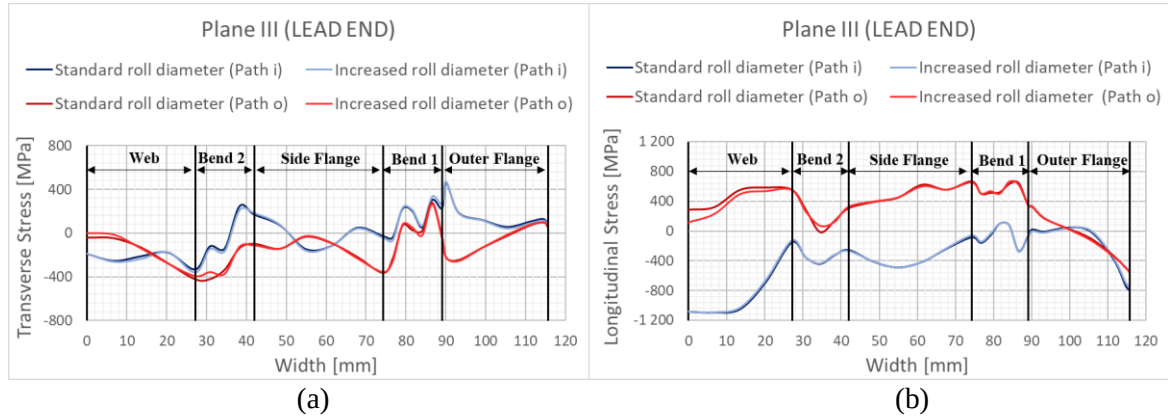


Figure 244 – (a) Transverse residual stresses across the width in plane III (lead end) for the reference model (standard roll diameter) and for the model with increased roll diameter; (b) Longitudinal residual stresses across the width in plane II (lead end) for the reference model (standard roll diameter) and for the model with increased roll diameter.

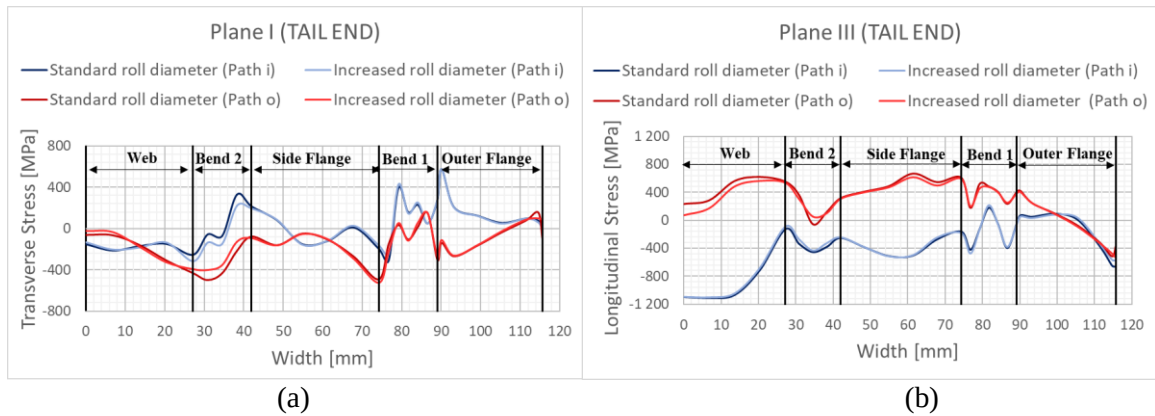


Figure 245– (a) Transverse residual stresses across the width in plane I (tail end) for the reference model (standard roll diameter) and for the model with increased roll diameter; (b) Longitudinal residual stresses across the width in plane I (tail end) for the reference model (standard roll diameter) and for the model with increased roll diameter.

- Residual stresses through the thickness**

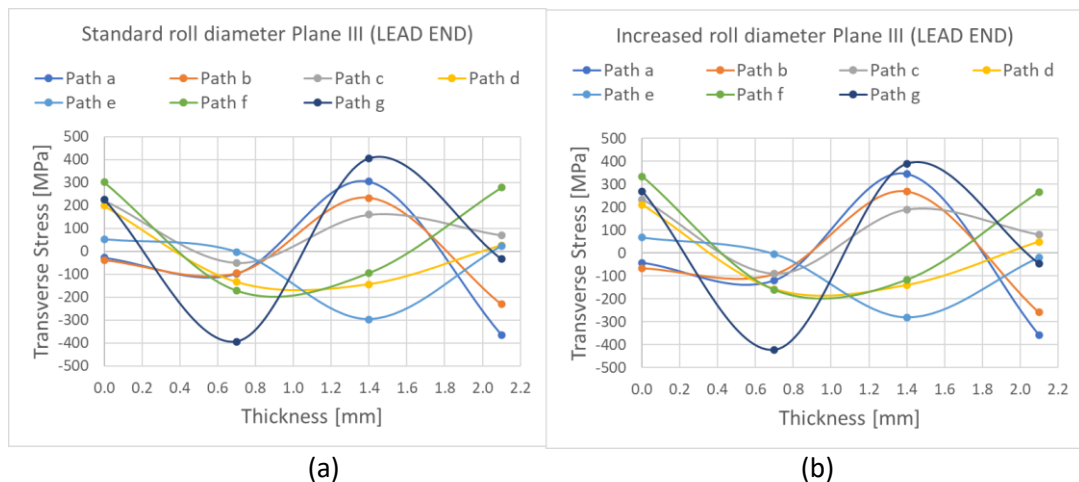


Figure 246 – (a) Transverse residual stresses across the thickness in plane III (lead end), for the model with standard roll diameter (reference model); (b) Transverse residual stresses across the thickness in plane III (lead end), for the model with increased roll diameter.

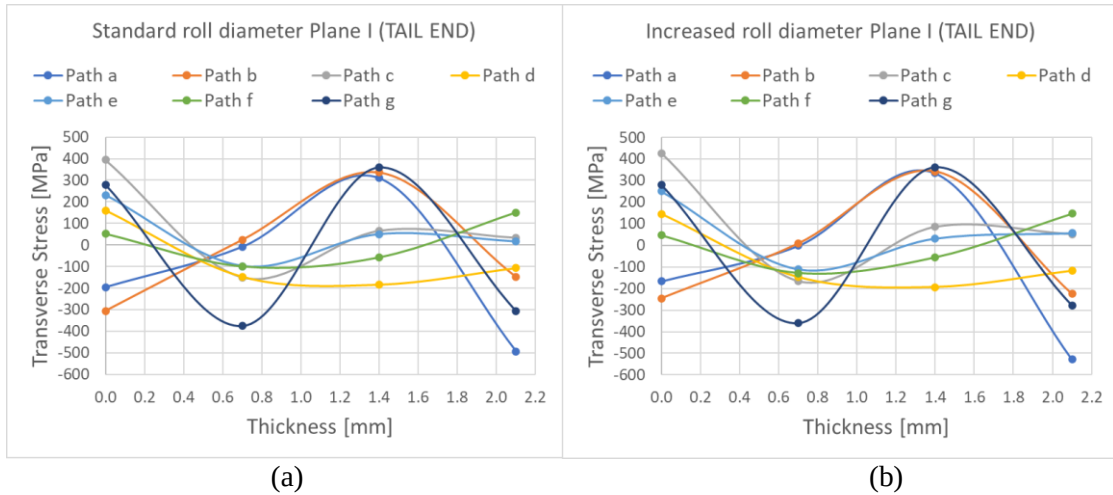


Figure 247 – (a) Transverse residual stresses across the thickness in plane I (tail end), for the model with standard roll diameter (reference model); (b) Transverse residual stresses across the thickness in plane I (tail end), for the model with increased roll diameter.

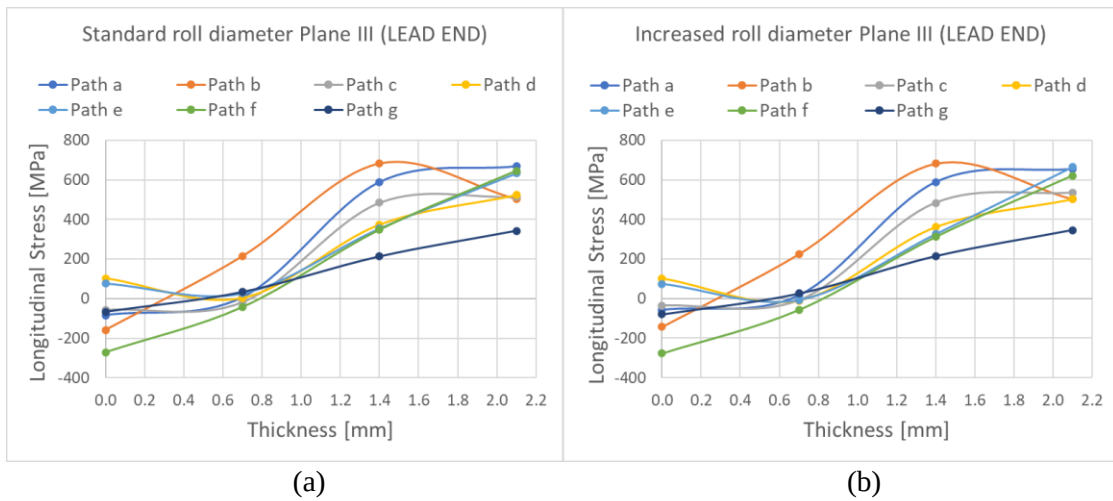


Figure 248 – (a) Longitudinal residual stresses across the thickness for the model with standard roll diameter (reference model), considering plane III (lead end); (b) Longitudinal residual stresses across the thickness for the model with increased roll diameter, considering plane III (lead end).

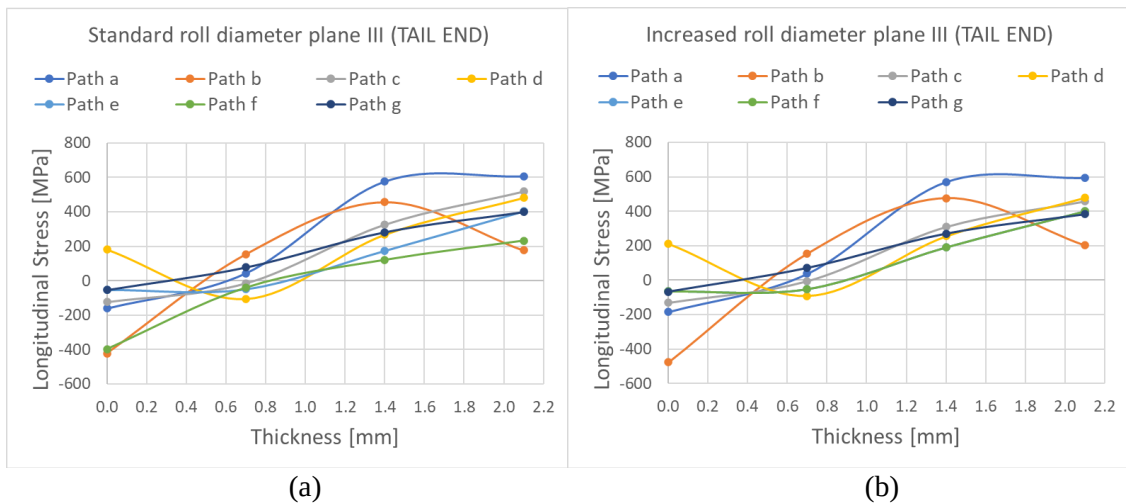


Figure 249 – (a) Longitudinal residual stresses across the thickness for the model with standard roll diameter (reference model), considering plane I (tail end); (b) Longitudinal residual stresses across the thickness for the model with increased roll diameter, considering plane I (tail end).

APPENDIX G: No friction vs friction

- Residual stresses across the width

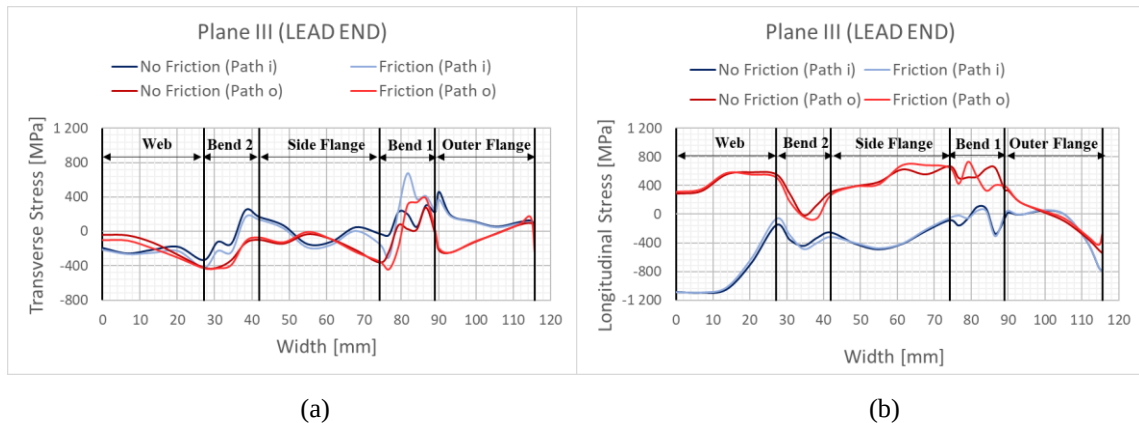


Figure 250 – (a) Transverse residual stresses across the width in plane III (lead end) for the reference model (no friction) and for the model with friction; (b) Longitudinal residual stresses across the width in plane III (lead end) for the reference model (no friction) and for the model with friction.

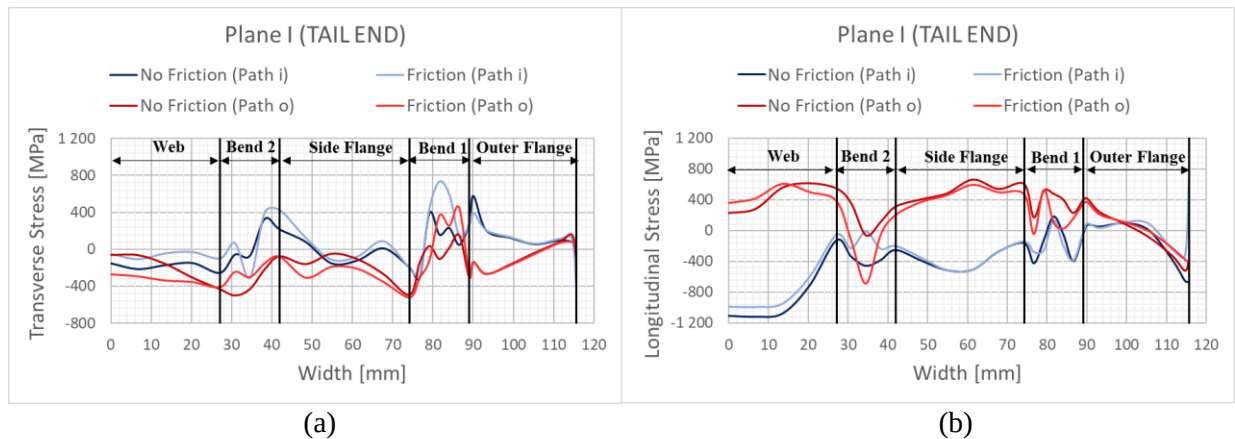


Figure 251– (a) Transverse residual stresses across the width in plane I (tail end) for the reference model (no friction) and for the model with friction; (b) Longitudinal residual stresses across the width in plane I (tail end) for the reference model (no friction) and for the model with friction.

- Residual stresses through the thickness

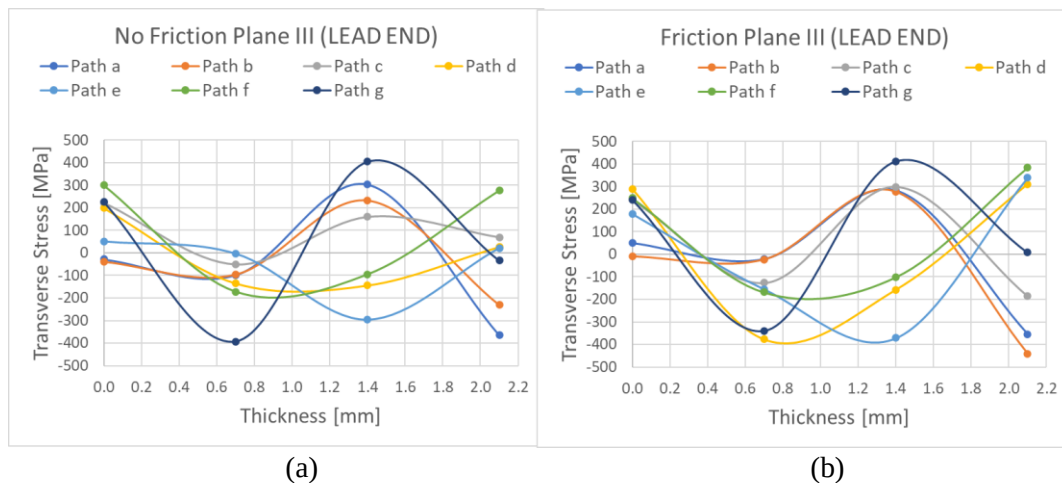


Figure 252 – (a) Transverse residual stresses across the thickness in plane III (lead end), for the model without friction (reference model); (b) Transverse residual stresses across the thickness in plane III (lead end), for the model with friction.

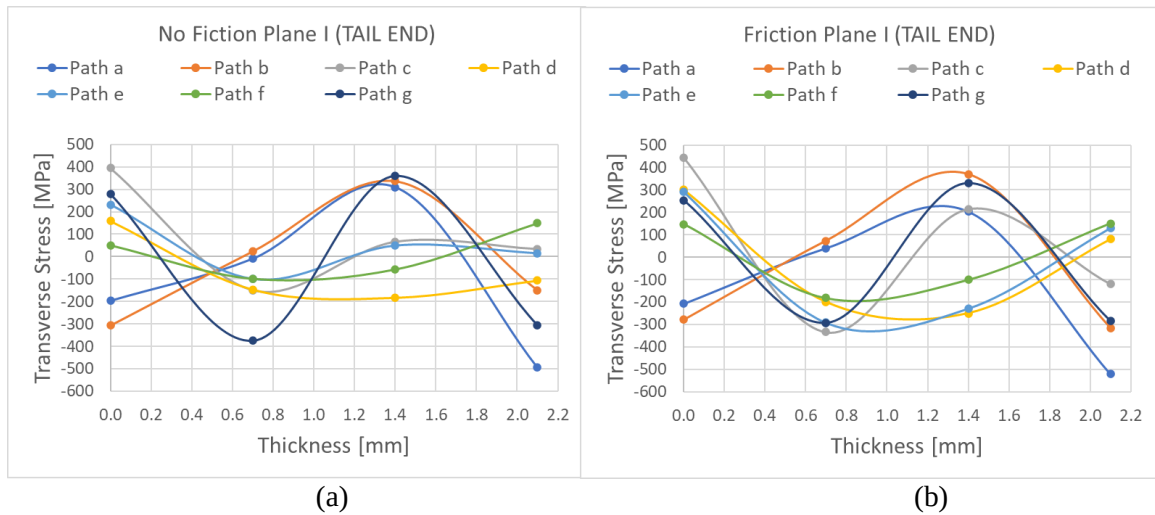


Figure 253 – (a) Transverse residual stresses across the thickness in plane I (tail end), for the model without friction (reference model); (b) Transverse residual stresses across the thickness in plane I (tail end), for the model with friction.

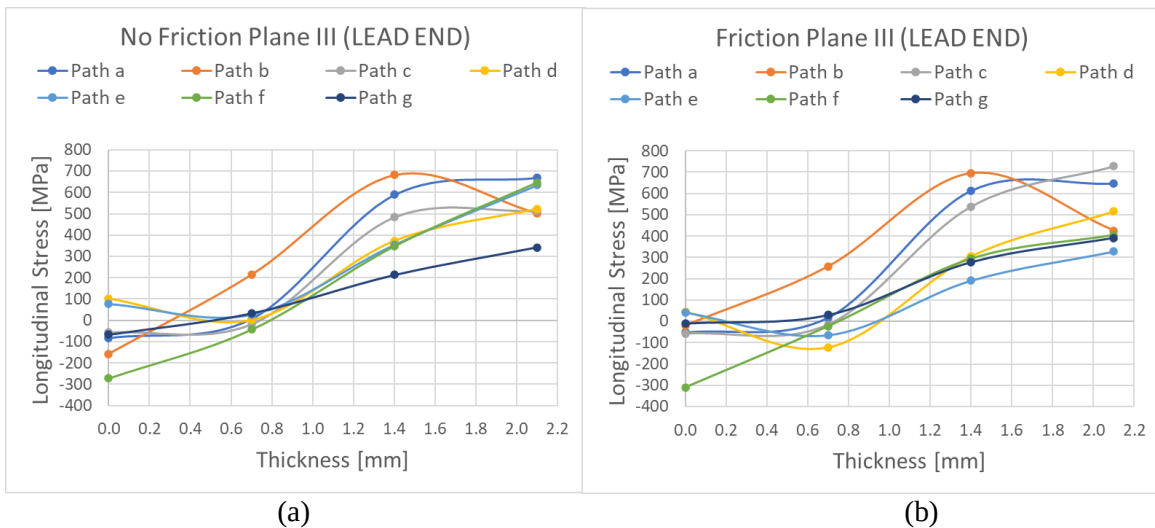


Figure 254 – (a) Longitudinal residual stresses across the thickness for the model without friction (reference model), considering plane III (lead end); (b) Longitudinal residual stresses across the thickness for the model with friction, considering plane III (lead end).

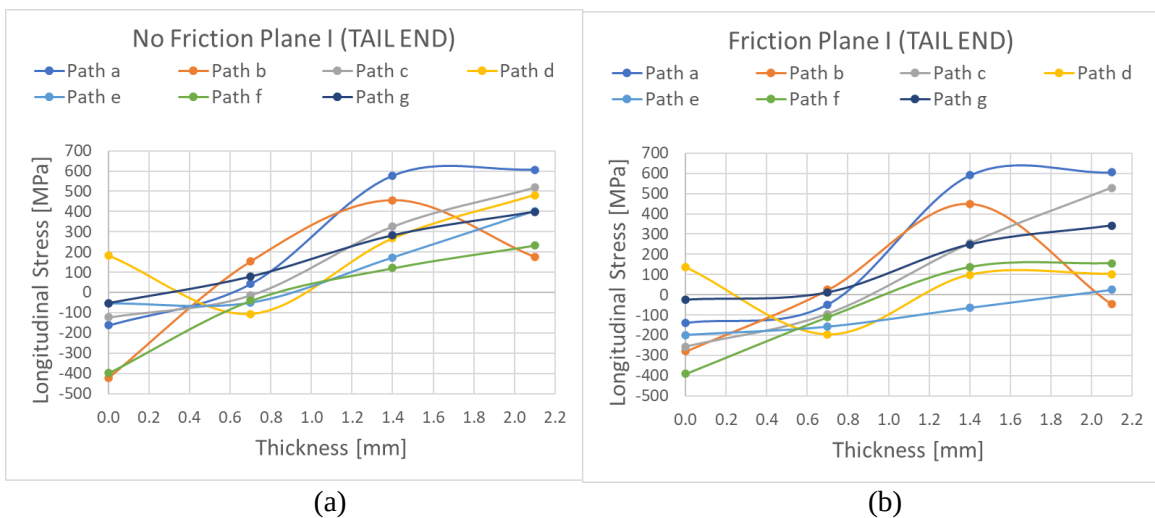


Figure 255– (a) Longitudinal residual stresses across the thickness for the model without friction (reference model), considering plane I (tail end); (b) Longitudinal residual stresses across the thickness for the model with friction, considering plane I (tail end).

APPENDIX H: Pre-cut vs Final cut

- Residual stresses across the width**

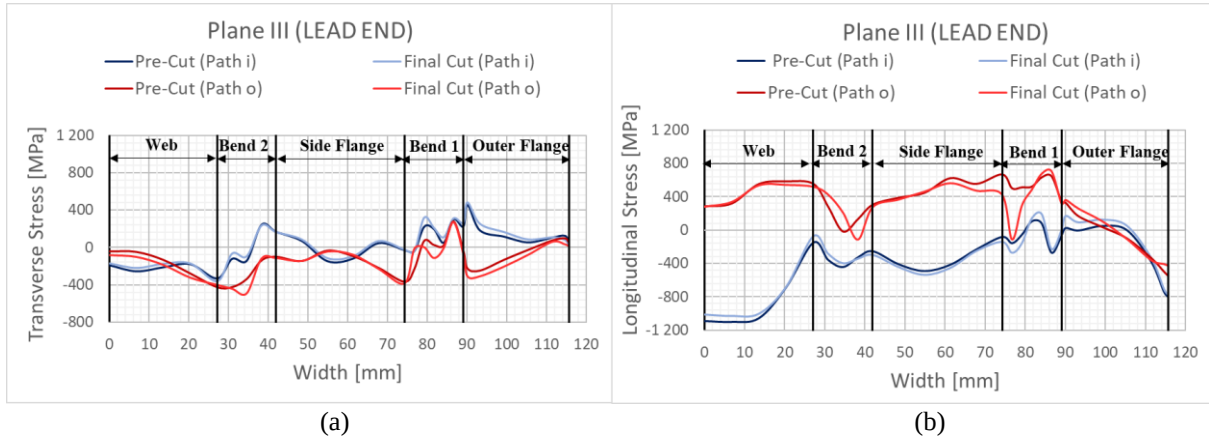


Figure 256 – (a) Transverse residual stresses across the width in plane III (lead end) for the reference model (pre-cut) and for the model with final cut; (b) Longitudinal residual stresses across the width in plane III (lead end) for the reference model (pre-cut) and for the model with final cut.

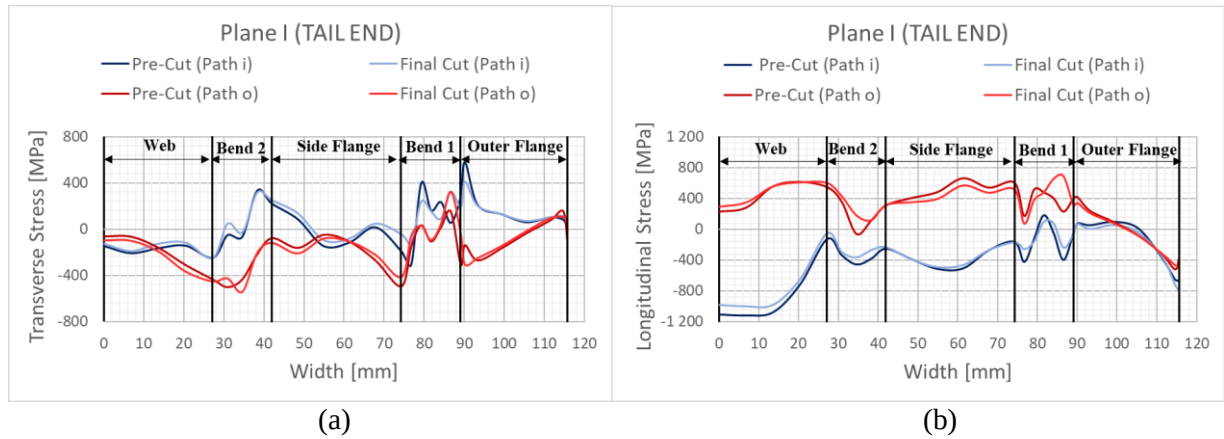


Figure 257 – (a) Transverse residual stresses across the width in plane I (tail end) for the reference model (pre-cut) and for the model with final cut; (b) Longitudinal residual stresses across the width in plane I (tail end) for the reference model (pre-cut) and for the model with final cut.

- Residual stresses through the thickness**

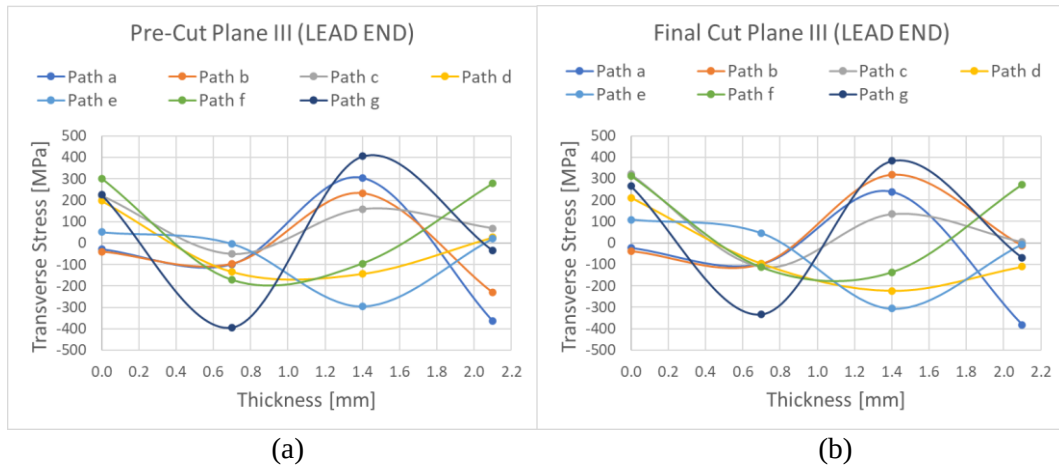


Figure 258 – (a) Transverse residual stresses across the thickness in plane III (lead end), for the pre-cut model (reference model); (b) Transverse residual stresses across the thickness in plane III (lead end), for the final cut model.

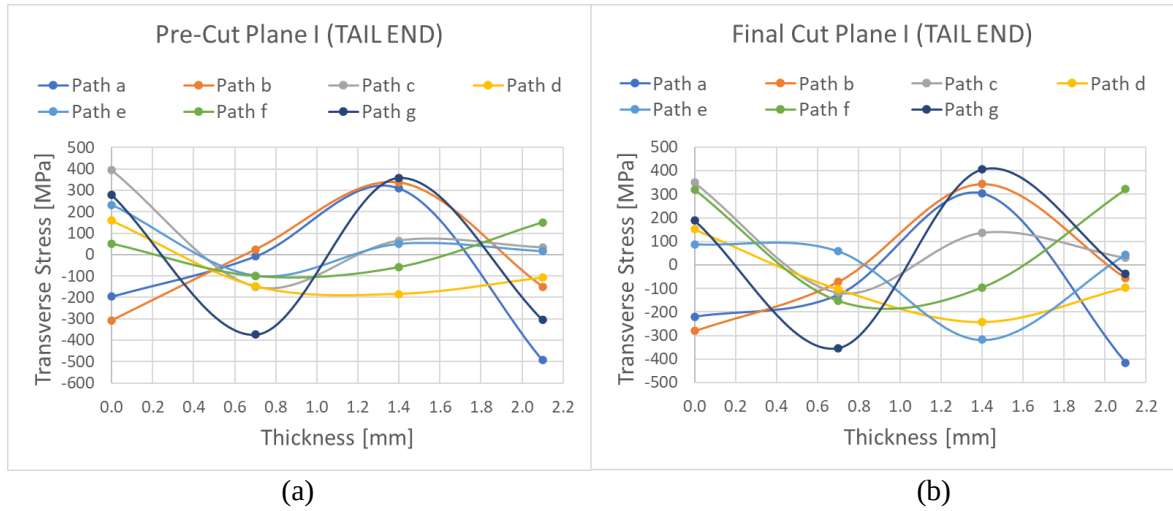


Figure 259 – (a) Transverse residual stresses across the thickness in plane I (tail end), for the pre-cut model (reference model); (b) Transverse residual stresses across the thickness in plane III (tail end), for the final cut model.

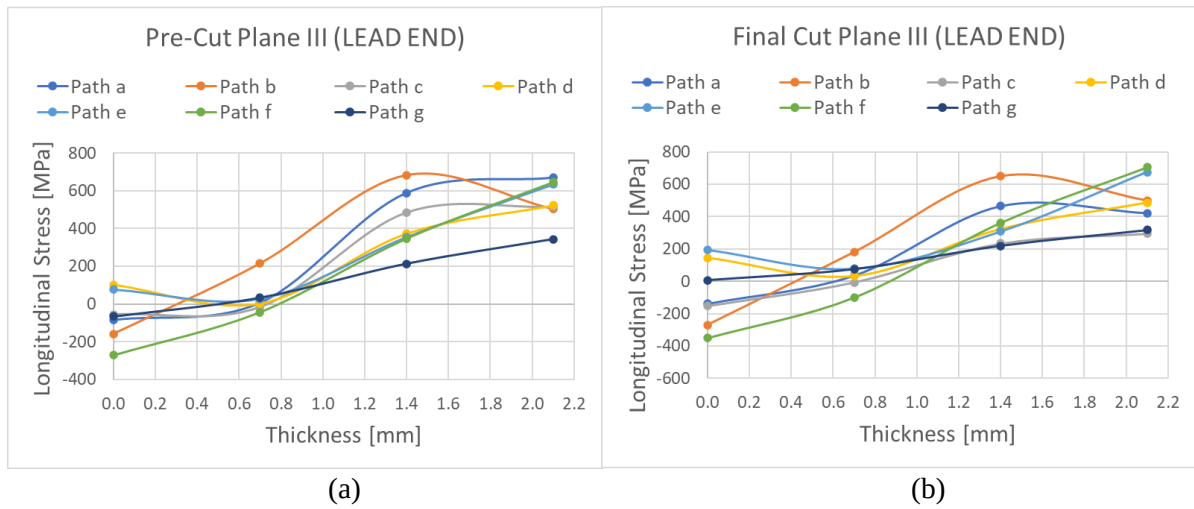


Figure 260 – (a) Longitudinal residual stresses across the thickness for the pre-cut model (reference model), considering plane III (lead end); (b) Longitudinal residual stresses across the thickness for the final cut model, considering plane III (lead end).

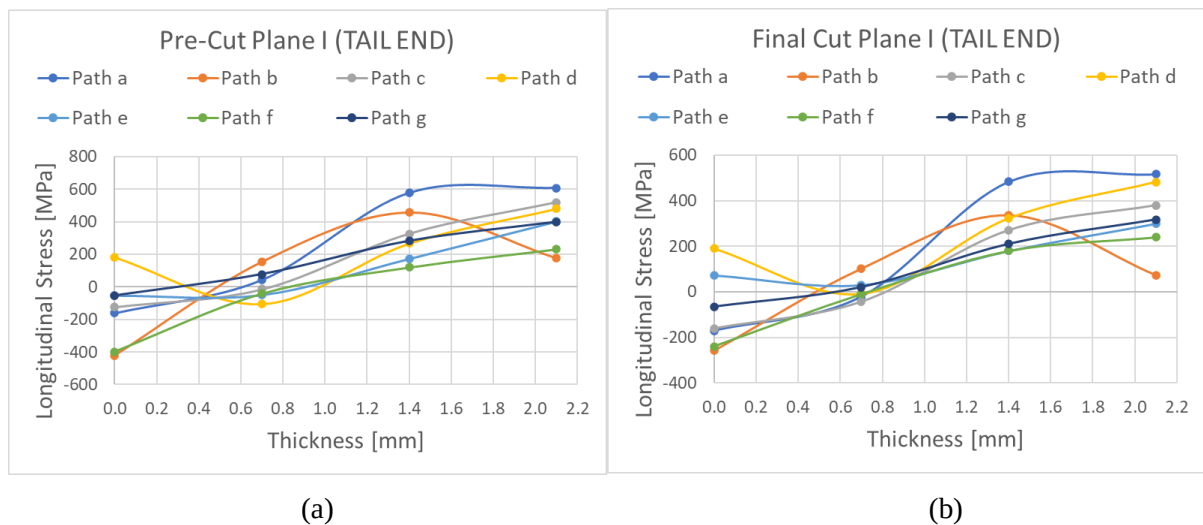


Figure 261 – (a) Longitudinal residual stresses across the thickness for the pre-cut model (reference model), considering plane I (tail end); (b) Longitudinal residual stresses across the thickness for the final cut model, considering plane I (tail end).

APPENDIX I: Rigid Shafts vs Deformable Shafts

- Residual stresses across the width

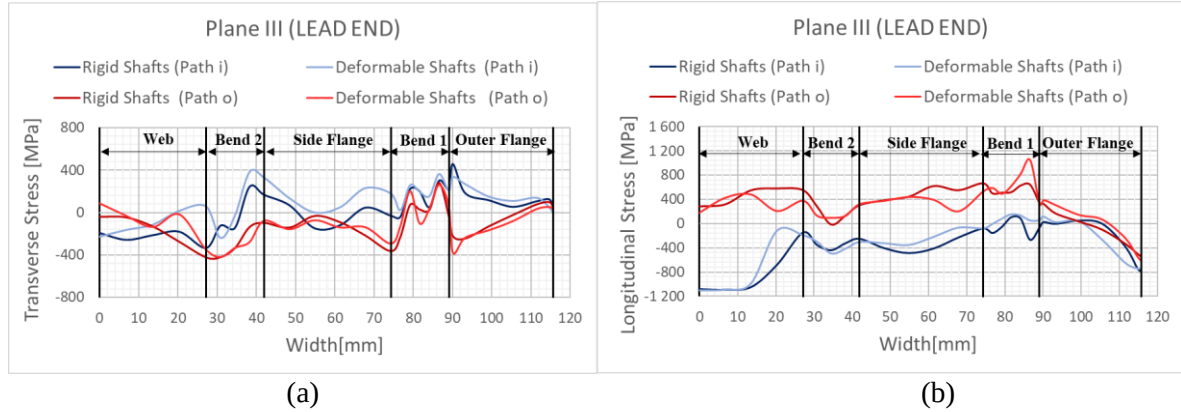


Figure 262 – (a) Transverse residual stresses across the width in plane III (lead end) for the reference model (with rigid shafts) and for the model with deformable shafts; (b) Longitudinal residual stresses across the width in plane III (lead end) for the reference model (with rigid shafts) and for the model with deformable shafts.

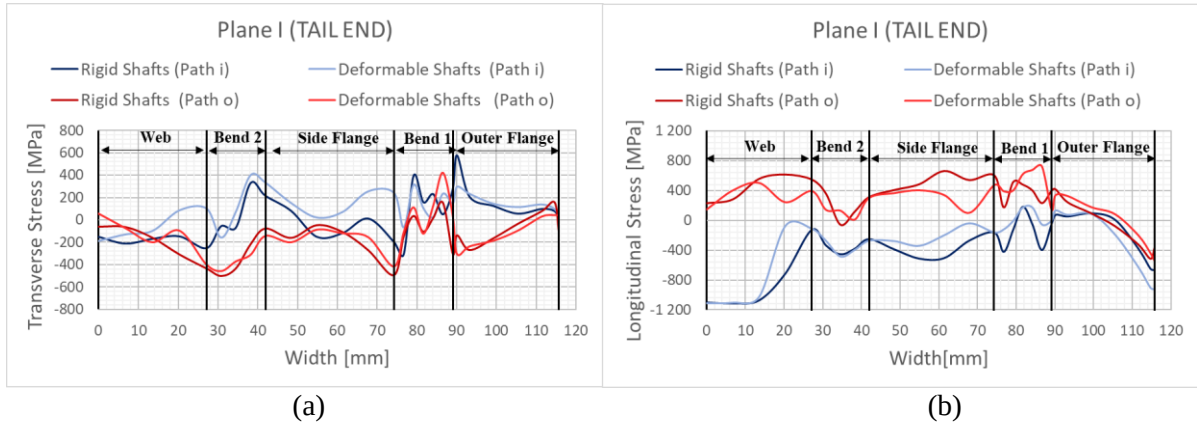


Figure 263– (a) Transverse residual stresses across the width in plane I (tail end) for the reference model (with rigid shafts) and for the model with deformable shafts; (b) Longitudinal residual stresses across the width in plane I (tail end) for the reference model (with rigid shafts) and for the model with deformable shafts.

- Residual stresses through the thickness

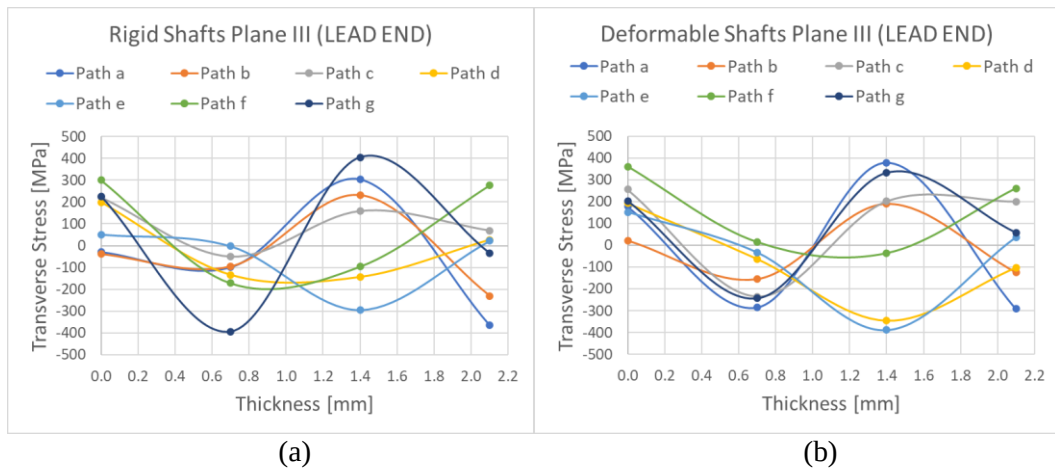


Figure 264 – (a) Transverse residual stresses across the thickness in plane III (lead end), for the model with rigid shafts (reference model); (b) Transverse residual stresses across the thickness in plane III (lead end), for the model with deformable shafts.

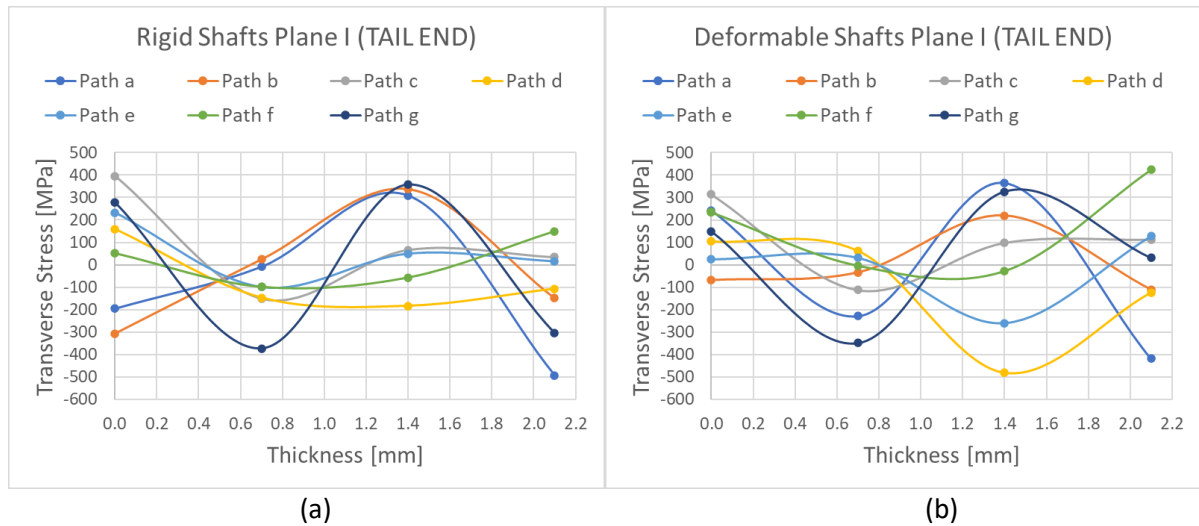


Figure 265 – (a) Transverse residual stresses across the thickness in plane I (tail end), for the model with rigid shafts (reference model); (b) Transverse residual stresses across the thickness in plane I (tail end), for the model with deformable shafts.

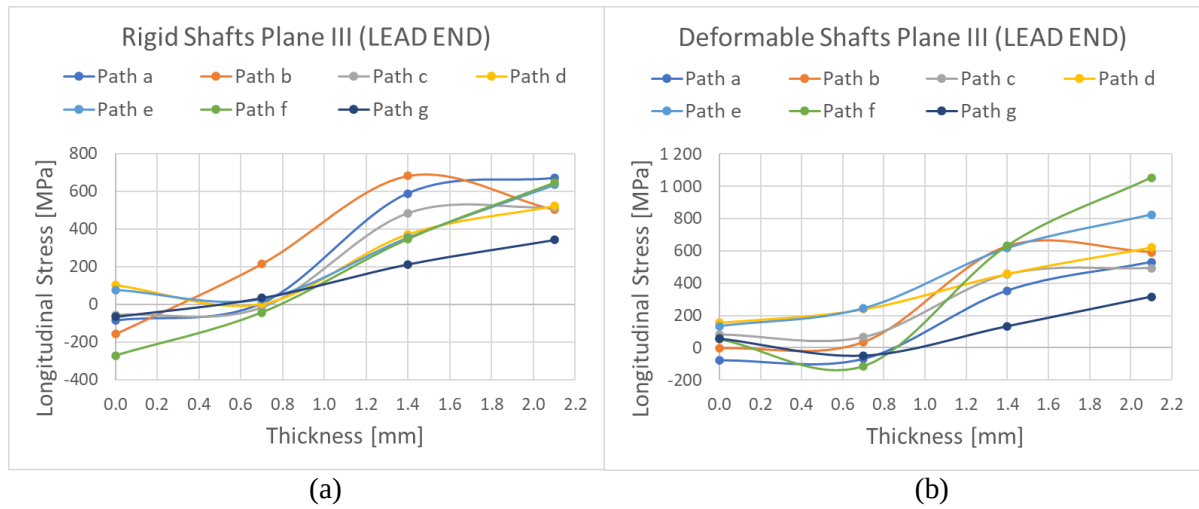


Figure 266 – (a) Longitudinal residual stresses across the thickness for the model with rigid shafts (reference model), considering plane III (lead end); (b) Longitudinal residual stresses across the thickness for the model with deformable shafts, considering plane III (lead end).

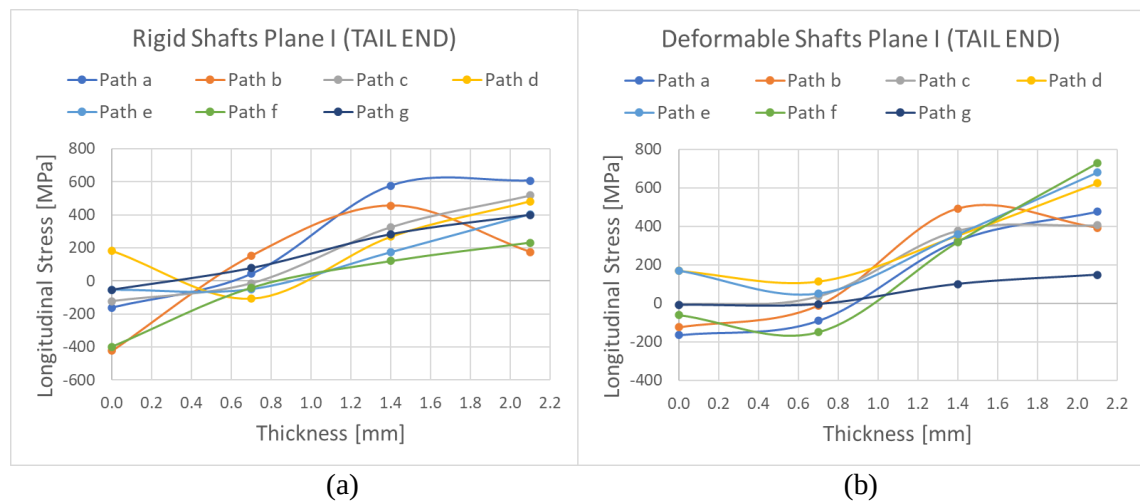


Figure 267 – (a) Longitudinal residual stresses across the thickness for the model with rigid shafts (reference model), considering plane I (tail end); (b) Longitudinal residual stresses across the thickness for the model with deformable shafts, considering plane I (tail end).

APPENDIX J: Bending Sequences

- **Coproget's Roll Forming Line with 16 stations**

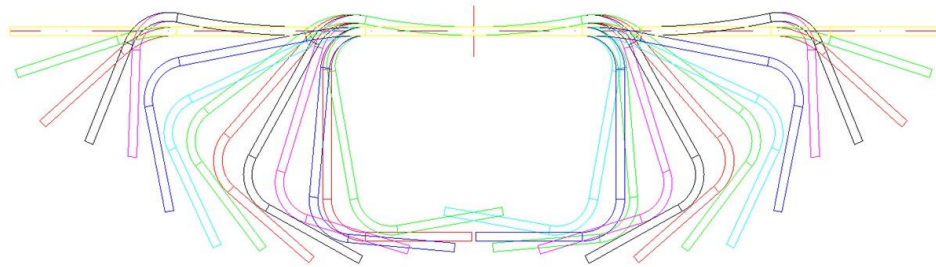


Figure 268 – Flower pattern of Coproget's roll forming line with 16 stations.

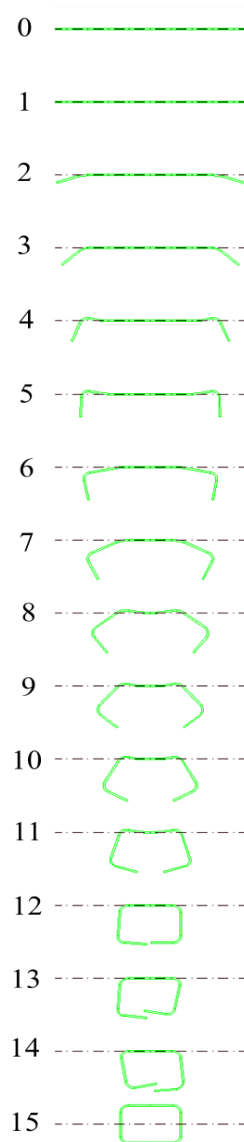


Figure 269 – Forming steps of Coproget's roll forming line with 16 stations.

- **Coproget's Roll Forming Line with 25 stations**

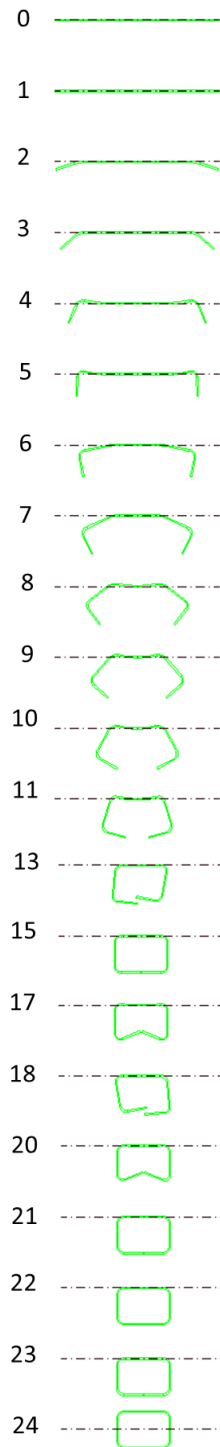


Figure 270– Forming steps of Coproget's roll forming line with 25 stations.

- **Model with 13 incremental stations**

	s = 2.10000		2. Entity	4. Entity	5. Entity	6. Entity	7. Entity	9. Entity
OK	Stripwidth		Angle	Angle	Angle	Angle	Angle	Angle
Profile	231.38620		90.00000	61.00000	12.00000	12.00000	61.00000	90.00000
				@ -6.00000			@ -6.00000	
11. Formingstation	231.38620		90.00000	55.00000	12.00000	12.00000	55.00000	90.00000
				@ -6.00000			@ -6.00000	
10. Formingstation	231.38620		90.00000	49.00000	12.00000	12.00000	49.00000	90.00000
				@ -12.00000	= 6.00000	@ -6.00000	@ -12.00000	
9. Formingstation	231.38620		90.00000	37.00000	6.00000	6.00000	37.00000	90.00000
				@ -12.00000	= 0.00000	= 0.00000	@ -12.00000	
8. Formingstation	231.38620		90.00000	25.00000	--	--	25.00000	90.00000
				@ -7.00000			@ -7.00000	
7. Formingstation	231.38620		90.00000	18.00000	--	--	18.00000	90.00000
				@ -7.00000			@ -7.00000	
6. Formingstation	231.38620		90.00000	11.00000	--	--	11.00000	90.00000

Figure 271 – Bending angles sequence for the model with 13 incremental stations.

- **Model with 13 non-incremental stations**

	s = 2.10000		2. Entity	4. Entity	5. Entity	6. Entity	7. Entity	9. Entity
OK	Stripwidth		Angle	Angle	Angle	Angle	Angle	Angle
Profile	231.38620		90.00000	61.00000	12.00000	12.00000	61.00000	90.00000
11. Formingstation	231.38620		90.00000	61.00000	12.00000	12.00000	61.00000	90.00000
				@ -12.00000			@ -12.00000	
10. Formingstation	231.38620		90.00000	49.00000	12.00000	12.00000	49.00000	90.00000
9. Formingstation	231.38620		90.00000	49.00000	12.00000	12.00000	49.00000	90.00000
				@ -24.00000	= 0.00000	= 0.00000	@ -24.00000	
8. Formingstation	231.38620		90.00000	25.00000	--	--	25.00000	90.00000
7. Formingstation	231.38620		90.00000	25.00000	--	--	25.00000	90.00000
				@ -14.00000			@ -14.00000	
6. Formingstation	231.38620		90.00000	11.00000	--	--	11.00000	90.00000

Figure 272 – Bending angles sequence for the model with 13 non-incremental stations.

- **New Roll Forming approach**

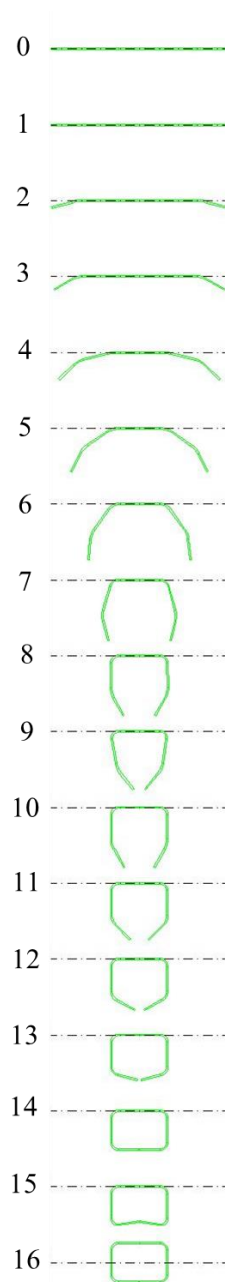


Figure 273 – New roll forming approach: forming steps

	s = 2.10			2. Entity	4. Entity	7. Entity	9. Entity
OK	Stripwidth			Angle	Angle	Angle	Angle
Profile	231.35			90.00	90.00	90.00	90.00
				@ 0.00 (9.21)			@ 0.00 (9.21)
15. Formingstation	231.35			99.21	90.00	90.00	99.21
				@ -9.21			@ -9.21
14. Formingstation	231.35			90.00	90.00	90.00	90.00
				@ -15.00			@ -15.00
13. Formingstation	231.35			75.00	90.00	90.00	75.00
				@ -15.00			@ -15.00
12. Formingstation	231.35			60.00	90.00	90.00	60.00
				@ -15.00			@ -15.00
11. Formingstation	231.35			45.00	90.00	90.00	45.00
				@ -15.00			@ -15.00
10. Formingstation	231.35			30.00	90.00	90.00	30.00
				@ 0.00 (9.21)	@ 0.00 (9.21)		
9. Formingstation	231.35			30.00	99.21	99.21	30.00
				@ -10.00	@ -10.00		
8. Formingstation	231.35			30.00	89.21	89.21	30.00
				@ -15.00	@ -15.00		
7. Formingstation	231.35			30.00	74.21	74.21	30.00
				@ -20.00	@ -20.00		
6. Formingstation	231.35			30.00	54.21	54.21	30.00
				@ -20.00	@ -20.00		
5. Formingstation	231.35			30.00	34.21	34.21	30.00
				@ -20.00	@ -20.00		
4. Formingstation	231.35			30.00	14.21	14.21	30.00
				= 0.00	= 0.00		
3. Formingstation	231.35			30.00	--	--	30.00
				@ -15.00			@ -15.00
2. Formingstation	231.35			15.00	--	--	15.00
				= 0.00			= 0.00
1. Formingstation	231.35			--	--	--	--
0. Entryguidestation	231.35			--	--	--	--
							0.00

Figure 274– Bending angles sequence of new roll forming approach.