The application of modelling techniques to identify material properties for cost effective and high quality profiling.

Gilmartin, Stuart J

DOCTOR OF ENGINEERING

The application of modelling techniques to identify material properties for cost effective and high quality profiling

STUART J GILMARTIN

Thesis submitted to Swansea University in candidature for the degree of Engineering Doctorate

Swansea University 2010

SUMMARY

Zinc and organically coated strip steels are products of Corus Colors, which are supplied to the roll forming industry and profiled for a variety of applications, including building cladding and composite floor decking.

Many profile designs include complex roll geometry which promotes intense deformation and as a consequence can create a number of defects within the steel strip. Cracking, wavy edges and spring-back are three of the more common reoccurring problems. To overcome such defects within the production line when they occur, simple procedures are carried out by experienced line operators. One method is to adjust the clearance between the upper and lower rolls of the problematic roll stand on either the outboard or inboard side of the production line.

In recent years the potential of Finite Element Modelling (FEM) has been realised for the simulation of such processes in both 2D and 3D. Due to advances in computer graphics and processing, the use of 3D FEM packages to simulate the effects on material properties within a roll forming line is becoming an area of high interest within the profiling industry.

Studies in this report have focused on using ABAQUS FEM software to simulate in 3D, profiling stands within a production line used to create a trapezoidal profile using HPS200 (Colorcoat) steel. Particular attention was given to the variables set during creation of the simulation, such as friction coefficients, roll clearance and speed of the rotating rolls used to transport the strip. A plant trial was conducted to determine the profile measurements of the strip at different stages of the process which were then used to perform a validation with the simulation model.

DECLARATIONS AND STATEMENTS

Declaration: This work has not previously been accepted in substance for any degree and is not being currently submitted in candidature for any degree.

Signed: **Date:** 01 APR 10

Statement: This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references.

Signed: **Date:** 01 APR 10

Statement: I hereby give my consent for my thesis, if accepted, to be available for photocopying and interlibrary loan and for the title and summary to be made available to outside organisations.

Signed: **Date:** 01 APR 10

ACKNOWLEDGEMENTS

The author would like to thank Corus Strip Products for permission to publish this work and gratefully acknowledges the support from the Engineering and Physical Sciences Research Council (EPSRC), for the duration of the study.

The author would like to thank the engineers at Corus Colors and Corus Panels and Profiles (CP&P), for their support and technical advice throughout the project.

The author would like to thank the supervisors for the EngD, Prof Dave Worsley from Swansea University, Dr Hastings McKenzie from the North East Wales Institute (NEWI) and Paul Jones from Corus. Wim Laging and Rutger Peeters from Corus Research Development & Technology (RD&T), for their help and training whilst based in IJmuiden, Netherlands. Last but by no means least, all the staff at the Engineering Doctorate Centre at the University of Wales Swansea who provided valuable support throughout the doctorate and furthermore more recently whilst preparing for submission of this thesis.

Finally the author would like to say a really big thank you to his family and friends for their help, support and patience when it was required the most.

NOMENCLATURE

μ	= Micro
A_0	= Original Area
e	= Melt Density
g	= Acceleration due to gravity
n	= Strain Hardening Exponent
°C	= Degrees Celsius
P_{max}	= Maximum Load
R	= Plastic Strain Ratio
R_{eH}	= Minimum Yield Strength
R_m	= Tensile Strength
R_p	= Permanent Strain
Ti	= Initial Thickness
Tf	= Final Thickness
Ti	= Initial Thickness
V	= Strip
Wf	= Final Width
Wi	= Initial Width
Y	= Yield Stress
ε	= Strain
η	= Dynamic Viscosity
σ	= Stress
E	= Young's Modulus
Z	= Reduction in Area

LIST OF ABBREVIATIONS

ALE	= Arbitary Lagrangian Eulerian
BOS	= Basic Oxygen Steel
C3D20R	= 20 node linear brick element with Reduced Integration
C3D8R	= 8 node linear brick element with Reduced Integration
CAD	= Computer Aided Design
CAE	= Computer Aided Engineering
CPP	= Corus Panels & Profiles
CPU	= Central Processing Unit
DOF	= Degree of Freedom
EPFEP3	= Elastic Plastic Finite Element Program
FE	= Finite Element
FEA	= Finite Element Analysis
FEM	= Finite Element Modelling
HCl	= Hydrogen Chloride
HDG	= Hot Dip Galvanised
HPS	= High Performance Steel
O_2	= Oxygen
PAC	= Product Application Centre
RDT	= Research Development & Technology
VB	= Visual Basic
VBI	= Visual Basic Interface
Wt	= Weight
YPE	= Yield Point Extension

GLOSSARY

Cold Rolling:	Metal forming process when the metal is below its recrystallisation temperature.
Formability:	Ease with which a metal can be shaped by plastic deformation.
Friction Coefficient:	Dimensionless value which describes the ratio of the force of friction between two bodies and the force pressing them together.
Hot Rolling:	Metal forming process when the metal is above its recrystallisation temperature.
Pickling:	Process used to remove oxide layer from surface of metal using a chemical solution.
Profile:	Structural outline/shape of the steel.
Profiling:	Steel forming process, also known as Roll forming.
Roll Forming:	Metal forming process using rotating or fixed forming rolls.
Roll Stand:	Roll forming lines consist of a number of roll stands positioned in parallel. Each stand consist of either a lower roll, upper roll or combination of the two.
Traction:	The mechanical force used to achieve motion.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

This Engineering Doctorate project is at the core of Corus multi-metals strategy and has involved working closely with Corus Colors, Corus Research Development & Technology (RD&T), IJmuiden and Corus Panels & Profiles (CP&P).

1.1 Background

The use of FEM to provide technical support to roll forming customers is not a new procedure. Research and consultancy for Corus and its customers in areas such as roll forming is currently performed by engineers from Corus RD & T in IJmuiden. Here they have performed years of FE analysis of roll forming production lines along with various other applications such as hydro forming. Their expertise has led them to create computer models to aid the analysis and as a result help to provide speedy responses to customer investigations, including CP&P and Kingspan. An example of a 3D model can be seen in Figure 1.1.

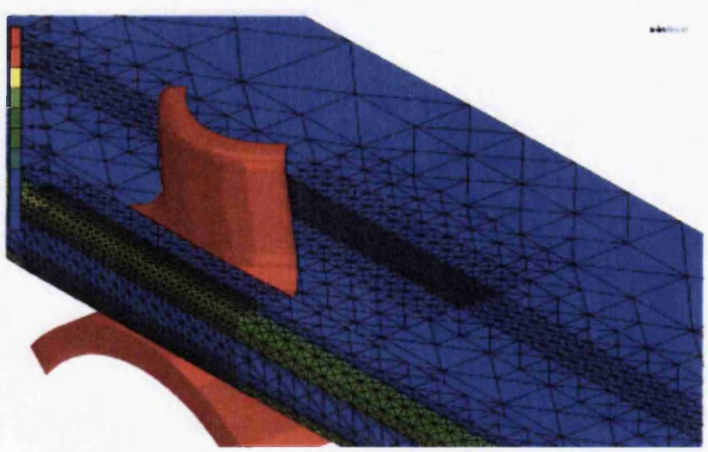


Figure 1.1: 3D Analysis using INDEED Finite Element Modelling (FEM) software (Laging W. & Peeters R, Corus RD & T)

1.2 Research Goal

The aim of this Engineering Doctorate research is to create a model to help understand the following:

- To identify the specific mechanical properties of profiled materials which give excellent roll formability over the broadest range of profiles and grades.
- To link these material properties to roll geometries and other rolling parameters to determine the fewest profiling steps whilst minimising problems such as spring back and wavy edges.
- To deliver design rules using new and existing materials from the Corus portfolio for optimum profile performance and cost effective processing.

1.3 Benefits

The overall long-term potential for the research is the ability to predict performance of new grades without using production line time.

At present the introduction of new steel grades to a roll forming line is a trial and error operation. The rolls within the particular line are designed to accommodate a specific grade and thickness of steel. Therefore, to trial run a new grade the production line has to be stopped and the setup of the rolls may have to be changed. This can be a lengthy and expensive process which in conclusion may not even prove successful. FEM of a steel grade can simulate the performance of the new grade through the actual production line in 3D. This indicates the suitability of the grade without using production line time and wasting material.

In addition, this new expertise within Corus UK will provide the following advantages:

- Provide technical support to business units.

Using the FEM software to predict material performance, technical support can then be provided to Corus business units and other potential customers within the steel industry. This could include predicting the performance of a new grade of steel or investigating the cause of defects within an active production line.

- Ability to provide an input into the design characteristics.

When the cause of defects that occur within a roll forming line are found using FEM, improvements can then be made to update the design characteristics of the rolls, the profile design or even the composition of the steel to improve quality.

1.4 Aims of the Programme

The aim of this programme was to produce a 3D simulation of a roll forming production line which could be used to deliver an understanding of the variables involved in the process, such as rolling friction and rotating rolls. The model could then be used to assist in the following:

- Ability to predict performance of new grades without using production line time.
- Help provide knowledge and expertise in this field in the UK.
- Provide technical support to business units
- Ability to provide an input into the design characteristics of future profiles.

The programme was designated to work with an existing roll forming line, which was easily accessible, relatively simple to operate and will simple roll geometry. Production lines with complex profile geometry were not desired for this programme but could be investigated in future work.

CHAPTER 2: REVIEW OF LITERATURE

This chapter explains the roll forming process and defects that occur in steel strip pre and post forming. Profiled products produced, grades of steels used and the technique of Finite Element Analysis (FEA) are discussed with focus on how each are adapted for simulating production lines in 3D.

2.1 Corus Production of steel

The production of steel sheet has seen advances in automated technology within the past few decades. However, the principle of its production is very much the same. Steel sheet is in demand from a variety of industries, including construction, packaging and the automotive industry. The process from ore to finished coated steel can be seen in Figure 2.1 and explained as follows:

Corus Ltd, Port Talbot:

- Iron ore in the form of pellets and sinter are reacted with coke in blast furnaces up to 2000°C. The iron oxides are then reduced to metallic iron via a reduction reaction process. During this process the liquid metal forms 15-20% of the total blast furnace output, a further 3-5% is a liquid slag that forms on top of the liquid and the remainder consists of chemical reactions, gas and heat losses.
- The liquid iron is then removed from the blast furnace and transported to a Basic Oxygen Steel Making (BOS) vessel where it is treated with Oxygen (O_2). The purpose of this procedure is to reduce the high level of carbon in

the iron, around 5 wt %, picked up from the coke. The O_2 is blown into the liquid composition to remove the carbon as CO and CO_2, to a 0.02 – 0.06% carbon level. As a result of reducing the carbon content the liquid iron now contains a high level of O_2, around 500 parts per million, and is consequently removed by de-oxidation with Al or Si. The excess O_2 is removed as Al_2O_3 or as SiO_2 in the slag. The liquid steel of required composition is finally removed at 1600 °C with an O_2 content of 0.0005 %.

- The liquid steel of desired composition is poured from a ladle via a turn-dish into a mould. An oscillating water cooled copper mould is used to promote rapid solidification of the liquid steel. The solidified slab that emerges is either hot rolled immediately in the same production line or sent to a hot rolling mill. The slabs are rolled from a thickness up to 250 mm down to 70 -90 mm in as many as 16 passes. The material is then cooled depending on the grain structure required. For example, very rapid cooling gives a fine grain structure and a strong material with high Yield/tensile strength. Slow cooling produces a material with a higher ductility, which as a result has a lower yield strength.

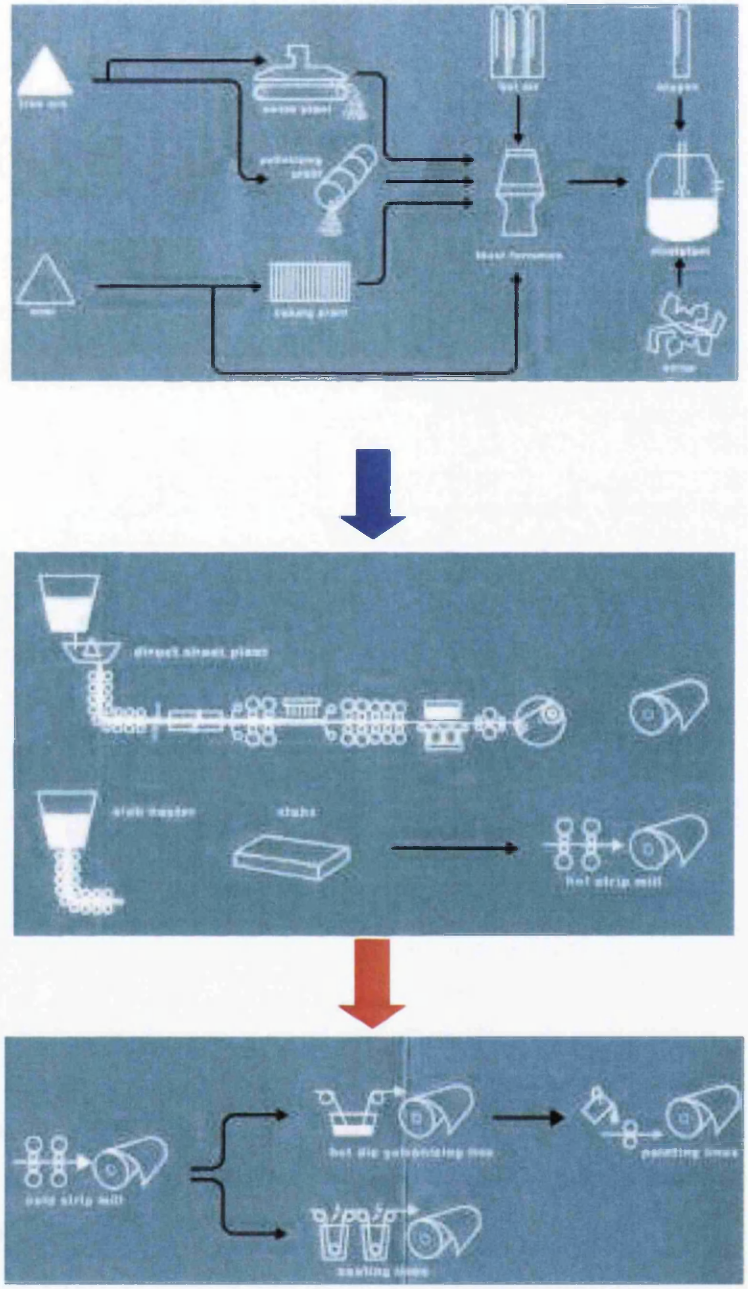


Figure 2.1: Steel production process diagram (Corus Steel brochure, 2001)

Corus Strip Products, Llanwern:

- Pickling

When steel strip is exposed to the atmosphere during hot rolling, its surface oxidises. Therefore the first requirement before cold rolling and coating is to prepare the sheet surface to remove such scale, but also to remove oil, rust and grease that can adhere to its surface. Initially the steel is uncoiled and then degreased using an alkaline electro-cleaning process. The oxide scale is then removed by reacting the steel with 10-20% aqueous HCI or 7% H_2SO_4 solution in water at 70-90°C, known as pickling. Following this treatment the surface is clean and scale free.

- Cold rolled

Pickled hot rolled coils are then cold rolled to 50-70% reduction in thickness. This cold rolling breaks down the ferrite grain structure of the hot rolled steel to ferrite grains that are elongated in the rolling direction. The strength of the steel is also increased due to cold rolling but this work hardening leaves the material with poor ductility.

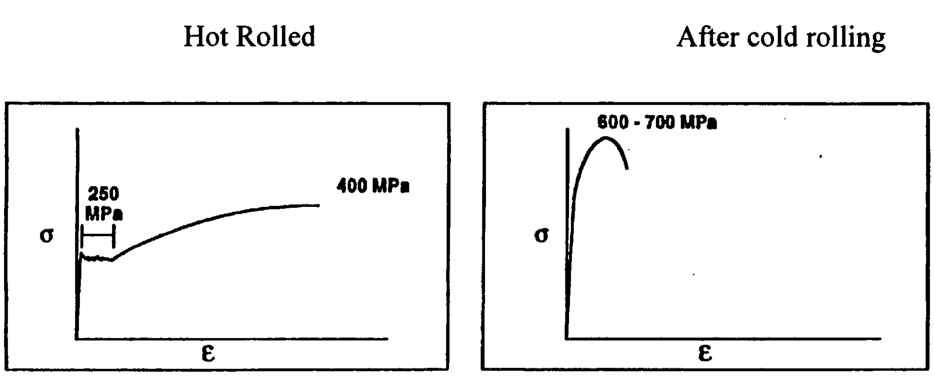


Figure 2.2: Graphs showing steel sheet properties during production

Figure 2.2, shows the affect of cold rolling sheet steel after hot rolling. The hot rolled Stress-Strain curve shows that the material has a defined yield point where the material experiences elastic strain. When this is reached at 250 MPa, Saw tooth Yielding occurs and plastic strain occurs in a region called the Yield Point Elongation. It is at this point where Stretcher-strain marks or 'Luders line', appear on the material surface.

The Cold rolled Stress-Strain curve shows that the Yield point and the Yield Point Elongation have been removed, and the strength of the material has been increased considerably (Dasarthy 2003).

The behaviour of materials under load is classified as either ductile or brittle depending on the materials ability to undergo plastic deformation. Therefore it can also be seen that the lower strength Hot rolled steel is extremely ductile, as it deforms plastically before failure. The cold rolled steel does have high strength but it can be seen that it fails with little plastic deformation, therefore has little ductility (Dieter 1998).

Corus Colors, Shotton:

Metallic coated steels used for roll forming techniques are generally Hot Dip Galvanised (HDG) at Shotton. HDG coatings give excellent corrosion resistance due to the fact that Zinc is a poor oxygen cathode and as a result corrodes fifty times slower than that of unprotected steel.

Two main types are Galvatite, which has a pure zinc coating or Galfan, which has a Zinc + 5% Aluminium coating. All Zinc coatings are applied by passing the sheet through a bath of molten zinc or zinc/aluminium and the coating weight is controlled using gas knifes. Gas is blown onto both sides of the sheet at high pressure according to the thickness of the coating required and this gives a uniform weight of coating without marking the sheet. An equation to calculate the coating thickness is used as follows:

$$T = \frac{2}{3} (V\eta / eg)^{\frac{1}{2}} \qquad \textbf{(Eq. 1)}$$

Where: T = Thickness

V = Strip

η = Dynamic Viscosity

e = Melt Density

g = Acceleration due to gravity

A typical coating thickness for HDG is 4 – 50 µm or 1/6 – 2 mm (McMurray 2003). Galvatite and Galfan strip steels are clearly identifiable by their appearance after galvanising. As the Zinc coating cools it crystallises producing a crystal/spangle flower surface finish, which is controlled according to sheets final purpose. The patterns of spangle are classified as either regular finish, minimised finish or ultra smooth finish. Cheap galvanised sheet is generally left with a regular spangle size and is commonly used for motorway barriers and construction applications. Fine powder, steam or an aqueous solution is blown onto the surface of the sheet to produce the minimised finish and can be temper rolled to produce an ultra smooth finish. When the sheet is to be organically coated then the spangle size is reduced to gain a much smoother finish ready for paining.

2.1.1 Environmental Issues

Steel is not only an excellent material to be used for roll formed products, it is also excellent for recycling. More than 50% of steel produced around the world today is processed from recycled steel. Other substances remain following steel production and almost 100% of these are recycled. More than 60% of these substances are used as raw materials in various other industries, e.g. blast furnace slag is used in road building and gases produced are re-used or supplied to the energy industry.

In an ideal world the steel manufacturing process would be designed to enhance production whilst minimising unwanted pollutants. As this is a goal for the future such a demand would require new costly plants and machinery. Therefore, the strategy is to develop 'end of pipe' techniques to remove potential contaminants before they are released in the atmosphere, known as control of particulate environment emissions.

The main atmospheric emission during steelmaking from iron ore is carbon dioxide, due to the enormous quantity of carbon used during chemical reduction of the ore and for the necessary energy output (Corus emissions 1999).

2.2 Roll Forming

The roll forming process is used to create a large range of steel components in industry sectors such as automotive and construction. This continuous forming process uses flat strip metal from large coils or the metal is pre-cut into desired lengths. The material is then passed through up to as many as 25 roll stations, each containing two or four rolls, at speeds ranging from 20 to 75 m/min (Peeters 2001). These rolls can be divided into the following groups:

- Forming rolls – Breakdown/finishing rolls
- Sizing rolls

The three basic steps to the roll forming process can be seen in Figure 2.3 below:

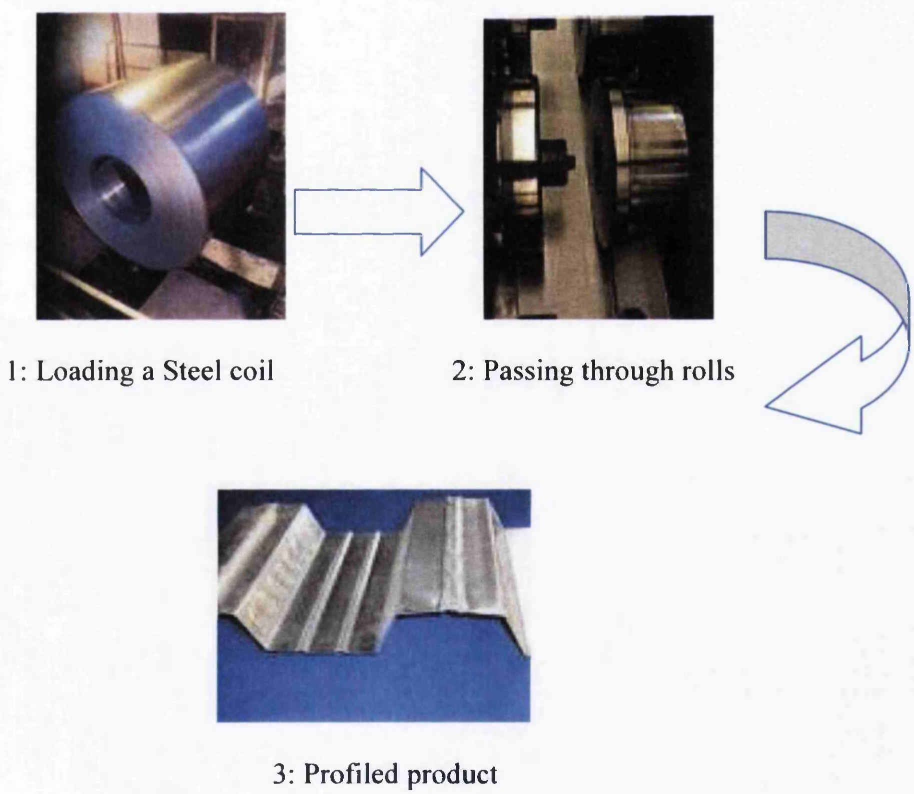


Figure 2.3: Roll forming stages

2.2.1 Types of Roll forming lines

Many different metal products are profiled using the roll forming technique. Therefore, roll forming lines come in many shapes and sizes depending on the complexity of the product being produced, and also the type and grade of material. Figure 2.4, shows a typical roll forming line used in the Steel industry.

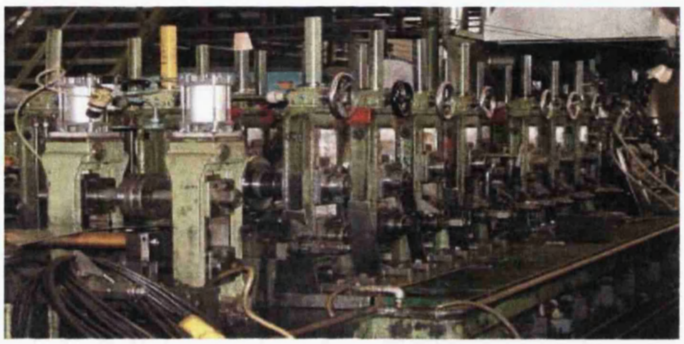


Figure 2.4: Example of a roll forming line (picture courtesy of Corus RD&T)

The number of roll forming stands in a production line have an important part to play in producing a high quality finished product. For example, a complex profile with high bend radii and/or features such as intermediate stiffeners will tend to have a higher number of roll stands, to reduce the amount of material deformation within each profiling step.

2.2.2 Profiled Products

Roll forming is used to manufacture many different components. Such components are classified into three main groups, as shown in Figure 2.5.

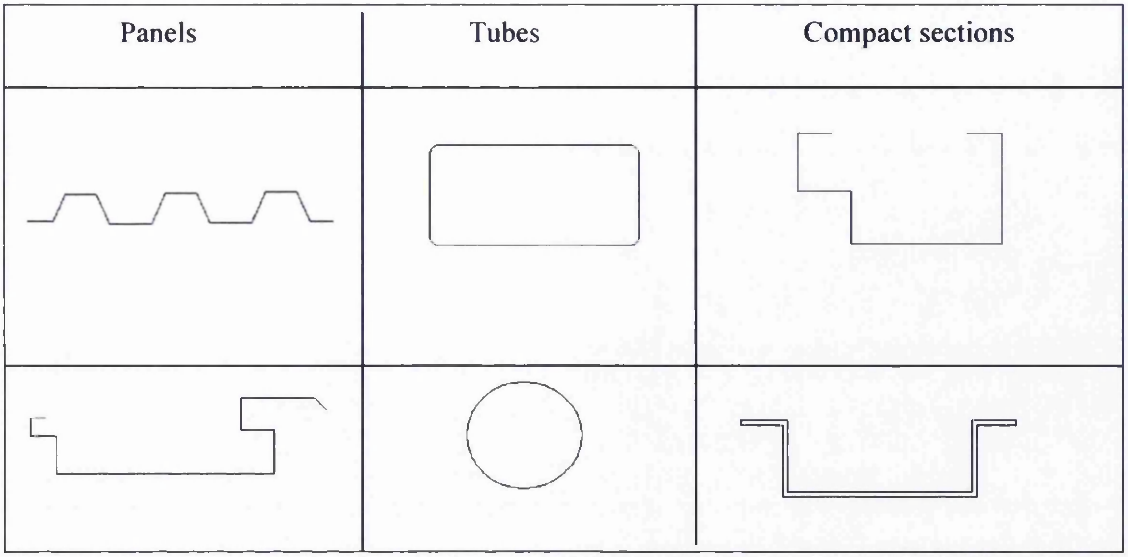


Figure 2.5: Roll formed products (Laging W, 2000)

2.2.3 Steel grades used in Roll Forming

Steel grades used in roll forming range from low strength mild steels up to dual phase steels for superior strength applications. They are either metallic coated (galvanised) or organically coated Z22 to Z55 grades, with yield strengths ranging from 220 to 550 N/mm^2. These have average Tensile strengths of between 403 and 690 N/mm^2. The elongation values range from 3.8% for Z55, to 32% for Z22. It can be seen from these values that profiling manufacturers have to choose steel grades carefully to fulfil the design requirements of the profile.

The most popular grades are Z28 to Z35. These offer a combination of high strength and good formability. Higher strength grades are used, but due to the low ductility have limited profiling applications.

2.2.4 Sheet steel formability

Formability is the measure of how easily a metal can be plastically deformed (Beddoes 1999).

During the roll forming process a number of different processes can occur, these include bending, stretching, and deep drawing and in most cases of sheet forming more than one process may be used.

The formability of any material can be characterised by its ability to:

- Avoid compressive forces in the plane of the sheet to eliminate buckling and wrinkling etc.
- Avoid changes in thickness, therefore preventing necking and failure.
- Avoid spring-back
- Distribute strain uniformly

Bending - is a process where a straight length of material is formed into a curved length, using a variety of forming techniques. During bending the sheet outer radius is in tension, whilst the inner radius is in compression.

Whilst this is a relatively simple procedure it is affected by a re-occurring problem known as spring-back. This occurs when the bending forces have been released and the material springs back due to elastic recovery. More detail regarding this can be found in Section 2.4.

Stretching - is a process of forming by forcing a tool against the sheet to create a deformation. The shape is formed entirely by tensile stresses in excess of the yield stress.

Spring-back is not a problem with this technique as the stress gradient is uniform. However, large deformations can only be obtained by this process in materials with good ductility.

Deep drawing - is an operation where elongation due to tension occurs in one direction and compression occurs in the perpendicular direction.

2.2.5 Effects of coatings on Formability

Steel readily corrodes in moist air and due to some of the harsh environments in which roll formed products are used, coated steels are used to eliminate short term corrosion. Two types of coatings are currently used. These are classified as metallic and organic coatings.

- Metallic coatings are applied by either galvanising or electroplating. This involves passing the steel through a bath of molten zinc which adheres to the metal surface. The sheet is then heat treated to cause the zinc to alloy to the surface material to form an iron-zinc alloy.

- Organic coatings are applied in various thicknesses depending on its application to enhance the corrosion properties of the sheet. It is applied in liquid form (paint), or as a film which is bonded to the sheet by using an adhesive.

Metallic and organic coatings do not affect the mechanical properties of the steel. However, organic coated steel can experience considerable problems during roll forming.

Organic coated profiles used for composite wall cladding and roofing are usually made from low strength steels as they are positioned vertically and are not subjected to high loading. The ductile nature of lower grade coated steels means that the steel can be formed easily without damage occurring to the coating. However, when high strength steels are roll formed the process is rigorous and therefore the organic coating can begin to flake, or crack due to the friction between the sheet and rolls.

Further information regarding the types or organic coated steels produced by Corus can be found in Section 2.5.1.

2.3 Roll Forming Parameters

In order to gain a better understanding of such a rigorous forming process it is essential to identify all parameters within the process and review their importance in relation to gaining a finished roll formed product. The following parameters are considered:

- Distance between the stands
- Position of the side rolls
- Friction

In the roll forming process friction between rolls and sheet causes many problems. There are many parameters that influence the amount of friction generated between the rolls.

- Type of material used for Rolls
- Height of stands
- Velocity of rolls
- Stiffness of the machine
- Variation in sheet thickness and width
- Internal stresses in coil

The stiffness of the machine, especially bending of the rolls can reduce the amount of forming per stand.

The variation in sheet width and thickness has a large influence on the roll forming process. Fluctuations in thickness can vary across the width of the sheet or along the length of the sheet. It is more common to find edge thinning on the width of the sheet and as a result the tools of the roll forming machine have to roll rather than roll form the steel. This increases the friction and loads imposed on the sheet as a result (Peeters 2001).

2.4 Roll Forming Defects

It is known that the quality of steel coil fluctuates. As a result, there will be variations in the physical properties and section thickness of the steel being formed. This combined with the accuracy of equipment setup, wear of components and operator skills all cause residual stresses in various sections of the profiled product. These stresses result in defects as shown in Figure 2.6.

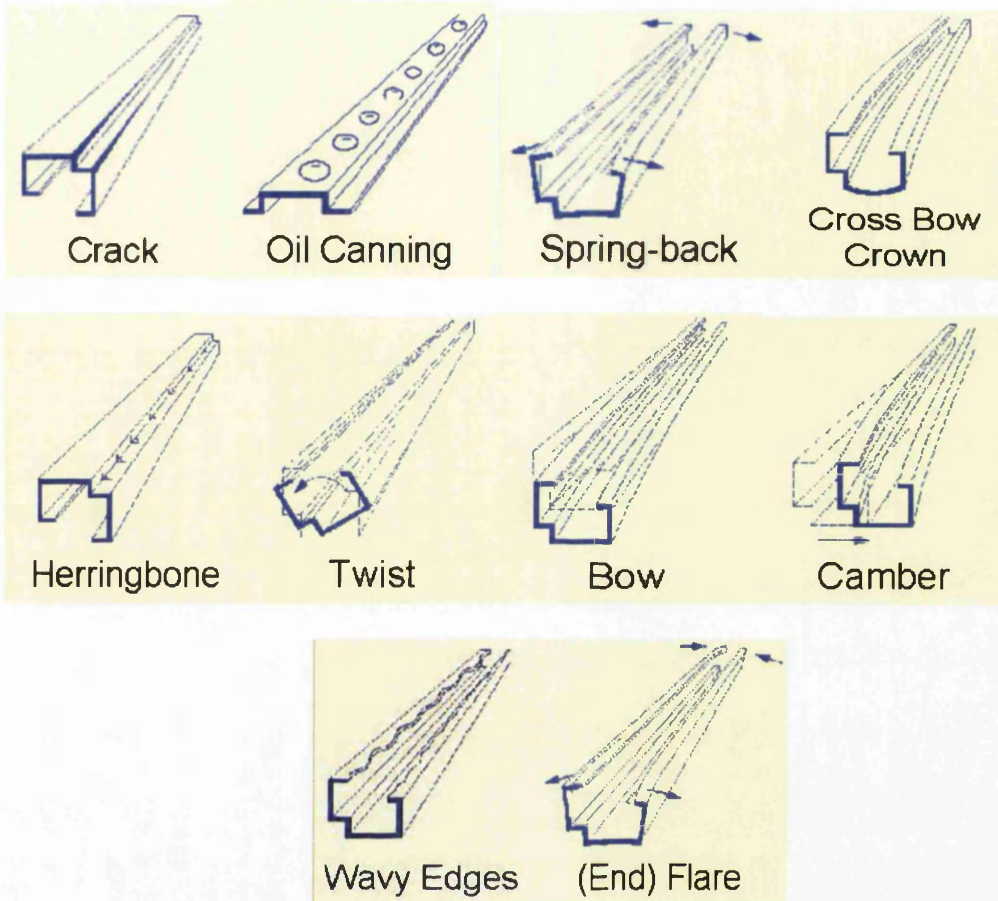


Figure 2.6: Defects caused by residual stresses during roll forming (Laging 2000)

The defects shown in Figure 2.6 occur during and after roll forming and on a regular basis. A full explanation to their cause and actions to prevent them reoccurring can be seen in the Corus roll forming defects catalogue (Laging 2000).

The defects shown have an undesirable effect on the finished roll formed product. However, the metal movement also has a considerable effect on the surface finish of the metal.

Actions to prevent such defects can include new rolling tools with less fluctuation in performance. Increased rolls per station and an increased number of stations reducing the amount of material deformation per stand can make a considerable difference.

2.4.1 Cracking

Also known as splitting, this defect is common during profiling of high strength, less ductile steel grades or when roll forming complex profiles which incorporate sharp angles into their design (Leslie 1981). The steel profile in Figure 2.7 shows a deck failure due to cracking in the longitudinal direction of the profiled sheet.

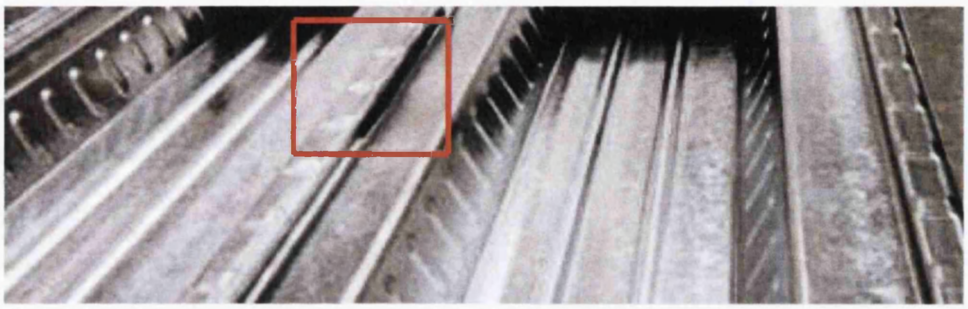


Figure 2.7: Cracking in the dovetail section of a profiled deck.

Precautions:

The use of more ductile steel grades and elimination of sharp complex shapes in the design of the profile can certainly help prevent cracking in a profile during forming. Increasing the number of roll stands the sheet passes through to gain the required profile would reduce the risk of cracking due to sudden material deformation.

2.4.2 Spring-back

Spring-back is the elastic recovery of a profile following plastic deformation when it has been formed and rolling forces are removed. It is encountered in all forming operations but is especially common in bending (Dieter 1998).

The spring-back or elastic recovery will be greater the higher the yield stress, the lower the elastic modulus and the greater the plastic strain. It also increases with the ratio between the lateral dimensions of the sheet and its thickness (Beddoes 1999).

It occurs in most roll forming processes and therefore compensations are made to eliminate the problem.

Precautions:

In most cases the material is over-bent so that when spring-back occurs the desired bend radius is achieved. The material can also be heat treated in the form of high temperature rolling, to reduce the yield stress and as a result the effect of spring-back.

2.4.3 Wavy Edges

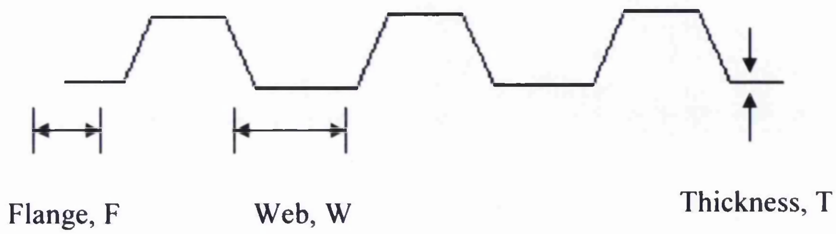
A wavy edge is recognisable by a series of buckles along the materials edge which form a wave appearance. It is caused due to an unequal distribution of the longitudinal compressive strain in the cross section and can be either elastic or plastic depending on the magnitude of the longitudinal strain in the formed edge of the sheet.

The amount of edge buckling increases with the average longitudinal compressive strain during the roll forming process.

Precautions:

One way to prevent this problem is to restrict the longitudinal compressive strain to within 0.3%, below the materials elastic strain limit.

Another is to limit the flange width to less than forty times its thickness (F/t <40), as shown in Figure 2.8 below:



For this profile $W/t = 30$. If $F/t < 40$ then wavy edges does not occur.

Figure 2.8: An example of how to eliminate wavy edges

Corus Colors have found that when coating the steel a wavy edge can form and remains in the sheet when recoiled. When the defect occurs it cannot be predicted and the cause is almost impossible to find.

Corus is currently looking into the potential cause so it can be controlled in the future. This is because until recently customers have demanded defect free coils. However, one company in particular have asked Corus specifically for sheets with a wavy edge. Kingspan, one of the biggest customers of Corus Colors, have found that steel sheet with a wavy edge actually performs better within their production lines. One of many products they produce is flat insulated panels used for wall cladding, also known as the 'Optimo' wall system (see Figure 2.9). When roll forming the flat panel, the material is deformed along its edges, whilst the centre section remains flat. Engineers have suggested that if the sheet contains a wavy edge, then the quality of the flat section is improved.

Figure 2.9: Kingspan Flat panel.

2.4.4 Oil Canning – Also known as wavy centres

The visual effects of oil canning are buckles in the centre of the roll formed material in a longitudinal direction, shown in Figure 2.10a.

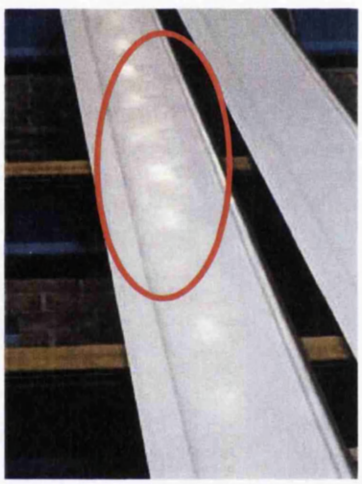


Figure 2.10a: Oil canning effect on profile

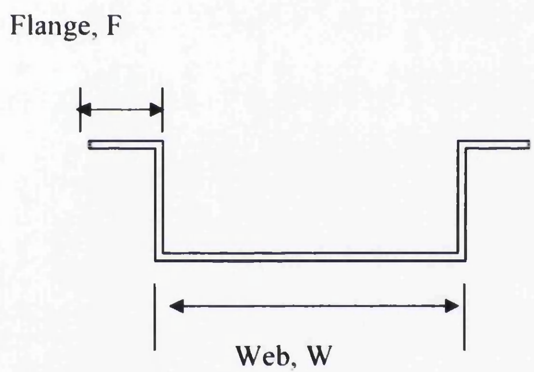


Figure 2.10b: Compact section

It is caused by an unequal distribution of compressive strains. The dimensions of the profile can also have an affect, due to its width. For example a profile with a narrow web experiences less oil canning than one with a wide web. Figure 2.10b shows the flange and web sections of a typical compact section type profile in which oil canning usually occurs.

Precautions:

Oil canning is caused by longitudinal compression in the profile and it has been found that applying tension to the wide profile during roll forming reduces this buckling effect.

The longitudinal compressive strains can also be reduced by decreasing the rate at which the material is deformed in one pass. This is achieved by increasing the total number of roll stands.

2.4.5 Stretcher strain marks

In many roll formed profiles, stiffeners are stretched into the metal in one of the initial roll stands. These stiffeners help strengthen the sheet and avoid buckling without using extra metal and reducing the overall sheet span. However, stretching the stiffeners into the steel can cause a visual defect in the material surrounding the stiffener. Lines appear around the stretched material, shown in Figure 2.11, in the shape of 'teddy bear ears', thus the name given to the phenomenon by roll forming manufacturers (Beddoes 1999).

Figure 2.11: Area of deformation in a floor deck product.

2.5 Profiled Products

Profiled panel sections are manufactured for different applications such as roofing, wall cladding and floor decking.

2.5.1 Composite Roof and Wall Profiles

These profiled panels are roll formed in the gauge range typically 0.4 to 0.7mm, which is coated with Colorcoat, Celestia, HPS200 and embossed Versacor finishes.

Colorcoat Celestia – This organically coated steel is available in wide variety of colours with smooth, textured or metallic surface finishes.

Colourcoat HPS200 – This steel offers superior durability, colour retention and resistance to mould growth.

The one metre wide panels are filled with foam insulation which provides both thermal insulation and fire protection. These panels are designed to span large distances with high resistance to bending and good shear strength. When fixed they provide a cost effective, attractive and environmentally friendly structure.

2.5.2 Composite Floor Steel Decking

Composite decking is roll formed from strip steel into a complex profile, which is designed to maximise the panel strength. The decking is then filled with concrete to provide a finished floor surface in a variety of structures, such as multi-storey car parks shown in Figure 2.12, office buildings and factories to name a few.

Figure 2.12: Composite floor structure (CP&P 2002)

Steel decking has become much more popular in recent years within the construction industry due to its following benefits:

- Speed - Steel decking is fixed to the steel girder structure of a building in its early stages of construction by welding it in place by rivets. Due to this method large areas can be laid rapidly into position at a rate of $400m^2$ per day.

- Working Platform - When the decking is fixed into place it can be used as a working platform, allowing other tradesmen such as electricians and plumbers, to begin work.

- Construction stage bracing – The decking acts as a lateral restraint to the steel beams and acts as a diaphragm which transmits the wind load from the outer steel work to the core. Therefore, once the decking is in place it contributes significantly to the stability to the structure.

- Weight – Due to the intrinsic efficiency of the composite construction and the displacement of concrete due to the profile shape, much less concrete is used in comparison to conventional reinforced concrete construction.

- Height – Composite beams use the slab as a compression element, this increases their stiffness and reduces their size. The composite slab has a low centre of reinforcement compared to a conventional reinforced slab and as a result does not need to be as deep. Therefore the reduction in the floor depth increases the height between floors in a multilevel structure.

- Fire prevention - Extensive fire testing has concluded that composite slabs have an excellent fire resistance even when the deck is exposed without protection.

Competition within decking manufacturers and the on going demands from the building industry has seen an increasing need to gain more panel coverage from the same amount of steel sheet used to form current profiles. In order to achieve this, the decking profile has to be redesigned and stronger more ductile steel grades have to be considered.

2.5.3 Pressed Profiles

These profiles are profiled from 0.7mm gauge steel using a brake press. This creates a rib profile which is fixed, but can be varied to produce unusual aesthetics. The press enables a variety of profiles to be produced, however, the length of the panels are limited to a maximum of 3.6m. Such profiles are usually limited for architectural applications, such as fascias.

2.6 Composite floor Decking

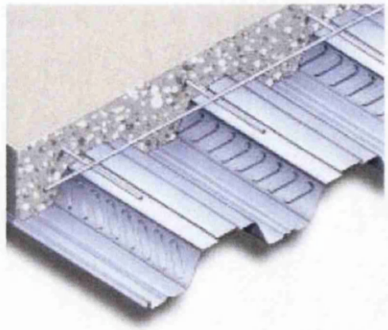


Figure 2.13: Profiled deck and concrete slab cross-section (CP&P, 2002)

2.6.1 Deck Design

The building industry encounters many different types of projects and as a result requires profiled products to adapt to many different problems. To deal with the demand, manufactures of composite floor decking have designed a wide range of profiles to fulfil most situations.

Three types of composite decking are available, these are as follows:

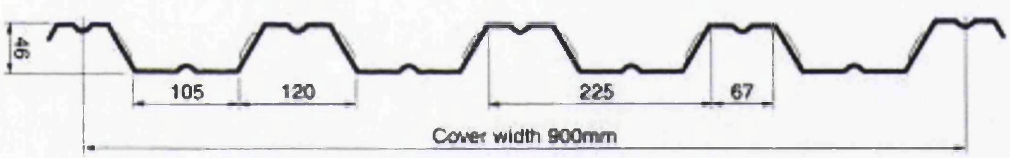
- Shallow composite floor decking – This design has a maximum depth of 100mm. It is positioned on the top flange of a steel beam and is securely fixed into place by steel studs. It can achieve a maximum un-propped span of 4.5m. The decking is designed to act compositely with the concrete floor slab

- Deep composite floor decking, see Figure 2.12 – This design has a maximum depth of 225mm and is positioned on the lower flange of a steel beam, which results in a reduced floor depth. It achieves a maximum un-propped span of 6m. The decking as before acts compositely with the floor slab and its reduced floor depth also reduces overall building height.

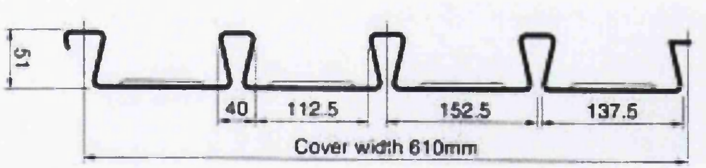
- Formwork – This is a non-composite design which means that the steel is permanent but unlike composite decking does not reinforce the concrete slab, it purely provides a base in which the wet concrete can be poured (CP&P 2002).

However, the range of decking is all designed around two profile geometries, trapezoidal and dovetail sections, see Figure 2.14.

Trapezoidal profile



Dovetail profile



Combination profile

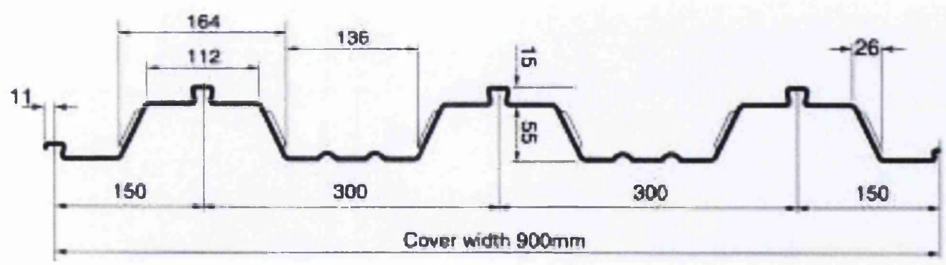


Figure 2.14: Trapezoidal, dovetail and combination profiles (CP&P, 2002)

The basic trapezoidal profile has a reasonable combination of coverage and strength. However, this profile is quite detailed and in most cases is very deep. As a result it generally has lower coverage than dovetail sections.

The dovetail profile has good coverage and has a simple forming technique compared to the trapezoidal section. However, the profile design is quite severe, due to the angles in which the steel is formed through to produce the shape. This leads to high residual stresses left in the material after roll forming.

A combined profile design is also used, as shown in Figure 2.14. This profile combines a basic trapezoidal with an added dovetail. This is used to increase the decking strength without having to give the profile more depth, explained in Section 2.6.2.

Floor decking design is generally influenced by a number of parameters. These include:

- Concrete type – dictates the minimum slab depth and influences un-propped deck span.
- Deck Span – un-propped, dictates general beam spacing.

- Fire rating – dictates minimum slab depth.
- Slab span – Propped, dictates maximum beam spacing.

The decking is then considered in two stages:

- Wet Concrete – carried by the deck alone.
- Cured Concrete – carried by the composite slab.

2.6.2 Strength of the profile

Composite decking is produced incorporating a variety of profile shapes, however the strength of the decking actually comes from the depth of profile. The problem that exists is that as the profile is made deeper to increase the strength of the decking, the span of the decking is reduced. Therefore, a compromise between material coverage and strength has to be made.

In order to increase the coverage of the decking, higher strength steels can be used, but as fully discussed in Section 2.7, this causes various other problems.

Composite floor decking, also known as thin-walled cold-formed steel sections are subject to complex forms of buckling and non-linear behaviour, even more so than hot-rolled sections. Therefore, extensive research has been undertaken over the past two decades to improve their structural performance.

An alternative method of increasing the strength of the profile without increasing the profile depth or grade of the steel is to introduce intermediate stiffeners into the profile.

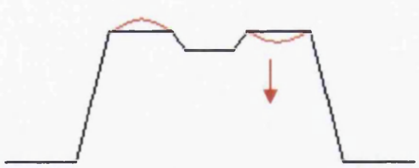
Two types of intermediate stiffener have been researched by Bernard (1993). These are:

- V – Stiffeners
- Flat-Hat Stiffeners

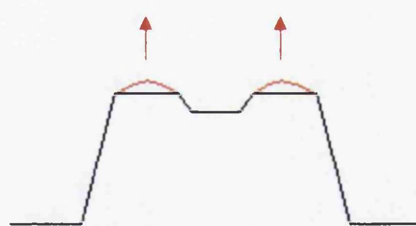
Bernard used finite strip buckling analysis and practical experiments with more than 27 profiled decking samples.

The geometry of both 'V' and 'flat-hat' stiffened panels was selected to produce both local and distortional buckling under pure bending.

The results obtained from the investigation found that intermediate stiffeners were found to have a clear connection between the size of the stiffeners and the strength of the panel. Distortional buckling resulted from small stiffeners and local buckling resulted from large stiffeners in the panels. The experimental results proved to agree with the computer analysis when compared.



a) Local Buckling symmetric



b) Distortional Buckling symmetric

c) Local buckling anti-symmetric d) Distortional Buckling anti-symmetric

Figure 2.15: Buckling trends in decking using flat-hat stiffeners (Bernard 1995).

Figure 2.15, demonstrates that local buckling which occurs before distortional buckling is much more favourable, therefore large stiffeners are potentially more suitable.

Therefore new methods are being used in the design of such panels. Two methods that are currently used are:

- Modified Winter formula - this method gives good results for panels that experience predominantly distortional buckling
- Unified Approach - this accounts for the interaction between local and distortional buckling modes and proves to be highly conservative.

Another concern when designing a profile with stiffeners is the effect on the sheet span.

In some cases the stiffeners are stretched into the profile, this does not reduce the sheet coverage but does introduce stretching defects, such as 'teddy bear ears' (Explained in Section 2.4.5). However, V-stiffeners and flat-hat stiffeners are roll formed into the sheet and as a consequence do reduce sheet coverage.

Therefore profile designers have to find the optimum size of a stiffener which provides good profile strength without loosing too much coverage (Bernard 1996).

2.6.3 Panel Loading

When designing a steel profile the designer has to consider the types of loads the deck will encounter when initially fixed into place as a working platform and when filled with concrete. The main types of loading are as follows (Selves 1999):

- Dead Loading – This refers to permanent loads on the decking, such as concrete, attachments, flooring and finishing products such as paint.

- Wind Loading – This is very difficult to predict as the decking will experience certain wind forces when it is exposed and these will change when the structure is completed. This it taken very seriously due to the fact that wind forces acting on the decking on a regular basis could lead to fatigue.

- Imposed Loading – This refers to temporary loading of the structure, such as furniture, weathering and the weight of people.

2.6.4 Composite deck Steel grades

Profiled products are mainly manufactured from galvanized steel. The most common grades from the Corus portfolio are in the range Z28 to Z35, with yield strengths 280 to 350 N/mm^2 respectively. These are Hot-dip galvanised with a zinc coating of 0.02 mm giving a total sheet thickness of 0.9 to 1.2 mm.

Steel with these properties is very ductile and is therefore suitable for profiling due to its ability to withstand the forces needed to produce a complex profiled panel. However, this ductile metal does not have the strength required to support a large load and therefore the profile has to be made deeper to increase its strength, thus reducing the sheet span and making it more expensive.

Corus in co-operation with its customers are now looking into the use of much stronger steels such as Z40, Z45 and Z55 for the same purpose. These have much higher guaranteed yield strengths ranging from 400 to 550 N/mm^2 and as a result the profile can be much shallower, giving more sheet coverage.

However, this less ductile steel cannot be formed as easily and current profile designs cannot be produced without defects occurring.

2.6.5 Profiled deck testing

The process is similar to that of testing beams. The decking is simply supported at both ends, as it would be in practice. A force is then applied to the deck steadily, simulating a potential load such as concrete. The deflections are then measured as the force is increased to cause failure in the form of local or distortional buckling in the panel.

It is essential that composite decks are tested and comply with BS5950 Part 4 or Eurocode 4. This states that a minimum of six deck specimens are tested at 150% of the designed load and if the deck exceeds this load it can be tested to destruction (Lawson 1989).

2.7 Properties of Roll Forming Steel

As explained in Section 2.6, steel grades used for roll forming generally have a good combination of strength and ductility. Figure 2.16 shows that regardless of the steel composition, its strength will be reduced when other material properties are increased.

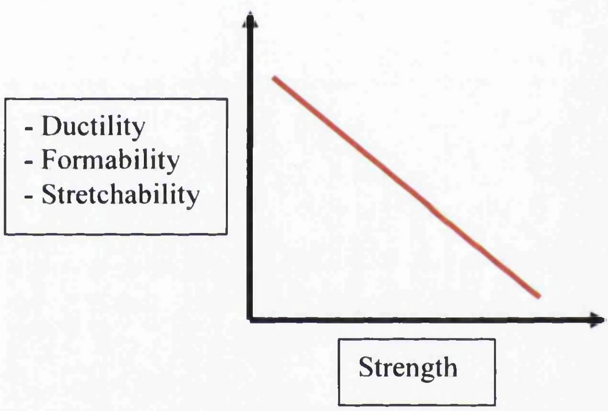


Figure 2.16: Graph showing steel Strength vs Ductility, Formability & Stretchability.

This section details the technical properties of the most common steels currently used by profile manufacturers and makes a comparison between them. It also looks at potential grades of steel that are likely to be introduced to profiling lines in the near future and the reasons why.

2.7.1 Influence of steel properties in roll forming

When selecting a steel grade for a desired purpose a number of properties are examined. The importance of these mechanical properties can be explained by using a typical engineering stress-strain curve, shown in Figure 2.17.

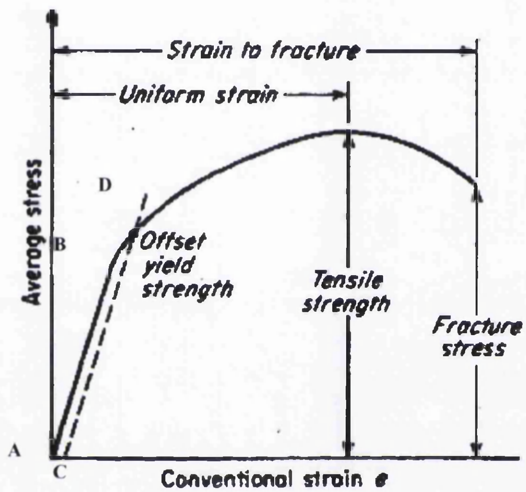


Figure 2.17: Engineering stress-strain curve.

The curve shown in Figure 2.17 represents the data obtained during a typical tensile test of a steel specimen. The shape of the curve will depend on the steel composition, heat treatment applied during processing and the prior history of plastic deformation. However, factors such as temperature, strain rate and stress imposed during the tensile testing also contribute.

The linear slope of the curve AB is the elastic region or modulus of elasticity. Point B is the point of maximum stress of the material without causing permanent strain/deformation when the load is removed, known as the elastic limit.

Parameters that are used to describe the curve are as follows:

- Yield strength
- Tensile strength
- Reduction of area
- Elongation

The first two properties describe the strength of the steel, whilst the remainder describes the materials ductility.

- Yield strength or Yield point (point B) – is the amount of stress required to produce a small amount of permanent deformation. This is usually defined as the offset yield strength or proof stress. This is shown by the line C-D parallel to the elastic region which is offset due to a strain of 0.2 or 0.1 %.

  This parameter is used during steel selection as it indicates how it likely to perform in use.
- Tensile strength or Ultimate tensile strength (UTS) – is the maximum load divided by the original area of the specimen given by the formula:

$$\mathbf{R_m} = \frac{P_{\mathbf{max}}}{\mathbf{A_0}} \qquad \textbf{(Eq.2)}$$

This value is the most frequently used from all the tensile testing results, even though is has little significance with the actual strength of the material. However, as it is easy to determine it is more commonly used for quality control and specifications of products.

- Reduction of area – This is the difference in cross sectional area of the material specimen before and after testing, expressed as a percentage in reduction.

- Elongation – When a material is tested to destruction it will initially stretch and elongate before fracture takes place. The two parts of the fractured specimen can then be reconnected and measured. The difference in length of the fractured specimen compared to the original specimen is known as the elongation and expressed as a percentage elongation.

When steels are used in roll forming further parameters are also considered such as the following:

- r-value or plastic strain ratio (Dieter 1998) – this is defined as the ratio of width true strain to thickness true strain in a tension test of a specimen cut from a sheet:

$$r = \frac{\ln (Wi/Wf)}{\ln (ti/tf)} \qquad \text{(Eq.3)}$$

where: Wi = Initial width.

Wf = Final width.

ti = Initial thickness.

tf = Final thickness.

- n-value or strain-hardening exponent – gives an indication of the sheet steel stretch-ability (Leslie 1981).

2.7.2 Steel grade comparison

Z28 Grade – S280GD +Z

Gauge: 0.4 to 1.0 mm = X605

1.0 to 2.0 mm = X384

This grade of steel has a guaranteed Yield strength of 280 N/mm^2. It is one of the lowest strength steels used for profiled products. Yield strengths range from 280 to 380 N/mm^2. Its elongation values range from 23 to 40% and has an average of 31%. Its tensile strength ranges from 370 to 485 N/mm^2 with an average of 415 N/mm^2.

This high strength steel grade is still one of the lowest strength grades used by roll forming manufacturers for profiled products today, however, it is also the most popular galvanized product produced. This is due to the fact that it boasts very good Elongation characteristics combined with high Yield and Tensile strength. The grade X605 with a gauge of up to 1.0 mm is preferred. However, profile manufactures generally use gauges between 0.9 and 1.2 mm. Applications of this product are suited to complex panel profiles such as roofing sections that interlock together and composite wall cladding which comprises of a double steel layer filled with an insulation foam or fibre. It is also used for composite floor decking, especially dovetail and combined profile designs due to its excellent formability to achieve sharp bends.

Z35 Grade – S350GD +Z

Gauge: 0.4 to 0.9 mm = X682

0.9 to 2.0 mm = X387

Zinc coated with a guaranteed Yield Strength of 350 N/mm^2. The Yield strength ranges from 335 to 440 N/mm^2. Its elongation ranges from 20 to 35% with an average elongation of 27%. Its tensile strength ranges from 440 to 515 N/mm^2 with an average of 496 N/mm^2. This galvanised steel is becoming more popular with roll formers due to its strength and formability. The formability is reduced slightly in this product but is similar to that of Z28. Therefore, the manufacturer can offer a higher guaranteed Yield strength for the same product. Again, roll formers generally use gauges between 0.9 and 1.2 mm. Its applications include roofing sections, wall cladding and floor decking.

Z45 Grade

Gauge: 0.9 mm and 1.2 mm

The average Yield strength of these gauges is 463 N/mm^2, ranging from a minimum of 435 to 495 N/mm^2 for both. The elongation ranges from 21 to 25%, with an average of 22%. The materials tensile strength ranges from 552 to 603 N/mm^2, with an average of 576 N/mm^2.

This grade has only recently been produced and tested in a small batch. As a result the information gained from initial tests is limited.

It is the hardest Tenform grade produced by Corus. Hot rolled, pickled and cold-rolled at Llanwern, it is then hot-dip galvanised at Shotton. It has been produced in two gauges, 0.9

and 1.2 mm. Profile manufacturers are now working with Corus to develop this grade with the potential to replace all existing steel grades in their profiling portfolio.

Its properties boast superior strength but reduced formability and would be used to replace profiles which are complex in design and already difficult to form. The advantage of this grade however, would be in the application to floor decking panels. These profiles currently use lower strength steel and gain strength by increasing the depth of the panel. Therefore, panels made from Z45 could be made shallower, whilst retaining an equivalent or higher strength of a Z28 or Z35 panel. This would increase the span of the sheet and also reduce weight.

Z45 Development

Many profiling customers are looking into the possibility to use higher strength steel grades to replace their current materials, and an example of this is in the production of composite floor decking. Such decking gains its strength by the depth of the profile and this is enhanced by stretching intermediate stiffeners into the steel to prevent the profile from buckling under load. The use of higher strength steel grades means that the deck profile depth can be reduced which in turn increases the span of the sheet.

However, when the strength of the steel is increased to such a high level its ductility is significantly reduced, thus limiting the complexity of the profile design. This causes problems associated with the tooling and has the potential for defects to occur during production.

Despite the concerns associated with higher strength grades, Z45 has been successfully put into production for composite floor decking by Corus Panel and Profiles (CP&P).

It is used to produce Comflor 80, a new steel decking profile to extend their already impressive range of floor deck designs.

Due to high strength of the steel the deck boasts an unsupported span up to 5m, subsequently reducing the number of structural steel supports and therefore reducing the overall cost of construction.

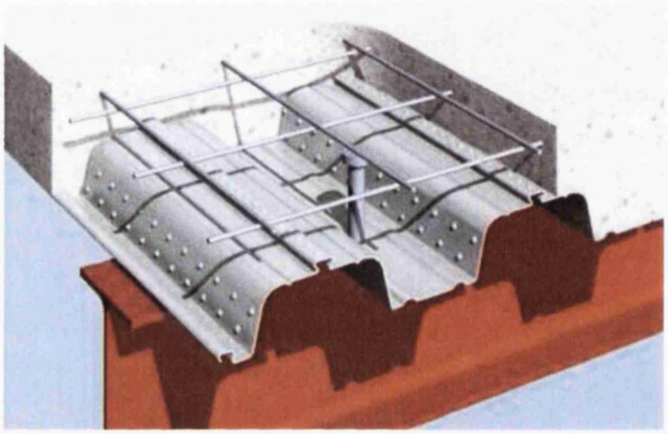


Figure 2.18: Comflor 80 deck working compositely with the concrete slab and steel beam (CP&P, 2002)

As with all of the CP&P shallow floor decking products, the new deck acts compositely with both the concrete slab and the structural steel I-beam, as shown in Figure 2.18.

This is achieved by the use of the dovetail sections and intermediate stiffeners profiled into the deck which lock the steel and concrete into place (see Figure 2.19). The steel beam works compositely with the deck as the concrete and deck are fixed into place by a steel shear stud which is welded into place on the beam and then covered with concrete.

Dovetail sections

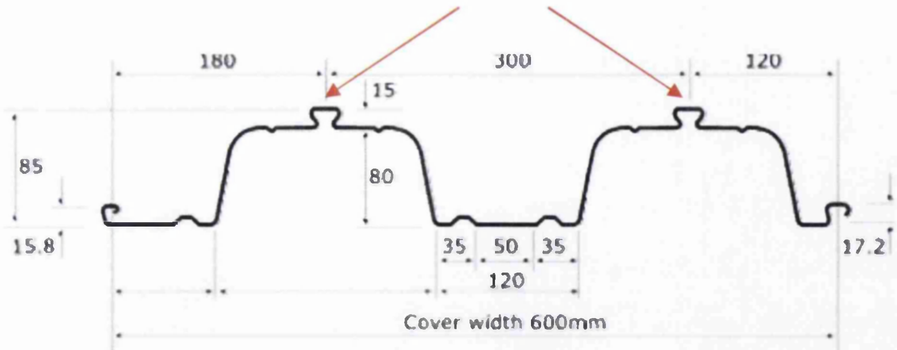


Figure 2.19: Dovetail sections and intermediate stiffeners

Z55 Grade – S550GD + Z

Gauge: 0.6 to 1.2 mm = X503

This grade has an average Yield strength of 684 N/mm^2, an average Tensile strength of 689 N/mm^2 and an average Elongation of 3.8%.

It is clear that this steel has superior strength and almost no formability. This is currently the highest strength steel sheet that is produced by Corus. It has limited applications for roll forming. However, profile manufacturers are currently researching into the use of this product to potentially replace their some current steel products within the range. The ductility of this product is extremely low, and therefore, the use of this grade to profile current products would result in high failure rates. However, Z55 has very high strength and the main reason for designing such complex profiles in the first place is to maximise the strength of the product. Therefore, future profile designs to use Z55 would be less detailed and have few intermediate stiffeners and sharp edges.

2.8 Finite Element Modelling (FEM)

First introduced in the 1950's, finite element modelling is an extremely complicated tool which has undergone many developments in past years to make it the leading numerical analysis technique used today.
It is now common software found within most branches of the engineering industry, including aircraft, car and construction industries (Fagan 1992).

In this section, the reason for using a specific finite element package for roll forming simulations and how it is used will be explained.

2.8.1 Finite Element Analysis roll forming application

FEM is a numerical simulation used to replicate a product or production process in two or three dimensions. Therefore it can be used very accurately to simulate a roll forming production line, enabling us to look at each stage of a production in detail, and identify problem areas that cause problems such as defects in the finished product.
Therefore the advantages of using such a package are as follows:

- Ability to replicate the production line process to exact detail in 2/3D, using CAD drawings.
- Model calculates, based on input data like strip and roll properties, the stresses and strains in 2 and 3 dimensions.
- Ability to run a simulation to observe the process.

- Simulation shows stress/strain distribution in the material throughout the forming process
- Therefore suitability of a material can be determined without production line time and identify occurring problems in a production line.
- Shape defects can be predicted.

The product is divided into elements, these are linked together to construct a model which is constrained by certain boundary conditions describing the problem. The data, boundary conditions combined with elements, lead to a complex system of mathematical equations describing the potential behaviour of the product. A computer is then used to find the numerical solution (Peeters 2001).

2.8.2 Choice of Finite Element Package

There are a range of 3D FEM packages available and these are generally suited to specific forming processes in different engineering disciplines. Therefore, choosing the most suitable package for roll forming is essential. A selection of available packages are as follows:

- **Indeed**
- **ABAQUS**
- Pam Stamp
- Autoform
- Dieka

- Marc
- Ansys
- Datam 3D

The majority of the packages used are multifunctional, having the potential to be used for many different applications, however, to create an accurate roll forming simulation only a selected few are suitable.

Past analysis of these packages has proved that Indeed and ABAQUS are the most suitable for roll forming, due to their criteria shown in Table 2.1.

To select the most suitable, the main criteria were assessed. These are scored for each package as positive (+), average (0) or negative (-).

Package	Stability	Pre-Processing	Post-Processing: -Strain -Stress -Geometry	Quality: -Describing Contact -Simulating springback	Availability/ Expertise
INDEED	O	+	+	+	PAC
ABAQUS	O	+	+	+	Corus/NEWI
DIEKA	-	+	O	-	PAC
ANSYS	+	+	+	O	PAC
MARC	O	+	+	-	IJTC

Table 2.1: Review of different FE packages (Peeters 2001)

The first criteria assessed were the objectives of the simulation. A package used to simulate roll forming should have the ability to visualise subsequent steps in the forming process, so that an ideal product can be created. Also, the package should have the ability to simulate processes downstream, such as bending (Peeters 2001).

- The stability of the package indicates if it is likely to crash easily and the kind of input that is required without the use of a pre-processor.
- Post-processing indicates that strains, stresses and the geometry should be visualised.
- Quality indicates if the package simulates spring-back and the way in which contact between the product and the rolls is described.

2.8.3 INDEED Vs ABAQUS

INDEED is a modern Implicit software package that has been developed by INPRO of Germany, and at the time of writing was still under development. The use of such an implicit code for roll forming simulations has only recently been possible due to the complexity of the analysis. This is due to the fact that implicit codes are computer CPU and memory intensive, and computers capable of handling such data have only recently been created.

ABAQUS is a powerful suite of programs that are based on the finite element method capable of solving problems from simple linear analysis to more challenging nonlinear simulations.

It consists of two different modules, ABAQUS/Standard and ABAQUS/Explicit. They are used for different purposes, for example, the standard edition can solve a range on linear and nonlinear problems. Explicit is a special purpose product more suitable for nonlinear problems such as roll forming. Both analysis products are controlled by the ABAQUS/CAE interface. This is the interactive environment for ABAQUS and once the model is complete, it submits, monitors and controls the simulations (Hibbitt, Karlsson & Sorenson, 2002).

Both packages were available for use during this study, however, the expertise in finite element modelling techniques and equipment that exists, was in favour of the INDEED software at the Product Application Centre (PAC), IJmuiden.

The latest software version and licence of ABAQUS was available at NEWI and was therefore, the preferred choice.

2.9 Indeed Finite Element Analysis

The structure of the Indeed software is shown below in Figure 2.20:

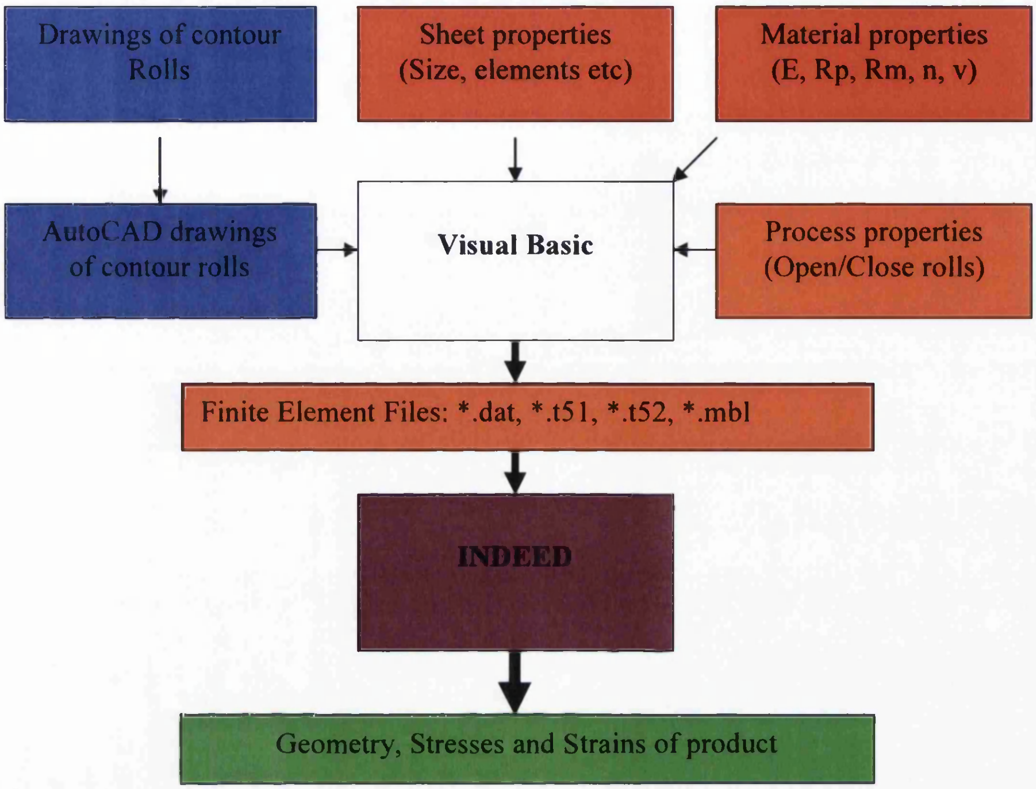


Figure 2.20: The structure of the INDEED simulation (Laging & Peeters, 2003).

2.9.1 Visual Basic Interface (VBI)

Figure 2.20, shows that a number of parameters of the simulation, such as sheet dimension and mechanical properties are transferred into an Interface called Visual Basic (VB).

The drawings of the contour rolls are used via AutoCAD. These drawings are provided by the roll designers who create the production lines. An example of such drawings can be seen in Appendix B. In certain scenarios the profiling manufacturers do not have copies of the AutoCAD drawings and due to the secretive nature of the roll design industry, drawings cannot be used. In such a case, software called COPRA can used as an alternative. COPRA was developed with roll forming in mind and is integrated into AutoCAD. This enables the user to draw the final profile of the product to be roll formed and import this into COPRA. This profile is then unfolded by the software, e.g. from a completed tube to a flat steel sheet, in a number of steps either manually or automatically. This is known as reverse engineering. A flower design is then created, Figure 2.21. COPRA then calculates strip width, Bend allowances and constructs a wire frame model that approximates metal movement during roll passes. The rolls are then created automatically when the dimensions and properties of the rolls are entered. The roll geometry can next be exported as a dxf-file and then transferred to the t52-file.

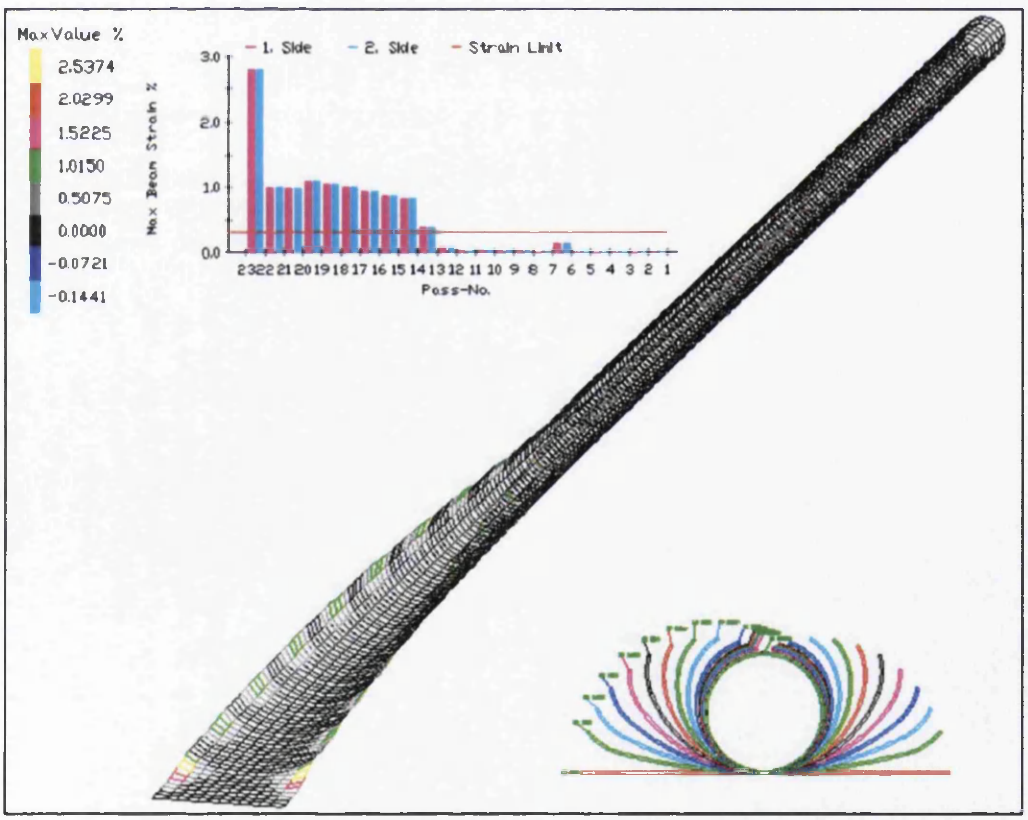


Figure 2.21: COPRA analysis and flower design

VB converts the parameters such as the material properties and AutoCAD drawings into files which are suitable for the Indeed model. Four separate files are created:

- Dat-file: Boundary conditions.
- T51-file: Initial sheet geometry.
- T52-file: Tool geometry.
- Mbl-file: Material properties and material model

2.9.2 Transporting the sheet

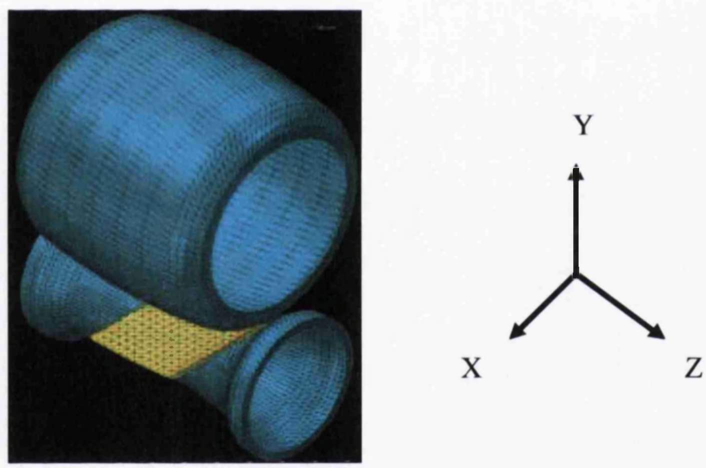


Figure 2.22: Sheet in first forming stand

The sheet is transported in the x-axis direction into the first forming stand, as shown in Figure 2.22. This shows the sheet as it enters the first set of stands.

There are two different ways of transporting the sheet in the simulation, these are as follows:

- Method 1 - Using fixed rolls excluding friction.
- Method 2 - Using rotating rolls incorporating friction.

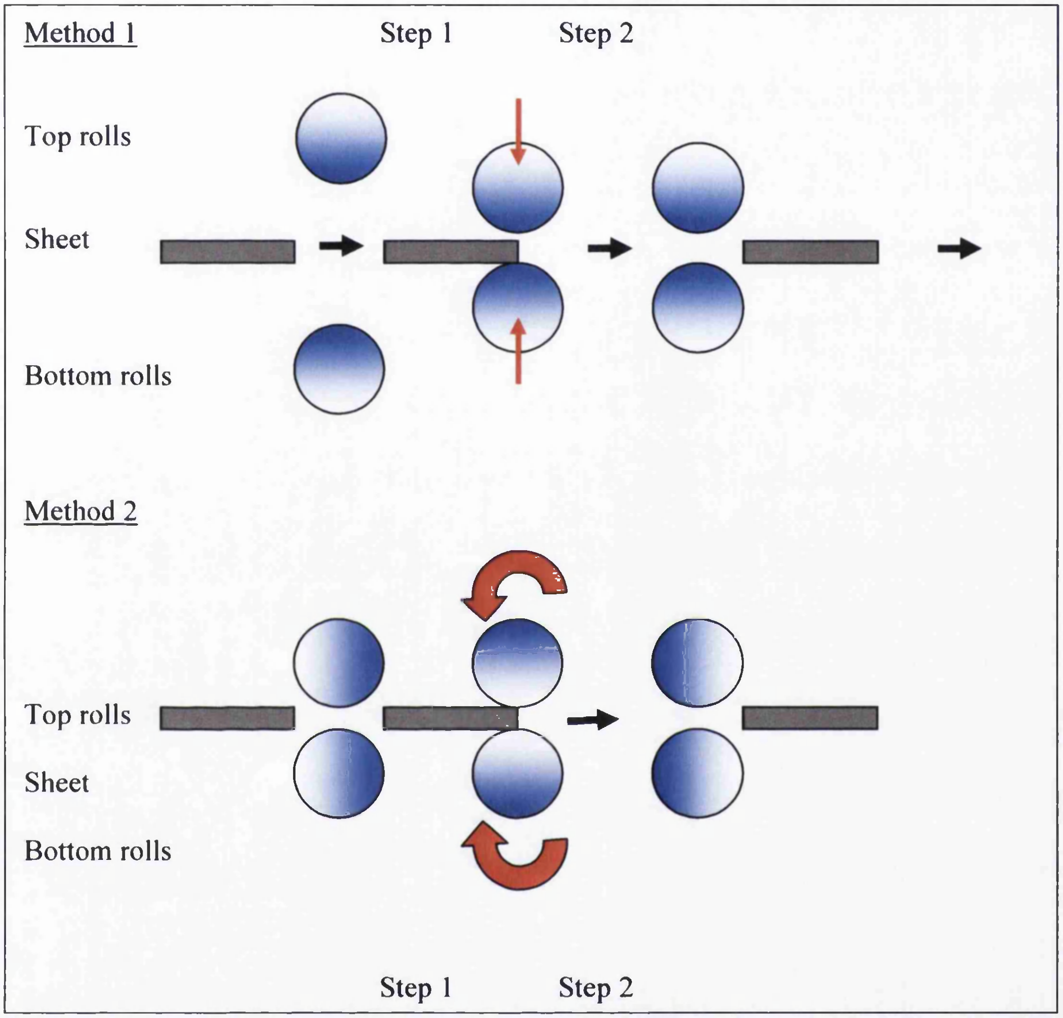


Figure 2.23: Transporting the sheet, Method 1 & 2

Fixed Rolls

When using fixed rolls the rolls remain fixed and a force is used to pull the sheet through the stands. Friction that would usually occur between the rolls and the sheet is eliminated which makes the calculation less complex but still provides satisfactory results.

Rotating rolls

When the simulation is run with rotating rolls, a number of the boundary conditions used within simulations with fixed rolls are eliminated. The friction between the rolls and sheet provide the force to move the sheet in the x-axis direction. However, the centre of the rolls is fixed in (X, Y) to eliminate movement.

2.9.3 Loading the sheet

Figure 2.23, demonstrates two different methods of loading the sheet into the first stand in the simulation.

Method 1 - shows the simulation where the rolls initially open after a displacement of the sheet and then close.

Method 2 - shows how the rolls can remain in a fixed position, however, this tends to cause instability in the model.

2.9.4 Length of the sheet

The length of the sheet is an important part of the model as it has to represent a continuous process.

In order for the simulation to run faster the calculation time has to be reduced, therefore, the size of the sheet has to be determined. The diagram in Appendix A is used to explain this

Fixed Rolls

When using fixed rolls the rolls remain fixed and a force is used to pull the sheet through the stands. Friction that would usually occur between the rolls and the sheet is eliminated which makes the calculation less complex but still provides satisfactory results.

Rotating rolls

When the simulation is run with rotating rolls, a number of the boundary conditions used within simulations with fixed rolls are eliminated. The friction between the rolls and sheet provide the force to move the sheet in the x-axis direction. However, the centre of the rolls is fixed in (X, Y) to eliminate movement.

2.9.3 Loading the sheet

Figure 2.23, demonstrates two different methods of loading the sheet into the first stand in the simulation.

Method 1 - shows the simulation where the rolls initially open after a displacement of the sheet and then close.

Method 2 - shows how the rolls can remain in a fixed position, however, this tends to cause instability in the model.

2.9.4 Length of the sheet

The length of the sheet is an important part of the model as it has to represent a continuous process.

In order for the simulation to run faster the calculation time has to be reduced, therefore, the size of the sheet has to be determined. The diagram in Appendix A is used to explain this process. It can be seen that at a random stage (*i*) in the process the sheet is fixed between the first three roll stands. A marked square is shown between the second and third rolls from the left. In the next four stages the sheet is moved the distance of one stand keeping the highlighted square consistently between two stands. This highlighted square therefore represents a continuous process.

If the sheet is made longer than that required to represent the continuous process the FE calculation time will be increased unnecessarily (Peeters 2001).

2.9.5 Sheet Meshing

The steel sheet in the simulation is meshed, consisting of many elements and nodes. The elements form areas of the surface of the material and the nodes are the points where the elements connect. The Elements and node coordinates are used to calculate the behaviour of the material in relation to the rolls.

In two and more importantly three dimensions, arranging a suitable mesh density takes careful consideration and planning. Figure 2.24 shows different methods in changing the sheet mesh density. Note it can be seen that that all nodes must be connected in adjacent elements. Figure 2.25, shows an incorrect method of meshing.

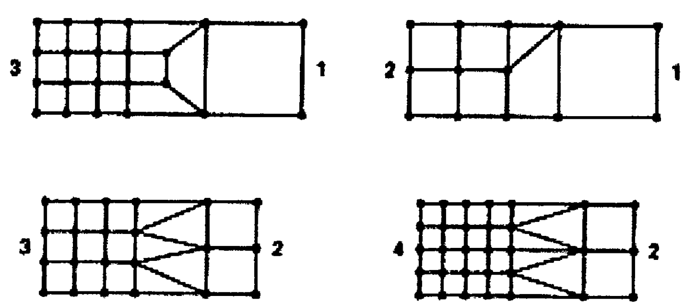


Figure 2.24: Methods in changing mesh density

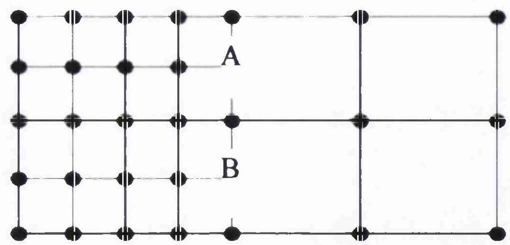


Figure 2.25: Incorrect meshing technique

It can be seen in Figure 2.25, that nodes A and B are not connected to the coarse mesh, which indicates that there is a hole in the material (Fagan 1992). This would show a discontinuity in the model at these points and the simulation would crash.

It can be seen in Figure 2.26 (see below), that the sheet consists of various densities of mesh. It can be seen in practice that the finer the mesh of the sheet, the more accurate the simulation. This is because a finer mesh contains more nodal points and elements. Therefore, more points and contact surfaces are in contact with the rolls and this creates a great deal more equations, making it much more accurate.

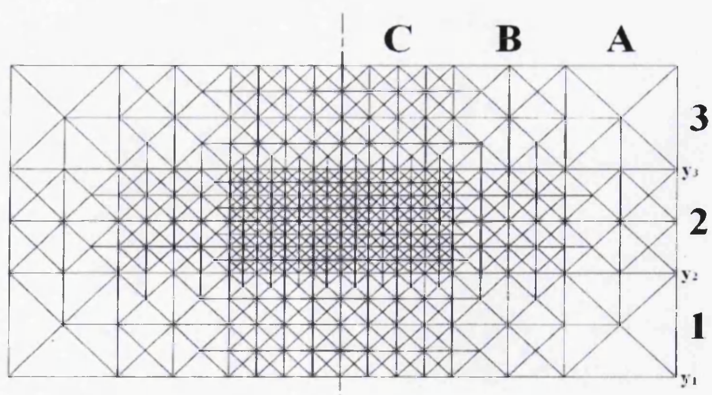


Figure 2.26: Sheet mesh example

However, using a dense mesh in the sheet leads to a very long simulation calculation time, so in order to reduce this, dense meshing in only used in areas of the sheet which are of special interest. These areas in most circumstances are where sharp bends will be formed and where accuracy is paramount.

The vast amount of calculations performed in simulation can take many days to complete. The sheet being modelled in the roll forming process may be very long. This means that at some stage the material will span the length of many of the roll forming stations and all the sheet mesh properties for that length are used and calculated. To make a simpler model, only a section of the sheet is modelled and the area of interest is created with a high density mesh.

Simulations initially performed for the EngD research, used fixed rolls with no friction. This is due to the high amount of computer power required to calculate using rotating rolls with friction.

2.9.6 Boundary conditions

To gain the most accurate results from the roll forming simulation it is necessary to introduce boundary conditions or constraints to the sheet. This is particularly useful in roll forming simulations, for example, when only half of the sheet is being profiled in the simulation.

Constraints are distributed to the sheet in very much the same why that a concentrated load would be distributed in a FE simulation. When a face of the sheet is being constrained it is important that all nodes on that face are constrained. Therefore the sheet has to be considered in 3D rather than 2D.

An example of applying boundary conditions to a sheet can be seen in Figure 2.27.

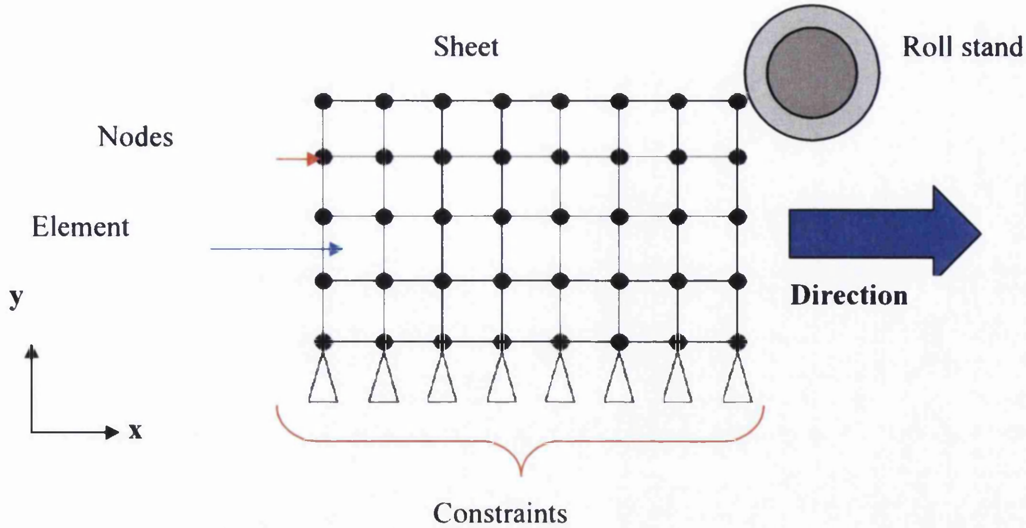


Figure 2.27: Applying constraints in the y-axis – 2D view

It can be seen in Figure 2.27 that the sheet consists of many nodes and elements. In this situation one half of the sheet is being modelled, so it only comes in contact with one side of roll forming stands in the production line.

The sheet is constrained in the y-axis on one side to keep it in a central position and is being pulled from left to right along the x-axis. As a result, when the sheet comes in contact with the roll stand the deformation that takes place will not affect the sheet position in the y-axis.

This procedure is useful due to the fact that only half of the sheet has to be modelled, this greatly reduces the number of nodal data in the simulation and therefore is much less complex. If the whole sheet was used, then boundary conditions could no longer be used in the y-axis as the force from the opposite roll stands would counteract the other. This would prove more realistic compared to reality. However, computational time would be significantly compromised.

2.10 ABAQUS for Roll Forming

The following section explains the procedure followed to create a roll forming model. It demonstrates the user friendly step-by-step operation sequence that ABAQUS follows.

2.10.1 Introduction to ABAQUS

The ABAQUS finite element modelling system consists of three programs:

- ABAQUS/Standard – this is a general purpose finite element program.
- ABAQUS/Explicit – an explicit dynamics finite element program.

  ABAQUS/CAE – this is an interactive environment that creates the input files for the models, submits the analysis, monitors the job progress and then evaluates the job when the simulation is complete.

To run a simulation an input file has to be created. This file contains all the data required for the analysis, such as geometry, material properties, applied forces and time increments etc. It also contains all meshing properties such as node/element co-ordinates and type of meshing used.

The input file is created by selecting options and submitting data in the first seven modules, Part through to Mesh, which are located in the modules toolbar on the desktop, as shown in Figure 2.28. This is designed to be followed in a logical sequence. However, a more experienced user will tend to develop their own sequence and move back and fourth through the modules.

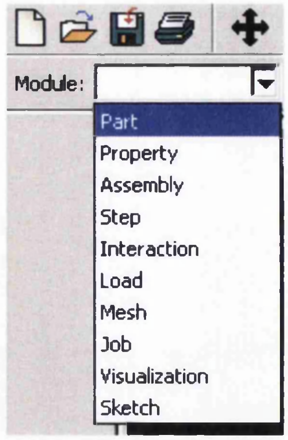


Figure 2.28: ABAQUS Module toolbar

The 'Job' option is selected when all of the model data has been selected. The last task is to create the Input file before starting the job and submitting the input file for analysis.

It is at this critical point where the input file is either submitted or rejected due to errors. Once submitted the view port at the bottom of the ABAQUS desktop is used to monitor the progress of the analysis.

Computational times for roll forming simulations vary significantly, but on a whole can take up to a few seconds for a very simple model, or many days for a more complex 3D model. Time affecting factors include computer power, meshing density and type, and also the size of the input file. As an example, a model containing ten roll stations will take much more computational time than that of a model containing one station etc.

When the simulation is complete without errors, the results are viewed in the visualization module.

2.10.2 Creating the model

Part

The part module is selected first to create all of the geometry to be used in the model. In a simple roll forming analysis the model consists of a roll and a steel sheet, therefore, creating two parts which are then saved.

The sheet is set as a deformable, three-dimensional solid and an approximate size is given. The roll is set as either a deformable body or an analytical rigid surface. When set as a rigid surface only 180 degrees of the roll can be modelled, this is explained in Section 2.3. If the roll is selected as a deformable body, then a 3D cylinder can be either given a material property definition, or can be defined as a rigid body within the 'interactions' module later in the setup. However, in most roll forming simulations the rolls are defined as rigid bodies to simplify the input file, due to the focus being on the sheet deformation not the rolls.

The sheet is created using a rectangular tool in 2D and two corners are plotted. The rectangle is then extruded to the desired width to create the 3D part.

To create a cylinder, the centre and perimeter points of a circle are defined and then also extruded to the desired width.

Property

Once a deformable part is created it must be assigned a material property, unless it has been defined as a rigid body so that it cannot deform, as explained in the previous section.

The materials mechanical options such as elasticity and plasticity can be specified including its yield stress, Young's modulus and Poisson's ratio. Various other variables can also be set such as thermal and electrical conductivity and solubility.

Assembly

In roll forming simulations the model will consist of the material and the rolls. Both of which will have been constructed separately during the 'Part' module of the software. Therefore they require assembly so that all of the constructed parts are positioned in the correct place within the simulation model.

Using the tools in this module the parts can be rotated, mirrored and also copied to create further parts.

Step

The step function is used to set the time period of the simulation, the number of steps within the simulation and mass scaling.

Mass scaling is used to create computational efficiency in dynamic analyses which involve complex contact conditions. Fixed and variable mass scaling can be used depending on the application. It is used to:

- Scale the mass of the entire model or of individual elements.
- Scale the mass on a step by step basis in a multi-step analysis
- Scale the mass at the beginning of the step and/or throughout the step.

The output variables of the simulation are also set to be saved at certain intervals. Output variables include stress, strains, displacements, forces and reactions that occur during the simulation.

Interaction

The interaction manager is used to setup the surface contact interactions, contact property and constraints.

The parts that are created and then assembled contain surfaces. As in a roll forming model with a roll and sheet some of these surfaces will contact with one another during the deformation. Therefore the surfaces are assigned an order, for example, the roll face in contact with the material can be assigned as surface 1, whilst the surfaces of the material that will contact the rolls can be assigned surface 2, and so on. However, if the rolls are defined as an analytical rigid surface then the rolls must be defined as the master surface or surface 1.

The contact property options can then be set to either Tangential or Normal behaviour. In roll forming simulations the tangential option is selected and a friction coefficient is set. This value is usually 0.3 or higher if more friction is required.

Finally the constraint manager is used if a part is to be defined as either a rigid body or analytical rigid surface. This function allows the user to select the part to be defined as a rigid body. If the part is to be defined as an analytical surface then this function must be set at the beginning of the analysis as explained in Section 2.3.

Once a part has been assigned as a rigid body, then a reference point is chosen. This point can be any point on the edge of the roll or for simplicity in the roll centre.

Load

The load function is used to create boundary conditions for all of the parts included in the model assembly.

A typical roll forming simulation will include a sheet passing through one or multiple roll stands with up to four rolls per stand. All of the rolls and parts of machinery within the production line and also the sheet will be restrained so they can only move in certain directions. Therefore the boundary conditions are applied to allow the rolls to rotate in a certain direction and to the sheet so it moves and deforms in set planes. Obviously if the simulation is 3D rather than 2D then more boundary conditions have to be set.

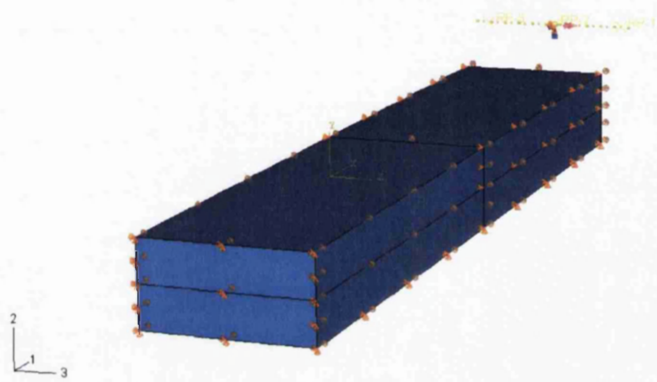


Figure 2.29: Boundary conditions applied

The model in Figure 2.29 has boundary conditions applied to it. In this case the sheet is restrained in the y and z-axis so it can only move in the x-plane.

2.10.3 Meshing Techniques

There are various types of mesh that can be used for both the roles and sheet geometry. This section discusses the use of linear C3D8R elements and Quadratic C3D20R.

Adaptive meshing

This tool enables the user to maintain high quality mesh throughout the duration of the analysis, even when large deformations occur. To do this it combines the features of pure Lagrangian analysis and also that of Eulerian analysis. It is also referred to as Arbitary Lagrangian-Eulerian (ALE) analysis.

It is very effective in an analysis such as roll forming, where a large deformation is anticipated, as the improved mesh helps to prevent the analysis from terminating due to a severe mesh distortion.

Pure Lagrangian Analysis

During this analysis it can be said that the mesh follows the material and therefore no material leaves the mesh. However, a pure Lagrangian analysis of roll forming applications will not run to completion due to excessive distortion on elements. Unless adaptive meshing is activated, then the mesh will be controlled and as a result will create a proper interpretation of most structural analyses.

Eulerian Analysis

This type of analysis can be described as the material following the mesh.

Adaptive meshing example

In this case a rectangular blank is to be deformed by a rigid die, as shown in Figure 2.30. The die is modelled with having an analytical rigid surface, as described in Section 2.3. The blank has elastic-plastic material properties.

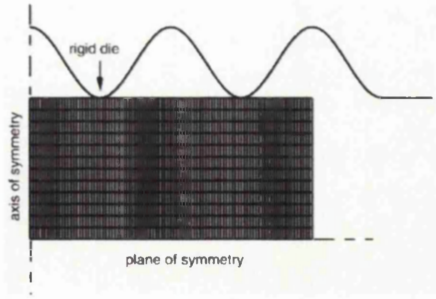


Figure 2.30: Rectangular blank and rigid die

When a pure Lagrangian analysis is performed it reaches an intermediate stage in the analysis where it terminates due to excessive element distortion at the initial contact point of the die, shown in Figure 2.31:

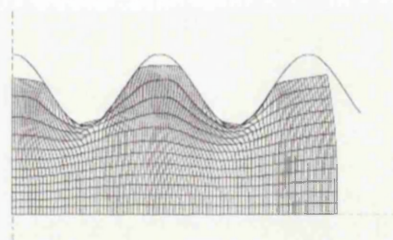
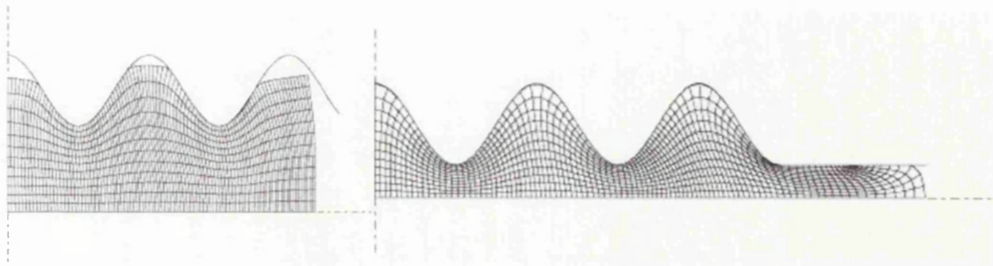


Figure 2.31: Pure Lagrangian analysis terminates due to element distortion at intermediate stage.

When adaptive meshing is activated it maintains high quality mesh and the simulation runs to completion, Figure 2.32:



(a) (b)

Figure 2.32: (a) Lagrangian with adaptive meshing control at intermediate stage.

(b) As (a) at completion stage.

Roll Meshing

This is an important factor when creating the simulation as it can cause large errors in the accuracy of the simulation.

The part is first mesh seeded, where the numbers of nodes within the part are specified. The element type is then set, in this case as either linear C3D8R or quadratic C3D20R elements, also known as 8 or 20 node, reduced integration, standard brick elements. The part can then be meshed.

C3D8/R Elements

This is a general purpose linear brick element (see Figure 2.33) and can be used with reduced integration. It has one integration point in the centre of the element. Characteristics of the element:

- The element tends not to be stiff enough in bending, caused by hour-glassing (explained later in this section).
- Stresses and strains are most accurate in the integration points.

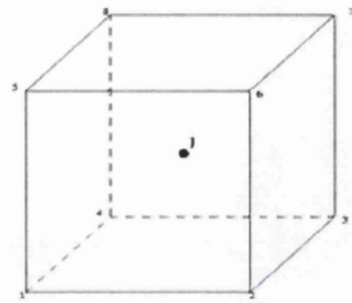


Figure 2.33: C3D8R Hexahedral element

C3D20/R Elements

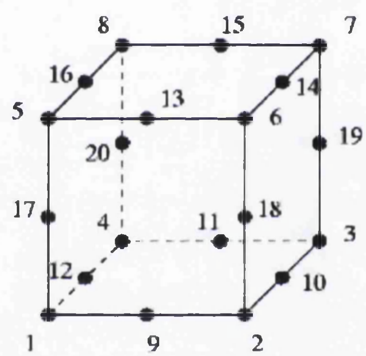


Figure 2.34: C3D20R Hexahedral element

The Quadratic 20 node element (see Figure 2.34) can also be used with or without reduced integration. Unlike the C3D8R this has more nodes and also four integration points, which tends to make it stiffer in bending. As a result of this, reduced integration is not normally used due to less hour-glassing.

Mesh Density

The parts can be mesh seeded to contain a desired number of nodes so that they have different mesh densities when meshed.

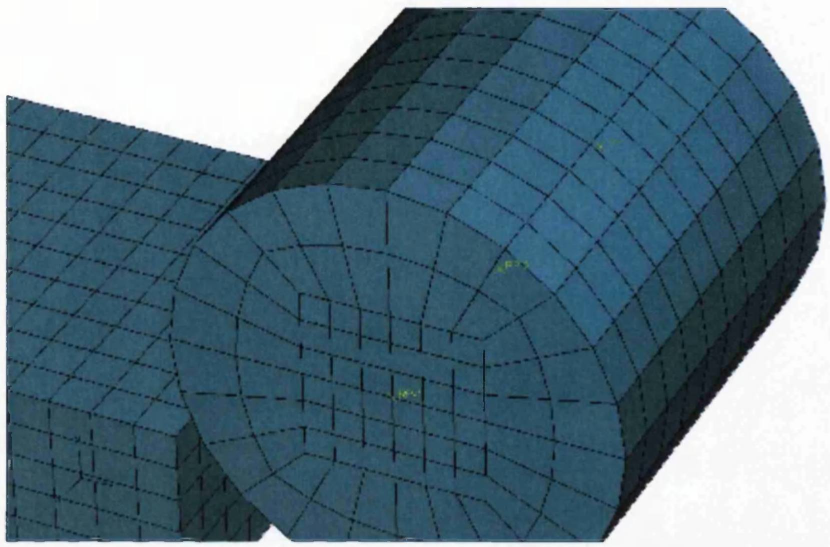


Figure 2.35: C3D8R roll mesh

Figure 2.35, shows a coarse C3D8R roll mesh which is sufficient for basic models, however, where more accuracy is required a much finer mesh has to be used.

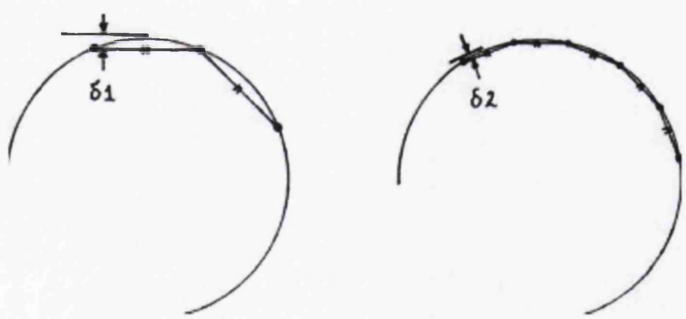


Figure 2.36: Element density in roll geometry

Figure 2.36 shows the effect of increasing element density in the arc of a roll. The fine mesh gives a better representation of the roll. However, the disadvantage of an increase in accuracy is a much more complex model due to a higher number of nodes resulting in longer computation times.

Reduced Integration

Hexahedral and quadrilateral elements can both use reduced integration. Tetrahedral, wedge and triangular elements are fully integrated. However, reduced integration and full integration elements can be used in the same mesh.

Reduced integration linear elements only have one integration point in the centre of the elements as shown in Figure 2.33. These elements also use a more accurate uniform strain formulation where the average strain values are calculated for the element.

However, linear reduced integration elements do tend to be very flexible because they suffer from a problem called hourglassing. This is where all the generated stress causes the element to distort but the stress at the integration point is zero and therefore no strain energy is generated. The element is unable to resist this type of deformation due to its low stiffness and when used in coarse meshes can often produce in accurate results. As a result "hourglass stiffness" is introduced to limit the hourglass problem and combined with a fine mesh, good results can be achieved from this type of simulation.

Job & Visualisation

The input file is then submitted for analysis. Once submitted the program checks that all the necessary fields were completed and correct. If any parameter in the input file was incorrect the simulation is aborted with errors. However, if correct the file is submitted and the simulation begins.

Computational times vary from a few seconds to many days depending on the model complexity. The progress of the analysis can then be observed.

Once completed the results are observed in the visualisation module. This allows the user to watch the simulation by animation step by step from multiple angles.

2.11 Analytical Rigid Surface

Rigid surfaces are geometric surfaces containing straight or curved line segments, rotated around an axis to form a 3D surface. The surface has a reference node that governs the motion of the surface, as seen in Figure 2.37.

The advantages of using such a surface for a roll forming simulation is that it eliminates the complex mesh usually found in roll geometry to increase accuracy. This makes the simulation less complex and speeds up the computational time. The surface is also defined as a rigid un-deformable surface. Therefore, material properties do not have to be assigned to the part.

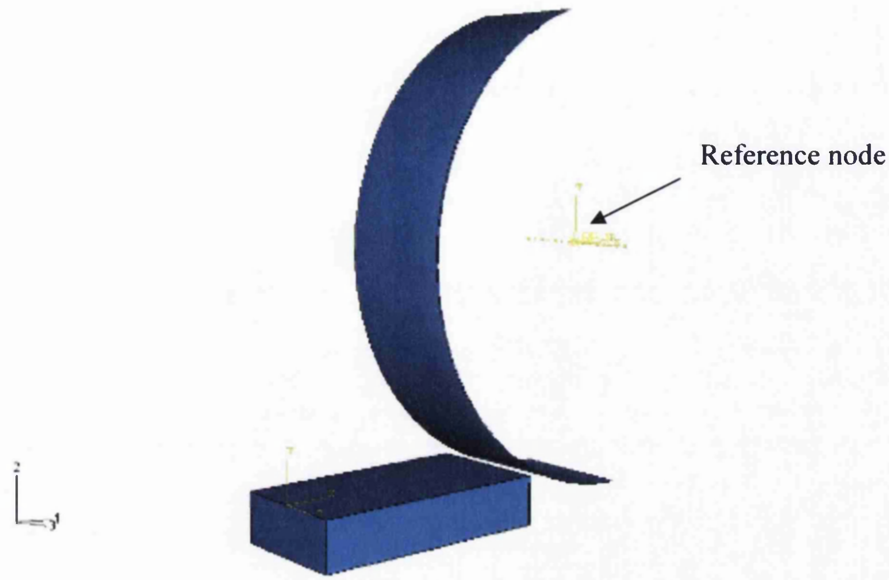


Figure 2.37: Analytical rigid surface

However, the procedure also has certain drawbacks:

- The rigid cylinder can only be modelled up to a maximum of 180 degrees.
- Contact forces and pressures cannot be contoured on the rigid surface.
- The rigid surface must be set as the master surface

2.12 Rolling friction

The effect of rolling friction has been investigated by scientists for many years due to its importance in this field of engineering. Publications on rolling friction date back to 1785, when Vince conducted experiments to determine the exact nature of friction laws.

Poschel, Scwager and Brilliantov (1999) investigated the rolling resistance of a ridged cylinder on a viscous plane. The viscous surface was modelled by a system of non-interacting damped springs. The results showed that the rolling friction coefficient shows non-linear dependence on the roll velocity, e.g. for low velocity the friction coefficient increases with velocity due to the material deformation of the surface. When a larger velocity is applied the coefficient decreases with velocity and material deformation. This therefore suggests that the rolling friction fluctuates with changes in roll velocity and rate of material deformation.

A publication by Alsamhan, Pillinger and Hately (2004) investigated the development of real time re-meshing for simulating cold roll forming using Finite Element methods. The objective of the work was to develop a re-meshing technique using a 3D implicit elastic-plastic FE program (EPFEP3), originally developed by Pillinger (1984).

The material used for the simulation was bright mild steel with a yield strength of 160 MPa and the experiments were conducted on cold-rolled trapezoidal sections. In many simulation examples researched it seemed to be a trend for scientists to eliminate rolling friction from the models, most probably to simplify the simulation. Most steel products used within simulations have a variety of surface finishes, for example, a steel sheet used for profiling could have a Galvalloy finish on the underside and a HPS200 plastisol finish on the face side. In such a scenario the friction coefficients of both surfaces would vary, the HPS200 having a higher coefficient.

2.13 Review of Literature Discussion

At the start of the EngD study the direction was to focus on a past and current problem that CP&P and their competitors experience, that of defects in composite floor steel decking. At present the majority of expertise in this field is situated in IJmuiden, therefore further knowledge in this area, here in the UK would be an advantage to the business. However, it was quickly established that to create a model simulating the profile of a steel deck section would be extremely challenging due to the complex profile of the deck. It was decided to start with a simpler profile which is produced in bulk using a roll forming line that engineers have gained a vast amount of experience using. At this point in the doctorate study, focus was diverted to wall and roof profiling lines.

The process of creating and meshing geometry using ABAQUS is discussed at depth in the literature review. The discussion focuses on linear C3D8 elements. However, many other element types exist, such as tetrahedral and wedge elements.

It was found during the literature review that linear C3D8 elements can be successfully used in simulations in which large deformations occur by using C3D8R. This uses reduced integration which helps to provide realistic plastic deformation characteristics of the material. The variation of this element type is discussed later in this report.

CHAPTER 3: BACKGROUND

To create a simulation model, various FEM packages were used in conjunction with the literature review of packages to determine the most suitable for the Engineering Doctorate study. This chapter looks at the training conducted on each package reviewed, including the work carried out at the Corus RD&T in IJmuiden.

3.1 ABAQUS Training

The Finite Element Modelling training initially began with using ABAQUS/CAE. This software being readily available throughout Corus and the University of Wales proved useful for training and could be used at a later date. It has similar properties as that of the INDEED software as discussed in Section 2.8.

3.1.1 3D Hinge Models

The training consists of tutorials, guiding the user step-by-step through the design of a hinge, see Figure 3.1.

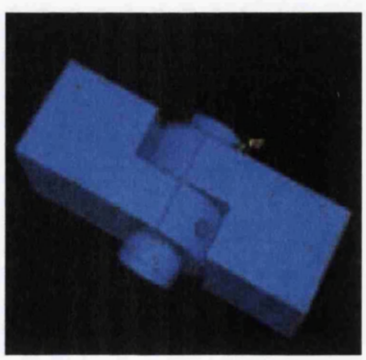


Figure 3.1: 3D construction of hinge

The hinge product was constructed, meshed, boundary conditions set and loads applied, before finally starting the simulation. A 3D stress plot in Figure 3.2 shows the stress distribution throughout the hinge once loads were applied. It can be seen that the area of low stress is focused on the join area as the two parts are rotated around the hinge axis (in this case the centre of the hole).

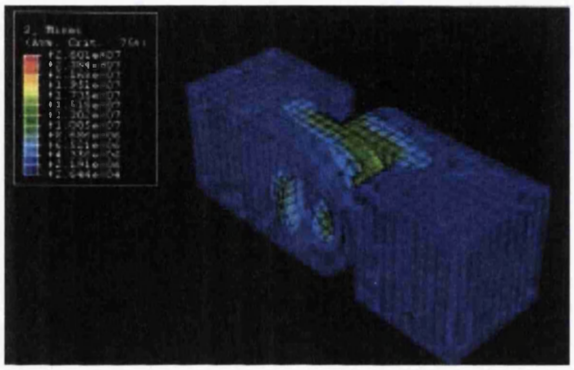


Figure: 3.2: Analysis of hinge

3.1.2 ABAQUS 3D Example problems

To gain experience using ABAQUS, sample tutorials were followed to gain familiarity with how the software could be used for roll forming simulations. Once completed and understood then the package was used to create models more realistic to the project goal. ABAQUS provided a number of forming analysis examples within its example problems manual, which is also available online. Three example tutorials that were relevant to the nature of this project are available as described below:

- Rolling of thick plates – A steel plate with an original cross-section of 40mm by 400mm and length of 92mm, reduced to a height of 30mm by passing it through a single roll forming stand consisting of one roll (radius 170mm).

- Flat rolling: Transient and Steady-state – A flat rolling simulation where three different methods are used. A pure Lagrangian approach, an adaptive method approach using a Lagrangian domain, and a mixed Eulerian-Lagrangian adaptive meshing approach. An explanation of the above procedures are given in Section 2.10.3. An example a model completed is discussed in Section 3.1.3, below.
- Section rolling – Analysis of a symmetrical I-section using two rigid rollers. The steel blank having dimensions 775x176.5x24mm representing a quarter symmetry model. Roll 1, radius of 747mm and all its degrees of freedom were constrained except rotation about the z-axis, where an angular velocity of 5 rad/sec was applied. Roll 2 had all degrees of freedom constrained except rotation about the y-axis.

As the doctorate research focused on roll forming of steel strip using multiple roll stands it was essential to practice the flat rolling and section rolling example tutorials. However, the aim was to gain experience using ABAQUS and learn the basic procedures, so it was decided to begin with flat rolling examples using a combination of Lagrangian and adaptive meshing techniques.

3.1.3 3D Roll forming model – Analytical Roll.

A 3D roll forming model was created to determine the effect of the following parameters:

- Adaptive Meshing
- Analytical Rigid Surface

The adaptive meshing analysis aid helps to maintain accurate mesh when large deformations occur. The roll could also be defined as an analytical rigid surface from the beginning of the model creation rather than creating a deformable cylinder, meshing the part and then defining it as a rigid body later in the setup.

Part Geometry

The sheet dimensions used were as specified in the tutorial as 224x20x50 mm. The rigid roll geometry had a diameter of 400mm and extruded to a width of 700mm.

The roll was positioned to deform the material and reduce its thickness from 20mm to 10mm as in previous simulations.

Sheet Meshing

The roll was defined as an analytical rigid surface with 180 degrees of the geometry being visible. This was possible due to the roll in this case being symmetrical.

Therefore the only part to be meshed in this analysis was the sheet itself. Linear C3D8R elements were used as there was no need for accurate roll meshing.

The number of elements in the sheet were set to (40, 6, 7), giving a total of 1680 elements.

Transportation of sheet

The friction of the roll in contact with the sheet would pull the sheet through. Therefore, the sheet was applied with an initial velocity to initiate the contact between the two. The velocity of the sheet was then governed by the roll velocity.

Results

The initial velocity applied to the sheet initiated the contact to the roll at this point the rotating rigid roll gained traction. The initial deformation was uniform and the result of using the adaptive meshing analysis was evident. Unlike the pure lagrangian analysis the material and mesh deformed together compressing at it deformed. This can be seen in Figure 3.3:

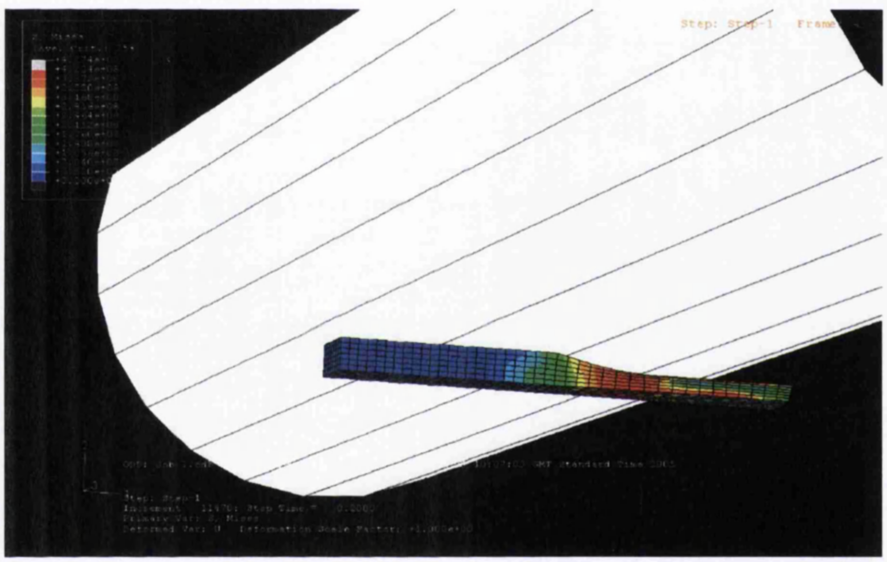


Figure 3.3: Rigid roll deforming the steel sheet

The size of the roll made an obvious impact on the accuracy of the simulation and due to its size the length of the sheet was deformed in less than one full revolution of the roll.

The sheet in Figure 3.4 shows a uniform stress distribution. The red area shows where the roll has exceeded the materials elastic limit (yield stress) of 168.2 MPa and then deformed plastically.

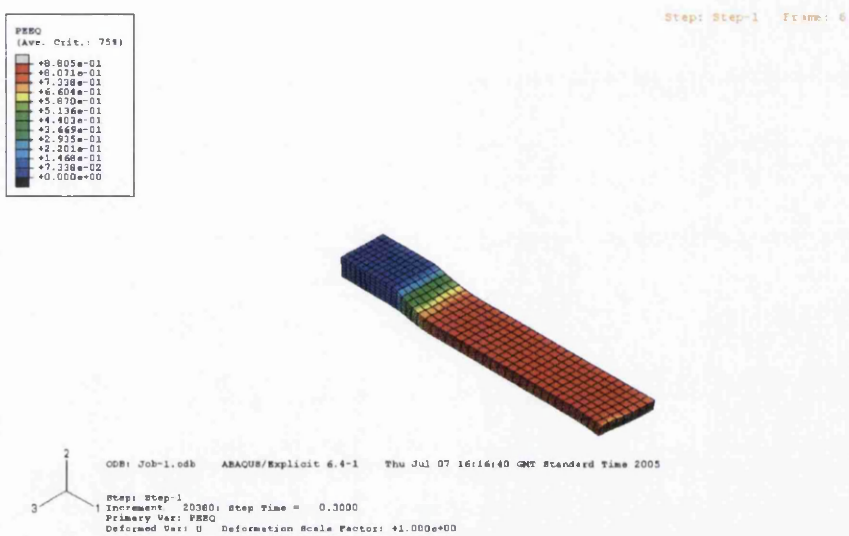


Figure 3.4: Sheet deformation with roll removed

The material coloured green in the sheet indicates that the material has been deformed but is still within its elastic region and would return to its original shape if the roll force were to be removed. The Blue area shows the material which is unaffected by the deformation.

Conclusion

The simulation performed was setup with similarities to the tutorial. However, in this simulation the roll diameter and width were increased and material properties changed.

The use of a large roll enabled the sheet to be deformed in one revolution.

The use of adaptive meshing ensured that quality mesh was maintained during the analysis and that the material and mesh worked together instead of one following the other, as seen in both lagrangian and Eulerian analysis.

3.2 MSC. Patran

Finite element modeling packages tend to have a similar procedure from creating the input file through analysis to visualizing the results. However, the toolbar layout, keywords and tool functions do vary from software to software. As a result when using a new FEM package an experienced user has to adjust to the unfamiliar layout and start with simple tasks for familiarization. Experience during the doctorate included a brief familiarization using ABAQUS and then a more detailed training period using INDEED. Therefore, the first task in the Patran training was to complete a number of simple example simulations. The following simulations were used to gain familiarity with the package:

- **Thick Cylinder Analysis** - The thick cylinder example was simulated in 2D. As the cylinder was symmetrical only one quarter of the cylinder was modeled. An internal force was then applied to act on the cylinder wall and the stress distribution was analysed.
- **Hole in a Plate Analysis** - performed using the software was also a 2D analysis. In this simulation the geometry was more complex with a more complex mesh. The plate was fixed with an external force applied and the resultant deformation and stress distribution analysed.

3.3 INDEED Doorframe Simulation

3.3.1 Introduction

Corus RD&T located in the Product Application Centre (PAC) in IJmuiden currently use Indeed along with various other FEM packages to run forming simulations.

Following basic Abaqus FEM training the next step was to learn the INDEED software (explained in Section 2.9) at the PAC.

The initial training carried out over a three week period commenced in March 2004. It consisted of basic FEM instruction and INDEED software familiarisation. An ongoing project conducted in IJmuiden was then used to progress training and set to be initially used back in the UK.

This section discusses the procedure and outcomes of an existing 3D FEM simulation of a doorframe product (see figure 3.5) produced by Overeem BV, a customer of Corus Colors. This product was used in order to develop the existing roll forming modelling software used for simulations of tubes. The development was essential to enable simulations of other profiled products to take place and to identify strain deviations along the cross section of the product, at sharp bends for example.

As Overeem BV produce a wide range of roll formed products the door frame profile was selected due to its trouble free record during the production process.

The company had previously agreed to their product to be used to adapt the simulation, as well as supplying data such as the setup of their roll forming line and strain measurements of the door frame panel itself.

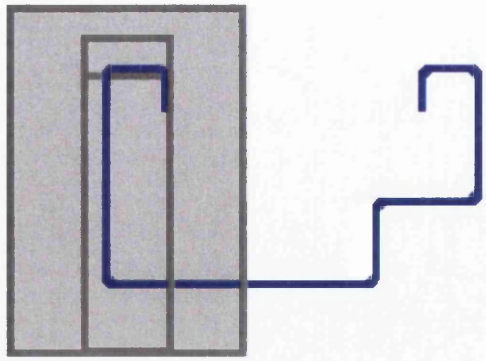


Figure 3.5: Door frame profile from Overeem

As a result, the computer model was adapted and one side of the door frame profile was successfully simulated. The simulation of the remainder of the profile for training purposes is fully discussed in this section.

Geometry of product

The doorframe profile was split into two sections to increase the speed of the simulation. As the product has a large centre web it was assumed that the left and right side of the profile would not affect one another and therefore symmetry conditions were applied to the centre of the web. Figure 3.6 shows the side initially simulated for the validation.

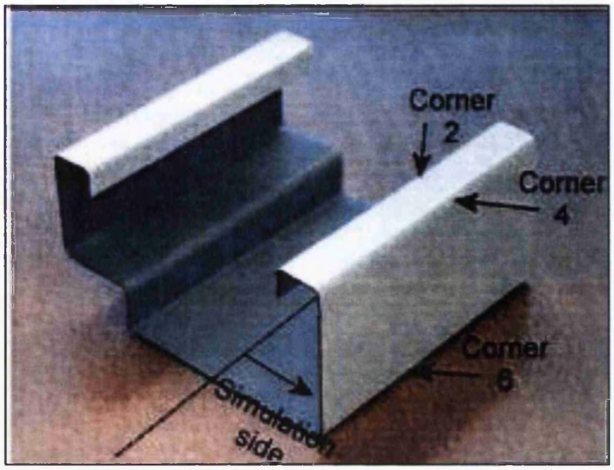


Figure 3.6: Selected side of doorframe profile

The right side of the profile was slightly more complex as it incorporates five, 90° bends in its design. To reduce the size of the simulation it was agreed to initially focus on two of them, shown in Figure 3.7.

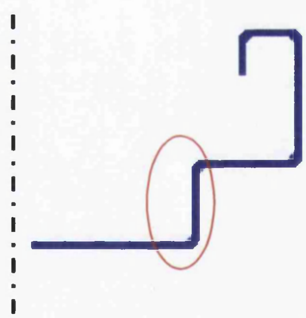


Figure 3.7: Bends modelled in right side of profile

3.3.3 Process

Colour coated strip steel provided by Corus Colors is supplied to Overeem, where it is passed through 24 roll stands. Figure 3.8, shows one roll stand in the production line. The finished profile is then cut to the required length specified by the customer.

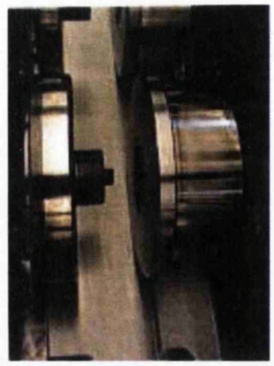


Figure 3.8: Rolls in the Overeem production line (picture courtesy of Corus RD&T)

The properties of the strip used are obtained by using tensile testing. The results are shown in Table 3.1.

E (MPa)	ReH (MPa)	Rp (MPa)	Rm (MPa)	n	C (MPa)
196333	340	314	371	0.167	590

Table 3.1: Material properties of strip used for doorframe

3.3.4 Meshing of sheet and rolls

As discussed in Section 2.9.4, the sheet is divided into various mesh densities, varying from 1 (rough) to 4 (fine). This is to gain more accurate results on the bends of the profile, whilst at the same time speeding up the simulation.

The central position of the bends were found from the existing simulation and entered. As a result, the areas on the sheet that were to be formed during the simulation were given fine mesh.

3.3.5 Boundary conditions

As only one half of the doorframe profile was being simulated, boundary conditions were applied to the edge of the sheet to keep it central throughout as it was passed through the roll stands.

An explanation of this procedure is explained in Section 2.9.6.

3.3.6 Running the simulation

The simulation was to profile two corners of the doorframe. To do this only seven roll stands were used to achieve the required bends in the sheet. Stands No.1 to 7 were used, where Stand No.7 was the set of guide rolls at the beginning of the production line and Stand No.1 the final set of rolls used to profile the bends.

3.4 Roll forming line Study.

The aim of the doctorate research was to simulate a roll forming line, therefore a suitable line was required to use for validation. However, before any analysis could take place it was essential to liase with Corus engineers to gain information on what was available. This section discusses the recommended profiling lines, specifications of the tooling and the chosen tooling for study.

3.4.1 Introduction

As a business unit of Corus, Panels & Profiles (CP&P) have over 40 years of experience in the metal profiling industry. They have an extensive product range that is unparalleled within the industry including products such as composite panel systems, roof and wall panels and composite floor decking. All of which are profiled using a large range of roll forming lines based at two locations in the UK, Tewkesbury and Ammanford, South Wales.

3.4.2 Selection of roll forming mill – Celtic Line

The majority of the profiles produced are trapezoidal sections, which vary in depth, width and steel grade. The selection of a suitable profiling mill was based upon the following parameters:

- Simple profile – no complex shapes or stiffeners incorporated into the design.
- Steel grade – a popular organic/zinc coated grade with average strength.
- Production line – easy access and availability for validation purposes.

The selection of a simple profile was paramount for the simulation of the first model, as more complex profiles also incorporate a more complex array of rolls, increased number of rolls and there is also an increased risk of defects. As a result CP&P offered two similar profiling lines which could be used in a validation trial.

3.4.3 Celtic Line profile

The Celtic line has been a leading agricultural and light industrial product for the past 20 years. Profiles include corrugated, trapezoidal and composite sections. Trapezoidal profiles are produced using two sets of rolls which are interchangeable when required. These are shown in Figure 3.9, below:

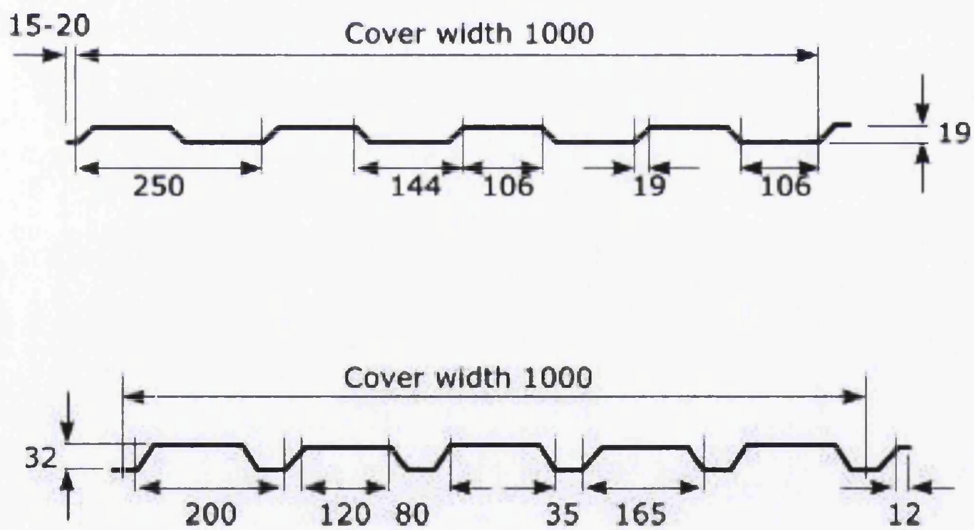


Figure 3.9: 1000/19 and 1000/32 profile.

The above Celtic line has the following specifications:

Roll set [mm]	No of roll stations	Adjustment roll stands	Steel gauge [mm]	Line speed [m/min]	Products
1000/19	18	10	0.4/0.5/0.7	39-48	HP200 & HPS 200
1000/32	18	17	0.7/0.9/1.0/1.2	39-48	HP200 & HPS200

Table 3.2: Celtic line specifications.

The roll sets in the Celtic line are solid one piece construction rolls which are replaced with new tooling in set intervals due to wear caused by the high forces, heat and friction during rolling.

The rolls for the 1000/32 profile are made from solid steel (see Figure 3.10). Due to the high forces involved in the process and heat generated the rolls are replaced with new tooling in set intervals to avoid creating any imperfections in the profile.

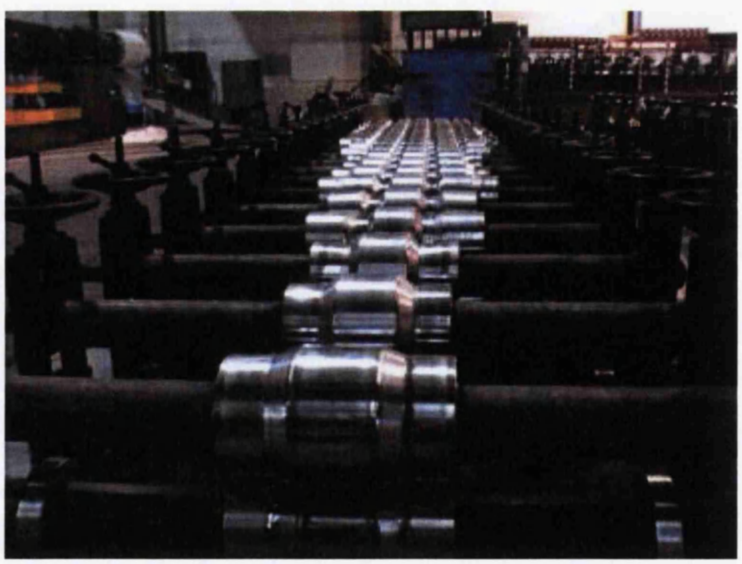


Figure 3.10 – Celtic 1000/32 roll stands (stand No.1 in foreground)

Roll stands No.1 & 2 (see Figure 3.11) form the centre web in the trapezoidal profile and as the sheet continues through stands 3 to 18 this is repeated towards the inboard and outboard edges of the sheet to complete the panel.

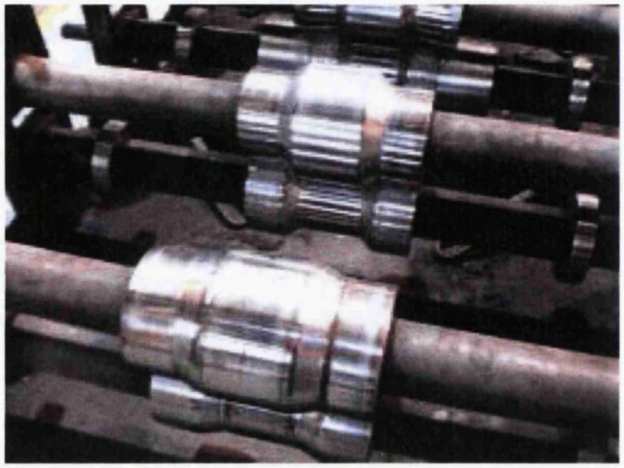


Figure 3.11 – Celtic stands No.1 & 2.

3.4.4 Profile Line No.2

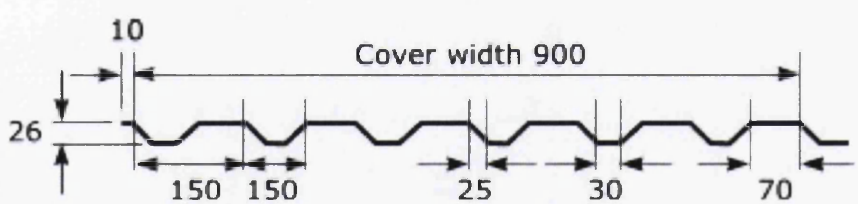


Figure 3.12: – 900/26 Profile.

The second line suitable for the simulation uses both HP200 and HPS200 products and has an almost identical profile to that of the Celtic profile. However, the final cover width of the profile is slightly less than that of the Celtic profile at 900mm. The profile has a depth of 26mm as shown in Figure 3.12, above.

Figure 3.13 – 900/26 production line.

The 900/26 production line in Figure 3.13, is more modern compared to the ageing 1000/32 line. Upon inspection modern computers are used for the operating stations, the rolls are reversed and each rolls is divided into two sections, Figure 3.14. The reason for the design is so the roll can be replaced if worn.

Figure 3.14 – Stand No.1 to 17

3.5 Selection of the Profiling line

The selection of the most suitable profiling line was determined by looking at the resource of information for both stands. Profiling line No.2 is a modern line with new tooling, however, stand information such as tooling geometry was unavailable.

Therefore, Celtic line No.1 was selected as tooling geometry was available and CP&P have a close working relationship with the tooling manufacturers, A.S.C Machine Tools in Washington, USA. It was desirable that operators have more line experience using the 1000/32 stand, which would influence the plant trials.

CHAPTER 4: FINITE ELEMENT MODELLING (FEM) CASE STUDIES

The roll forming simulations performed at Corus RD&T incorporated fixed rolls without friction. The steel sheet was then pulled through the roll stands causing the deformation stage by stage until the final shape was achieved. This approach works very well for roll forming simulations and in most cases provides accurate information which is comparable to the actual production line.

This chapter looks at the development of basic FE models starting with a fixed rolls, leading on to rolls with an angular velocity and finally a profiling line model with rotating rolls and a friction settings.

4.1 Fixed Roll Simulation

4.1.1 Rationale

A number of simple models were created to gain a better understanding of how roll forming simulations are executed using ABAQUS. The models could then be used as a platform to be developed into more complex simulations.

- **Aim**

To create a basic model roll forming model consisting of a single roll and thick strip. The aim of the initial analysis was to apply a velocity to transport it beneath the fixed roll to cause the deformation.

- **Parameters**

Geometry

The sheet and roll cylinder were created using the techniques discussed in section 2.10.2. The sheet measured 224x20x50 mm as in the tutorial, however, the roll dimensions were much smaller with a diameter of only 40mm. It can be seen in Figure 6.1, that the roll geometry is reasonably small in comparison with the sheet. In a working profiling line the ratio of roll diameter to sheet thickness would be around 200/1. However, the purpose of this model was to create a simple flat rolling example, more accurate dimensions are used in later models.

During assembly of parts the roll was positioned 10mm from the leading edge of the sheet and 10mm lower than the top surface, enough to deform the material to half the sheet depth.

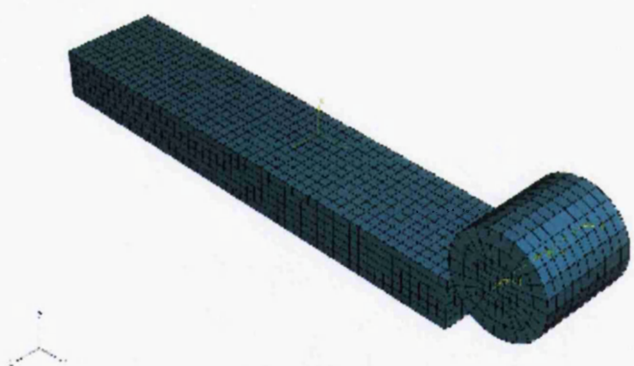


Figure 4.1: Fixed roll simulation sheet and roll geometry.

Meshing

The mesh was generated using large linear C3D8R elements in this model to reduce the number of nodes to below 100,000, the maximum permitted when using the ABAQUS teaching licence, which was being used at the time.

To mesh seed the roll, the cylinder was partitioned via a square through the centre of the cylinder which was then extruded through the cylinder to the opposite side. Partitioning using this method divides the roll into quarter segments making it much easier to mesh seed and mesh a cylinder. This can be seen in Figure 4.2.

Boundary conditions

The boundary conditions within this model included the following:

Roll – reference points 1, 2, & 3 fixed in (x, y, z) axis with zero angular displacements.

Sheet – Velocity applied to the whole sheet of 2 m/s.

Sheet – Bottom of the sheet fixed in (y, z) axis.

With above conditions set the sheet was free to move with a velocity in the x-axis until it contact was achieved. The velocity was set for the duration of the simulation in order to force the sheet under the fixed roll and allowing the sheet to deform in any direction.

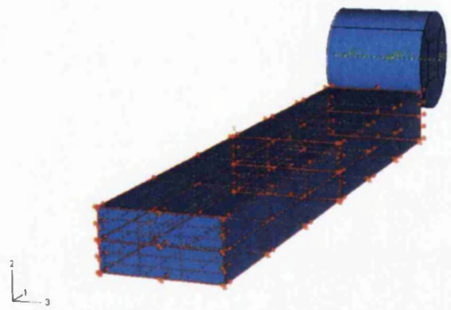


Figure 4.2: Fixed roll simulation model boundary conditions on strip section.

- **Analysis 1**

The results shown in Figure 4.3 clearly showed that the material was deformed intensely. The steel strip was deformed as intended and its thickness was reduced to 10mm. However, the material displacement was in the z-axis to both sides of the roll. As a result the sheet width increased by 50%.

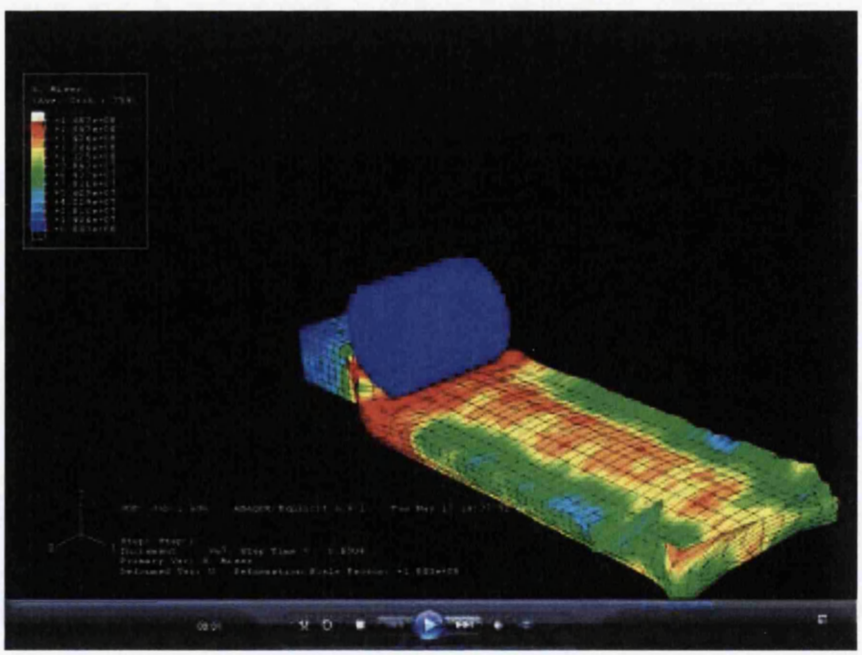


Figure 4.3: Analysis 1 – Sheet deformation

The mesh and material deformation was as expected as the adaptive meshing technique was not used. However, the mesh distortion was quite severe in specific areas which created some non uniform material deformation which was unexpected.

In conclusion the analysis performed well considering the setup of a fixed roll, high sheet velocity and no meshing control applied. However, the results were unrealistic in comparison to the same simulation carried out in the ABAQUS tutorial, where the material and mesh deformation was precise and stable.

Therefore, it was decided to carry out further work to this model and experiment with its boundary conditions and roll dimensions in an attempt to make the mesh and material deformation stable.

- **Analysis 2**

Model refinement

The model created and observed in Section 4.1.4, performed as predicted. However, work had to be carried out to gain similar results to that of the flat rolling tutorial. Therefore, separate analyses were carried out with different boundary conditions to the initial model to observe any variation in the result.

The previous analysis saw a velocity applied to the whole strip of 2 m/s. This was reduced to 1 m/s and applied to the bottom surface of the strip. The change would replicate the strip being transported by rotating rollers on the underside.

Results

The strip deformation shown in Figure 4.4 is less intense and it can be seen that the maximum stress reached is lower throughout the strip during the simulation. However, due to the change in velocity applied to the bottom of the strip, the material at the top of the strip was stopped by the roll towards the final stages of the simulation, causing the material to stretch. As a result further attention was required looking at the position of the applied velocity on the strip.

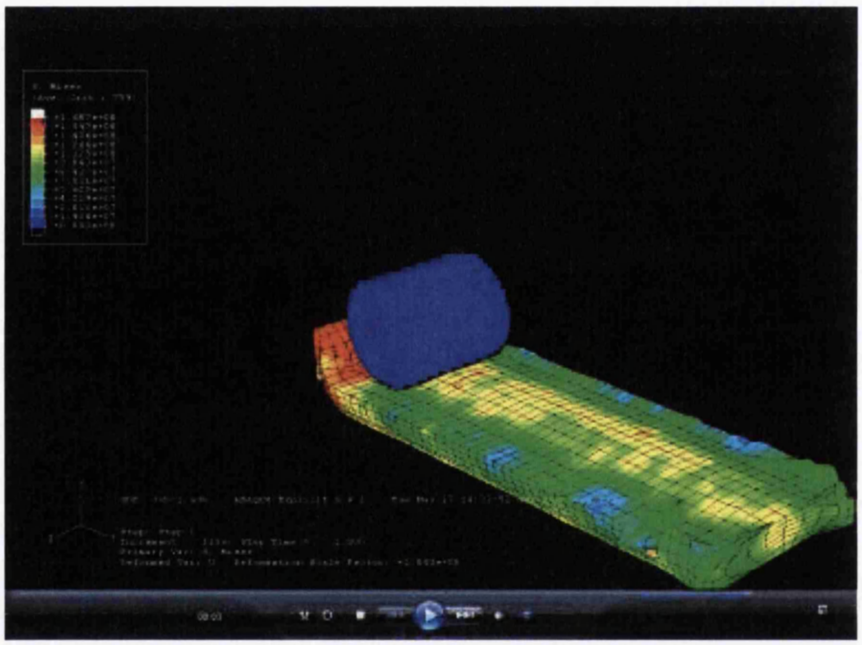


Figure 4.4: Analysis 2 – Sheet deformation

- **Analysis 3**

The applied velocity was changed from the lower surface of the sheet and applied to the front surface of the sheet. This was intended to replicate the sheet being pulled passed the roll.

Results

The material collected at roll, obstructing the deformation and the sheet stretched in a similar way to the final part of the simulation in Section 4.1.5. However, due to the increased obstruction with the roll the material stretching was more severe and therefore unrealistic.

- **Discussion of Analysis Results**

It was found that to successfully deform the sheet using a fixed roll the velocity had to be applied to the entire sheet. This was found to be the only method to reduce the sheet thickness to half its original thickness without material collecting at the roll surface and subsequently causing the sheet to stretch.

In conclusion, Analysis 1 was deemed the most successful. However, further work to this model could include reducing the amount of deformation by the roll to less than 10mm to 5mm for example. The velocity of the sheet could also be reduced. The original speed of the sheet was set to 2 m/s and later to 1 m/s in Analysis 2. This velocity is still high when compared to a typical roll forming line operating speed of 0.3 to a maximum 1.25 m/s.

4.2 Rotating Roll Simulation

4.2.1 Rationale

The results gained in Section 4.1.4 were as predicted, however more work was required to make them realistic. The use of a fixed roll caused unexpected mesh and material distortion which was probably increased due to the strip velocity and the position of the applied velocity.

4.2.2 Aim

The aim of the next procedure was to apply an angular velocity to the single roll and introduce sheet and roll friction. The prediction being that with added roll velocity the sheet velocity could be removed as the friction between the roll and sheet would pull the sheet through. The model created in Section 4.1 was used, again using pure lagrangian analysis and meshed rolls.

4.2.1 Parameters

Applying an angular velocity to the roll:

The procedure to apply rotation to the roll was straight forward. In this analysis the roll surface was defined as a rigid surface so that no material definition had to be applied in the property module. The rigid surface option was applied in the interactions module with three reference points along the roll axis defined as the centre of rotation.

The angular velocity was set in the boundary conditions option in the load module. As the strip was to move in the x-axis the roll rotation was around the z-axis. An initial angular velocity of 6.28 rad/sec was applied, as specified in the ABAQUS tutorial. Therefore, the following calculations were used to find the resultant strip speed:

Roll circumference = $2\pi r = (2 \times \pi \times 20) = 126$ mm.

6.28 rad/sec = 360 deg/sec or 1 full rotation.

Sheet speed = 126 mm/sec or 0.126 m/sec.

Therefore, assuming the roll would be in continuous contact with the strip with no losses due to slip, the strip would travel at 0.126m/sec.

Transporting the sheet

The sheet in this model was to be pulled and deformed by the roll simultaneously. Therefore there was no need to apply a velocity to the sheet. However, as the sheet and roll in the model were assembled with a 10mm distance between them, an initial velocity had to be applied to the sheet to initiate contact before friction could take over.

An initial velocity as specified in the tutorial of 0.3 m/s was applied in the boundary conditions menu. This time the velocity was applied to the whole sheet section.

4.2.2 Analysis 1

The simulation started as predicted, rolls rotating and initial deformation of the sheet. However, the time period for the simulation was set at 1 second. Due to roll diameter being small and having an applied angular velocity of 6.28 rad/sec the roll movement for the total duration of the simulation was minimal in comparison to the tutorial example roll which had a diameter of 350 mm and deforms the length of the sheet in one step.

4.3 Roll Pass Simulations

4.3.1 Rationale

Following the simple deformation simulations consisting of a thick sheet and small roll cylinder the next stage was to take the model one step further and make the simulation more realistic by introducing multiple rolls and various parameters such as rotation and roll friction.

4.3.2 Aim

Using similar roll and strip geometry previously used for models in Sections 4.1 to 4.3, the aim of this simulation was to successfully pass the steel strip through two rotating rolls using roll contact and roll friction, without causing permanent material deformation to the strip.

Also to investigate what effect if any, the mesh density has on the outcome of the simulation by using a coarse and a fine mesh in two separate analysis.

4.3.3 Geometry & Assembly

Rolls

The purpose of this particular model was to focus on the behaviour of the steel strip passing through the roll stand with a friction setting and angular velocity applied to the rolls. To do this a second identical roll was added to the model to represent the lower roll of roll stand. The resultant rolls had a diameter of 40mm and width of 100mm, which were small in comparison to the full size production rolls looked at in this thesis, but suitable for the purpose of this simulation.

Strip

In this scenario the steel strip was to pass through two rolls (An upper and lower). Therefore, boundary conditions were applied to the strip centre to restrain the centre of the strip in both x and y axis. This would enable the upper and lower surfaces of the strip to be deformed by the rolls and at the same time ensure the strip remained aligned as it passed through the rolls.

To do this two strip sections were created both measuring 224x10x50 mm, positioned together and merged together to create one thick strip section, measuring 224x20x50 mm. This procedure created a centre surface in the strip which was used to apply boundary conditions.

Assembly

The rolls were assembled with the strip as shown in Figure 4.3, with elements aligned, as if the surfaces of each part were touching. The rolls were also positioned -10mm from the leading face of the strip to ensure there was maximum contact between to parts.

The strip was positioned on the outboard side the rolls as this is the best vantage point for viewing the simulation.

4.3.4 Steel Properties

Rolls

To ensure the surface of the rolls could not deform during the analysis the rolls were defined as rigid bodies.

Strip

The strip mechanical properties were taken from the Corus materials portfolio. It was decided to use the mechanical properties of Z35, giving a yield strength of 350 MPa.

4.3.4 Partitioning and Meshing

Partitioning

Before meshing the rolls the parts required partitioning. The procedure used is explained in Section 4.1.2, and shown in Figure 4.5.

Meshing

C3D8R elements were used to mesh the model as in previous simulations. However, to increase the accuracy of the model a more dense mesh was used. This was achieved by increasing the number of elements on the roll circumference and width.

The strip was given a coarse mesh containing 3000 elements.

- **Boundary Conditions**

Rolls

Boundary conditions were applied to all reference points in the centre of the upper and lower rolls (see Figure 4.5). Conditions applied were to restrain the rolls were as follows:

- Displacement – Set to (0, 0, 0), to maintain the rolls in a fixed position.
- Angular velocity – Set to (0, 0, -6.28) upper roll and (0, 0, 6.28) lower roll.

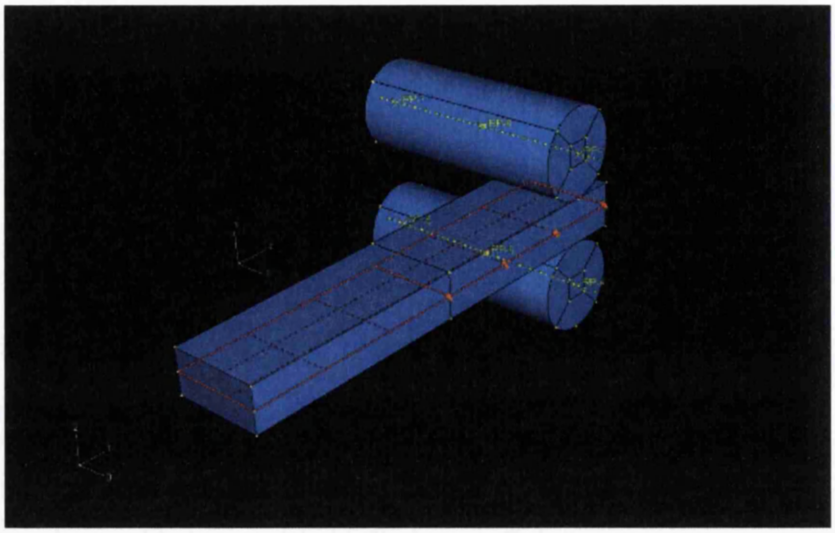


Figure 4.5: Partitioning and Boundary conditions applied to the Roll Pass model.

Strip

The strip was created by merging two sections together which creates a centre surface. This can be seen in Figure 4.5, highlighted in red. Boundary conditions (x, 0, 0) were applied for displacement which would allow the centre of the strip to move in the x-axis but fixed in both the y and z-axis.

Interaction

The friction coefficient required for the model was unknown. As a result flat rolling tutorial examples from ABAQUS have the friction set to 0.3. However, Flat/cold rolling simulations usually incur large deformations and reduce the thickness of the section, thus having a low friction coefficient. The centre for Advanced friction Studies recommended that steel-on-steel friction coefficient should be 0.57. Therefore it was decided to use this coefficient as the model was assuming an all steel geometry.

- **Analysis 1**

Using the initial settings defined above, the rolls were unable to grip the strip and rotated on the surface without moving the strip. As a result the roll gap was reduced in small increments to apply pressure on the strip. The gap was reduced by 0.0025 mm in each increment and the simulation restarted. However, this had little effect until the gap was reduced by a total of 0.01 mm which provided sufficient compression for the rolls to grip the strip and pull it through the rolls. Therefore each roll was pushed into the strip surface by 0.005 mm, resulting in a strain value of 0.2.

The result shown in Figure 4.6, shows the rolls pulling the strip once sufficient traction had been achieved with the strip surface. The area of high stress (shown in red) can be seen where the rolls started rotating on the strip and in a small area have plastically deformed the material whilst gaining traction. However, once in motion the strip continued in the x-axis and the stress dissipated, causing little or no element distortion.

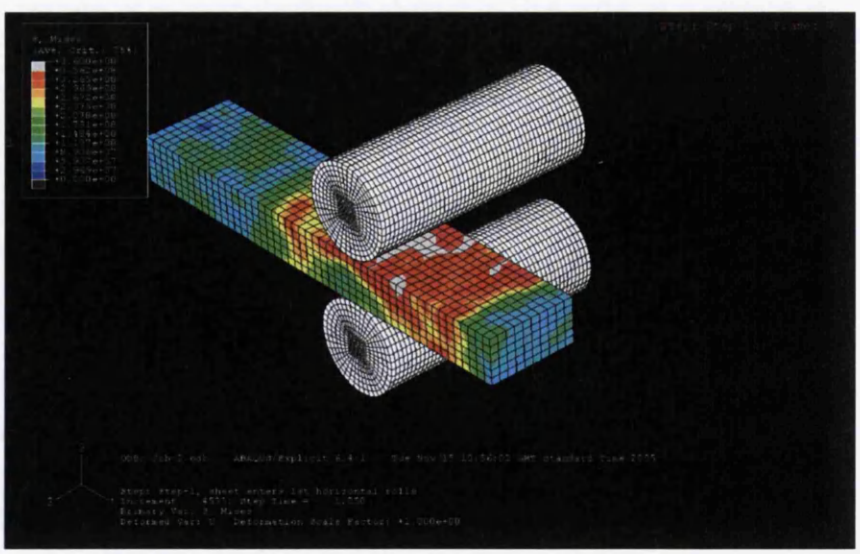


Figure 4.6: Analysis 1-Stress distribution through the strip

- **Analysis 2**

Rationale

Despite being satisfied with the small amount of deformation which was seen in Analysis 1 (Figure 4.5), a second model was generated to refine the sheet mesh. The main reason for running such a simulation was in order to observe the effect of increasing the mesh density. As discussed in the review of literature, Section 2.10.3, when using C3D8R elements a fine mesh is required to gain satisfactory results. Therefore, the element density was increased to 20,000 elements.

The refined mesh model, shown in Figure 4.7, clearly highlights the deformed surface area where the rolls were initially positioned. It can also be seen that once the rolls gain traction with the strip and it begins to move the distortion disappears.

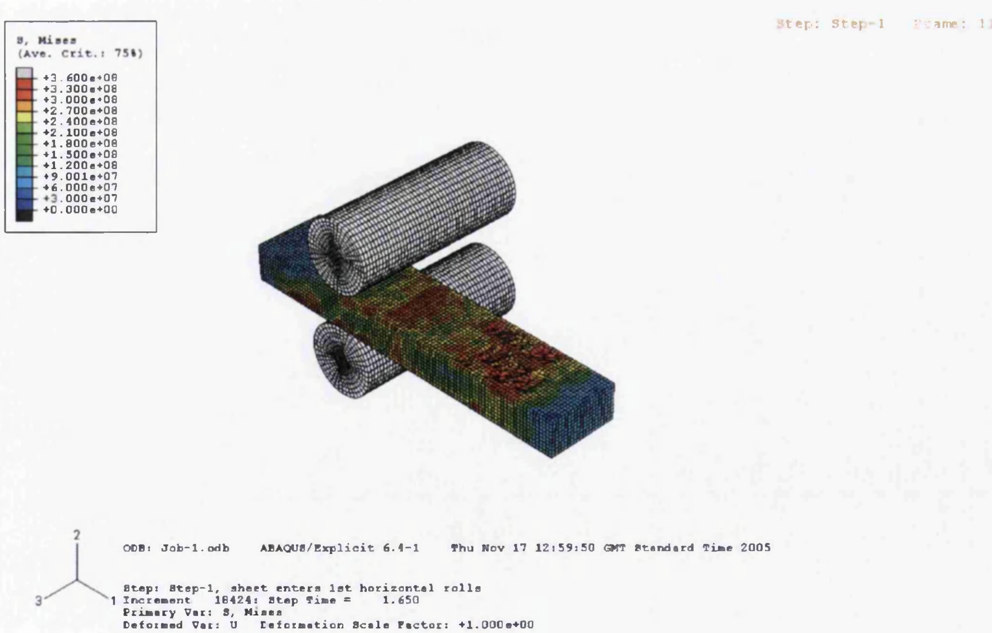


Figure 4.7: Analysis 2 - Refined mesh model

The results of this simulation prove that a higher mesh density gives a clearer picture of the stress applied and resultant strain on the material. However, the consequence of an increased mesh density is an increased computational time and therefore a compromise between the two has to be established.

4.4 Roll Pass 2 Simulations

4.4.1 Rationale

Following the simulations in Section 4.3, a similar model was created using larger rolls and a thinner gauge strip.

4.4.2 Aim

The first aim of this model was to pass the strip through the rolls using friction without causing material/element deformation.

The second aim was to run two models to investigate the effect of Reduced Integration in the mesh control (discussed in Section 2.10.3).

4.4.3 Geometry and assembly.

The assembly included two rolls and a strip as before, however, the roll size was increased to represent rolls from a profiling line roll and the strip depth was reduced. The geometry dimensions were as follows:

Rolls		Strip	
Diameter	200mm	Length	400mm
Width	200mm	Width	50mm
		Gauge	10mm

Table 4.1: Geometry settings

The rolls were positioned at the leading edge of the strip and the clearance was reduced to 9.99mm.

4.4.4 Partitioning and Meshing

The rolls were partitioned following the same method as used in roll pass 1. No partitioning was applied to the strip.

The model was mesh seeded as in previous models. However, the mesh density for both the rolls and the strip was increased due to the results gained in Section 4.3.8, where the analysis proved that a fine mesh gives more accurate results when using elements with reduced integration.

Due to linear elements having a single integration point in the centre of the element and two rolls being used in this simulation, the strip was given a thickness of two elements.

The model size was as follows:

Number of elements in the model: 13762

Number of nodes in the model: 15500

Total number of variables: 46506

4.4.5 Analysis 1

Sufficient traction was achieved between the rolls and strip which pulled the strip through the stand. Figure 4.8, shows the stress distribution throughout the strip with the top roll removed. It can be seen that the stress generated during the contact is relatively high throughout the element thickness, which suggests that the clearance between the rolls was set too low. Despite the high forces exerted on the strip the material yield was not reached and as a result no element distortion occurred during the simulation.

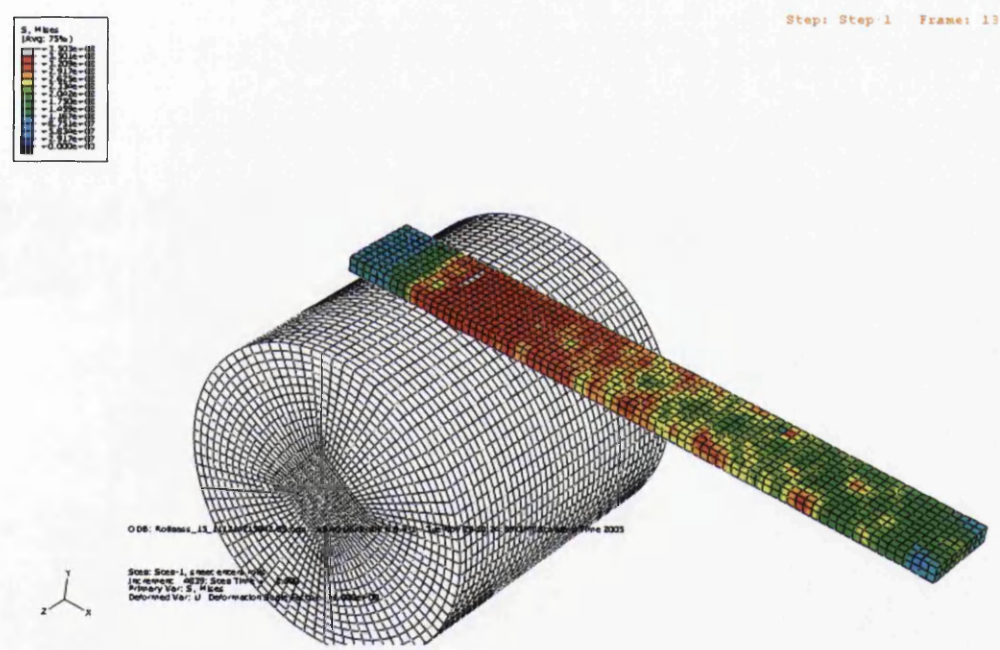


Figure 4.8: Roll Pass 2, Analysis 1 - Stress distribution through strip

4.4.6 Analysis 2

In order to investigate the use of Reduced Integration (as discussed in chapter 2), a second analysis was performed using C3D8 elements, without reduced integration. This meant that the elements within the strip were now fully integrated, which in linear hexahedral elements is not recommended for simulations that experience large material deformations. Full integration also increases the stiffness of the elements, therefore, it was predicted that the stress distribution throughout the strip would be lower than the level seen in analysis 1.

Figure 4.9 shows the stress distribution in the strip and it can be seen that the maximum stress is much lower than that seen at the same point in analysis 1.

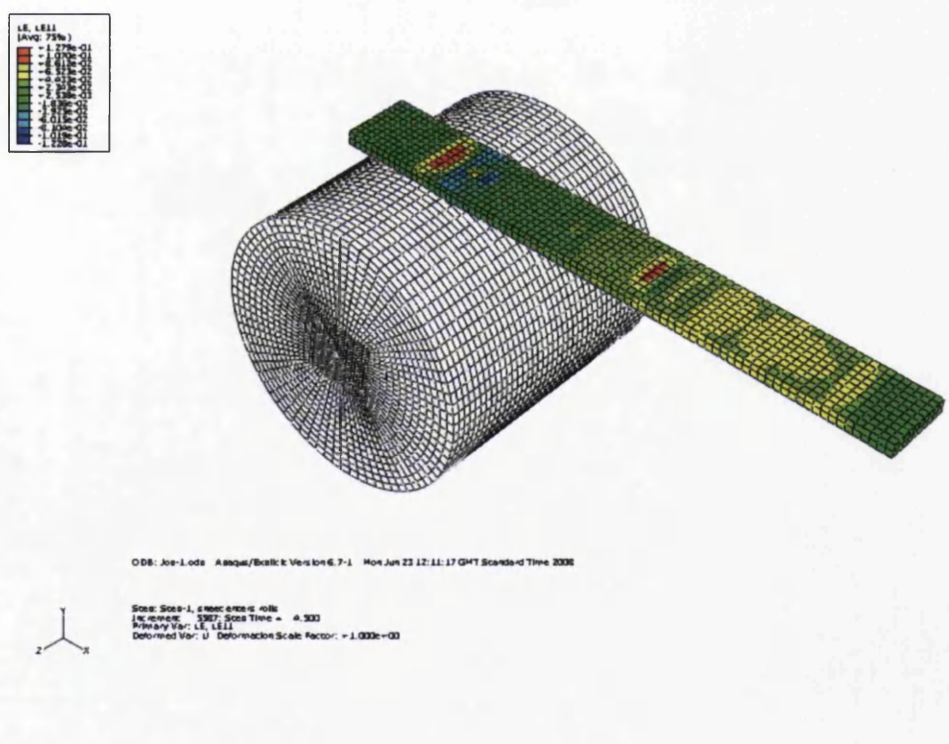


Figure 4.9: Roll Pass 2, Analysis 2 - Stress distribution using C3D8 in the strip.

4.5 Simulation of Celtic Guide rolls

The Celtic production line is fed steel from a coil. The coil is initially fed through guide or lubrication rolls. These rolls are used to lubricate certain grades of steel and guide the material to stand No.1. This procedure is not performed on the 1000/32 profile. However, as these rolls are permanently fixed to the line the steel sheet does come into contact with the rolls before reaching stand No.1, due to the slack in the sheet from the de-coiler. The angle at which the sheet enters the guide rolls is 10° from the horizontal, as shown in Figure 4.10.

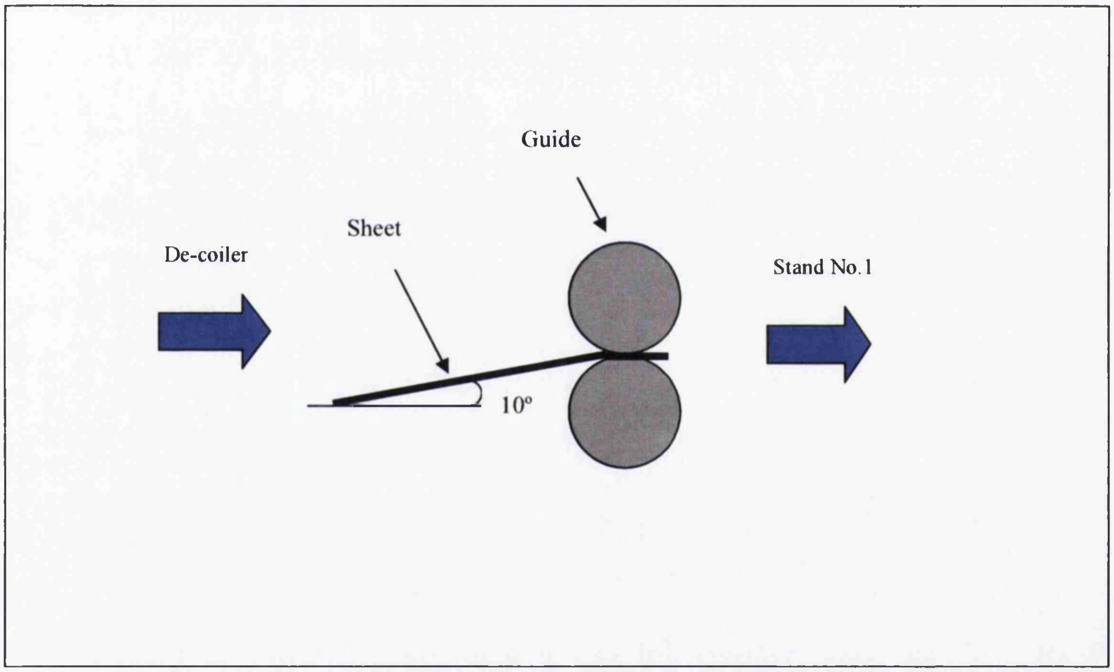


Figure 4.10: Incline of sheet to guide rolls

The geometry of the guide rolls was created, with the intention that if required could be imported into the final model.

4.5.1 Geometry

The dimensions from the Celtic line were taken and used to create a 3D model in ABAQUS to correct scale. The dimensions were as follows:

Rolls		Sheet	
Diameter	41mm	Length	1000mm
Width	1270mm	Width	618mm
		Thickness	0.9mm

Table 4.2: Guide roll simulation - sheet properties.

Symmetry was assumed for the model, therefore, only the outboard side of the sheet was modelled. This reduces the number of elements within the model and is less complex as a result. The rolls at this stage were modelled in full.

4.5.2 Material properties

The sheet mechanical properties were taken from a current grade used for the 1000/32 Celtic profile (Shotton properties 2005):

HPS200 = Galvalloy hot-dip metallic coated – S220GD + ZA

Average Yield = 378 N/mm^2

4.5.3 Boundary Conditions

As the sheet is modelled on the outboard side of the stand, boundary conditions were required to constrain the sheet in the centre of the rolls. The inboard edge surface of the sheet was constrained in y & z-axis to prevent the material from moving.

The guide rolls in the profiling line do rotate freely, but are not driven. Therefore a velocity of 0.5 m/sec was applied to the sheet.

4.5.4 Meshing

The rolls were meshed as in previous simulations using C3D8R elements, and defined as rigid bodies.

The sheet was meshed with a thickness of 1 element. The reason for this is because the simulation is focused on the cross-sectional deformation of the sheet, apposed to cold rolling the sheet as in previous simulations.

4.5.5 Results & Discussion

Due to the angle of the sheet entering the rolls, it was predicted that the force applied to the lower roll would be high compared to the upper roll. Another problem that existed was the fact that the guide rolls are free to rotate and are not shaft driven like profiling rolls.

Therefore, the sheet was passed through the rolls with a velocity equal to a production line speed of 0.5mm/sec. The rolls were stationary with minimal surface contact with the sheet, so no surface deformation occurred.

The final simulation proved that the sheet could pass through the rolls without any surface deformation. However, due to the problems involved with the angle associated with the entry into the guide rolls it was decided that if the simulation was used again the angled entry into the rolls should be disregarded. This would allow the sheet to pass directly through the guide rolls.

4.6 Profiling line – Stand No.2

At this stage a simulation had been run successfully which transported a strip through two rotating rolls using friction (see Section 4.4). The guide rolls to the Celtic production line had also been modelled (see Section 4.5). Therefore, Roll stand No.2 from the 1000/32 Celtic line was created.

4.6.1 Rationale

As this was the first profiling simulation representing the Celtic line, stand No.2 geometry was used. The material deformation in this stand is high and as a consequence the potential of the model could be recognised.

In order to reduce simulation time strip and roll symmetry was assumed and therefore only the inboard side of the rolls and sheet were modelled.

4.6.2 Aim

The main purpose of this simulation was to pass the strip through the roll stand to create the profile, and at the same time record how the strip behaves when using parameters such as rotating rolls and friction. Stand No.2 was used due to the fact that when comparing stand no.1 and 2, the maximum material deformation occurs in this stand.

4.6.3 Method - Roll Stand tooling geometry

The geometry for the rolls could have been created in two different ways. Firstly, the roll geometry could have been imported into ABAQUS using a CAD or Pro-Engineer file. In this instance the geometry would have to be refined to enable the parts to be meshed. However, this information proved difficult to gain from the tooling manufacturer, therefore, 2D tooling drawings from CP&P were used. The drawings were expanded in size and scale measurements were taken to gain the full size dimensions of the rolls (see Appendix B)

To create both rolls they were each divided into two sections. The geometry for each section was created and both parts were merged together, creating an instance. Unlike the procedure explained in Section 4.3, where an internal surface was required, all internal surfaces were removed so the instance was identified as one.

To reduce the complexity of each roll, the centre section was removed, which would reduce the number of elements within the meshed roll, and as the roll would be defined as rigid this procedure would speed up the simulation.

4.6.4 Geometry Meshing

Roll Mesh

The rolls were each partitioned into 4 segments to aid the mesh, as explained in Section 4.1.3. The sections were mesh seeded and meshed using C3D8R elements, Figure 4.11.

The rolls were both defined as rigid bodies in the interactions menu and assembled.

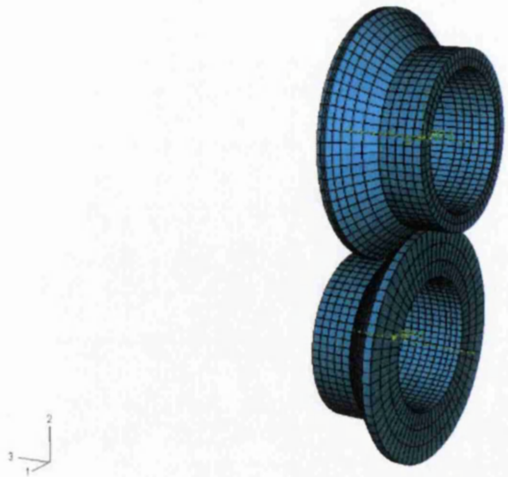


Figure 4.11 : Celtic roll geometry.

Sheet Mesh

The sheet mesh used for the initial simulation consisted of C3D8R elements. The density of the mesh was increased towards the centre of the sheet, where the deformation would occur, Figure 4.12.

Centreline of strip

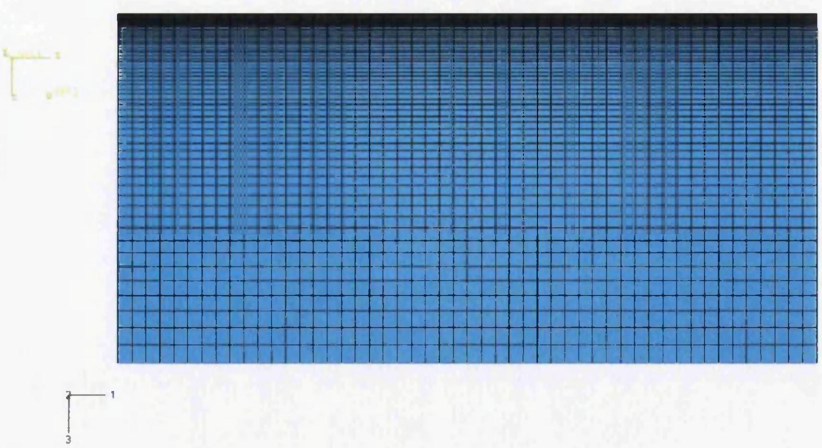


Figure 4.12: Density of sheet mesh

The size of the simulation was as follows:

Number of elements:	9352
Number of nodes:	16764
Total number of model variables:	50298

4.6.5 Boundary conditions

Rolls

The rolls were restrained by using the same method used in the Roll Pass simulations, seen in Section 4.3. A clearance of 1mm was given between the top and bottom rolls (see figure 4.13).

A centre axis was created through each cylinder and a reference point selected on the axis between two points, one at each end of the cylinder. The reference point was could then be used to assign the boundary conditions.

The rolls were fixed in all DOF (except z-rotation), at the reference point and an angular velocity applied to provide the rotation. Velocity initially set to 6.28 radians/sec or 1 revolution per second. As the maximum roll diameter is 194mm, the sheet velocity would be approximately 36.5 m/min, which is below the actual operating speed of the profiling line.

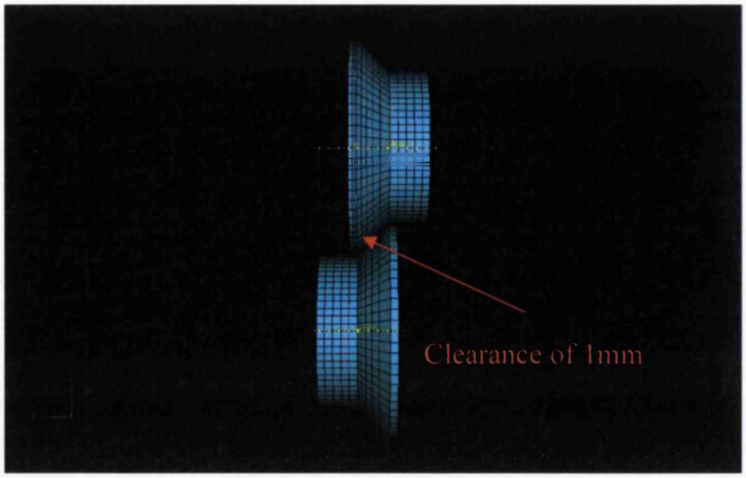


Figure 4.13: Model Boundary Conditions

Sheet

The sheet was restrained on the inboard edge surface in the (y, z) axis. This boundary condition was used to replicate the invisible second half section of the sheet.

An initial velocity of 20 mm/sec was applied to the sheet in step No.1. This was used to transport the sheet into the rolls. In step No.2 the velocity was removed so that the sheet would pass through the rolls using traction.

4.6.6 Results & discussion

On the first attempt the sheet entered the rolls and began to deform as expected. The stress observed along the profiled section looked to be low compared to the yield strength of the material and it was undecided if the material would maintain its profile when it exited the rolls.

The steps in the simulation were too short and the sheet would only pass 500mm through the rolls. Therefore, the steps were increased and the simulation restarted, to allow the sheet to travel further and more deformation to occur.

It was clear from the second attempt Figure 4.14, that the sheet was retaining its profile, when exiting the rolls.

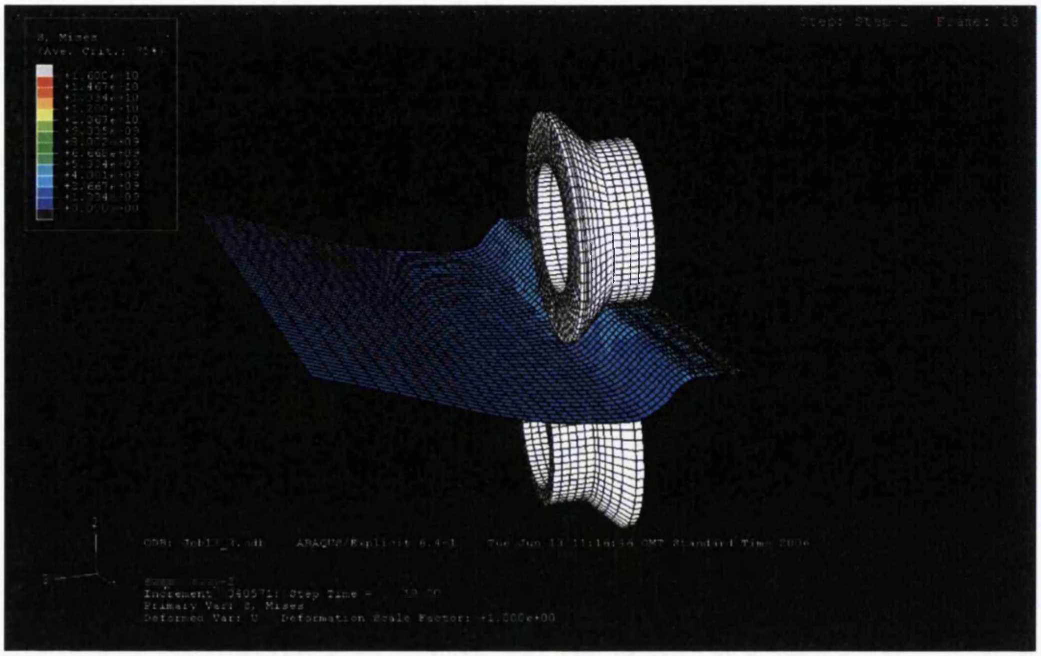


Figure 4.14: Profiling sheet through stand No.1.

The model simulated the inboard (left) side of the sheet flexing up and down as the sheet entered the stand. This would occur in the actual line, however, it can be predicted that if more stands were introduced into the model the sheet would be subjected to tension forces and this movement would be eliminated.

It was also observed that during the simulation the elements were being compressed towards the centre-line of the sheet. An explanation to the problem could be associated with the inboard edge of the sheet flexing as the sheet is profiled. This edge of the sheet was unrestrained and therefore free to be drawn into the rolls and to the centre line of symmetry. However, if the sheet was positioned further into the production line the sheet would be restrained in tension, eliminating any edge flexing and therefore, the sheet would not be drawn into the rolls.

4.7 Profiling line - Full Stand Geometry

4.7.1 Rationale

The simulation in Section 4.6 showed that the sheet elements were being compressed towards the centre-line of the model. An explanation for such compression could be due to the inboard edge not being restrained by the remaining 16 roll stands (explained above) or due to the centre-line of the model sheet being restrained with boundary conditions. Therefore, a model containing the full stand geometry was created so that no boundary conditions had to be applied to the sheet, and it was unrestrained to move in all directions.

4.7.2 Aim

To pass the sheet through the full roll geometry without setting sheet boundary conditions, to observe the behaviour of the elements.

4.7.3 Geometry & Boundary conditions

The full geometry was created using the tooling drawings provided by CP&P, as shown in Figure 4.15.

The boundary conditions from Section 4.6.5 were used and applied to all the rolls in the model. No boundary conditions were applied to restrain the sheet, except for an initial velocity of 20mm/sec as used in the previous simulation.

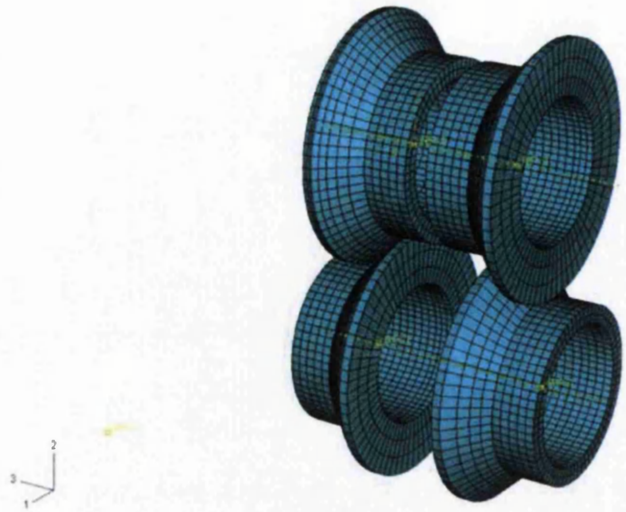


Figure 4.15: Full roll geometry

The size of the simulation was as follows:

Number of elements:	19520
Number of nodes:	34142
Total number of model variables:	102438

4.7.4 Results & Discussion

The simulation shows that the sheet enters the rolls and is deformed creating the profile as predicted, see Figure 4.16. However, the elements contained in the centre of the sheet are again compressed towards the centre-line.

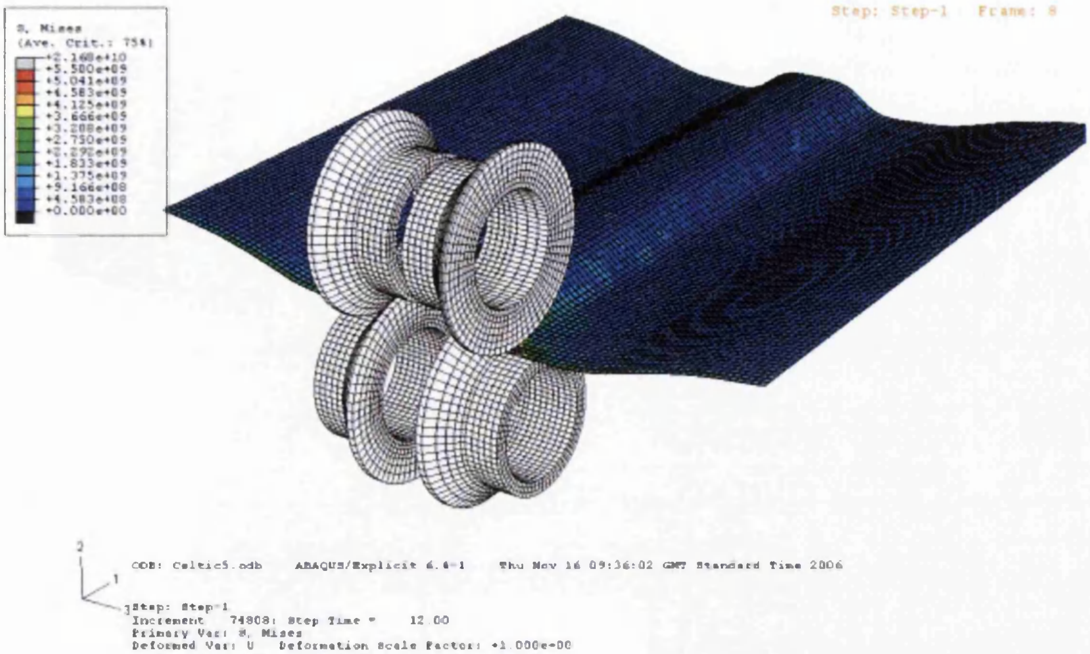


Figure 4.16: Sheet deformation using full roll geometry.

As the sheet has no (x, y, z) restraints the material is forced into the cavity between the top rolls, whereas in the restrained model the sheet is compressed towards the centre-line. This behaviour, as shown in Figure 4.17, is unrealistic as it does not occur in the actual production line and was therefore unacceptable.

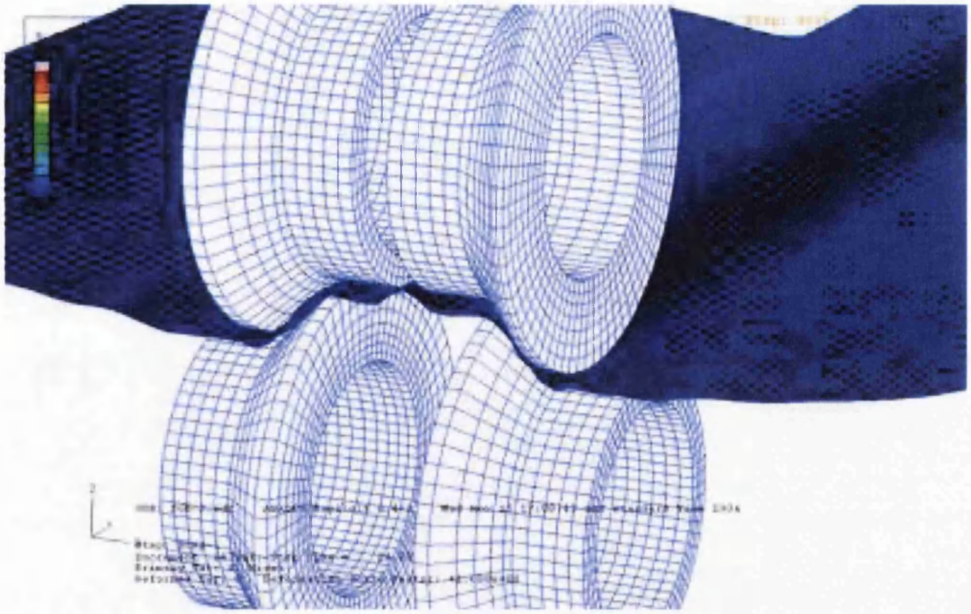


Figure 4.17: Full geometry deformation into top roll cavity.

The inaccurate deformation could have been caused due the following reasons:

- Sheet Mesh – The mesh used has a simple pattern with constant element density throughout the sheet. A more complex partitioned pattern with a fine mesh in the positions where the sheet is deformed would make the model more accurate and possibly reduce the unwanted deformation.
- Roll stand No.2 of the production line was used and as a result the large amount of deformation in this step may be too great. A model containing roll stand no.1 would reduce the amount of deformation in this stand and possibly eliminate the unwanted deformation.

CHAPTER 5: SIMULATION OF CELTIC PROFILING LINE.

5.1 Aim

The aim of this model was to simulate a strip of HPS200 steel passing through roll stands No.1 and 2 of the Celtic production line, using friction and rotating rolls in order to create the centre profile in the sheet.

5.2 Geometry and Meshing

Roll Geometry

The roll geometry (see Figure 5.1) was created using tooling geometry information from the manufacturer. The procedure used was the same as in Section 4.6 and 4.7.

Sheet Geometry

The sheet was created to replicate HPS200 with a gauge of 0.9 mm. This included the paint coating. However, the material property definition in the model was set as steel with a yield of 350 N/mm^2.

The sheet length was calculated for the model and set at 500mm. Only two roll stands were being represented in the model with a separation of 450 mm (centre to centre, see Appendix B), this meant that the profile of the sheet could be determined whilst in both stands at the same time, as in the line trial, discussed in Chapter 6.

The sheet width was reduced to 150mm (see Table 5.1) to reduce the size of the model and number of elements to reduce the computational time.

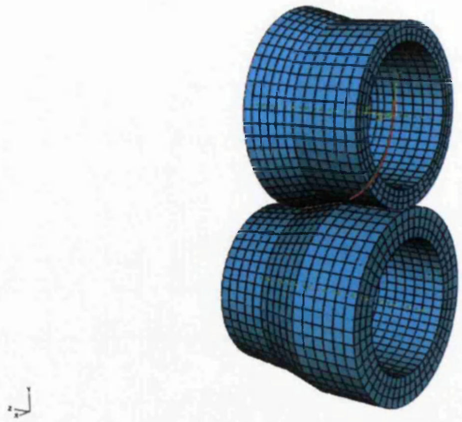


Figure 5.1: Roll Stand No.1 geometry

Meshing

The rolls were assigned a C3D8R mesh with 50 nodes on the roll circumference and 10 nodes across the width of the rolls.

The sheet was assigned the same element type and a fine mesh for simplicity, as shown in Figure 5.2.

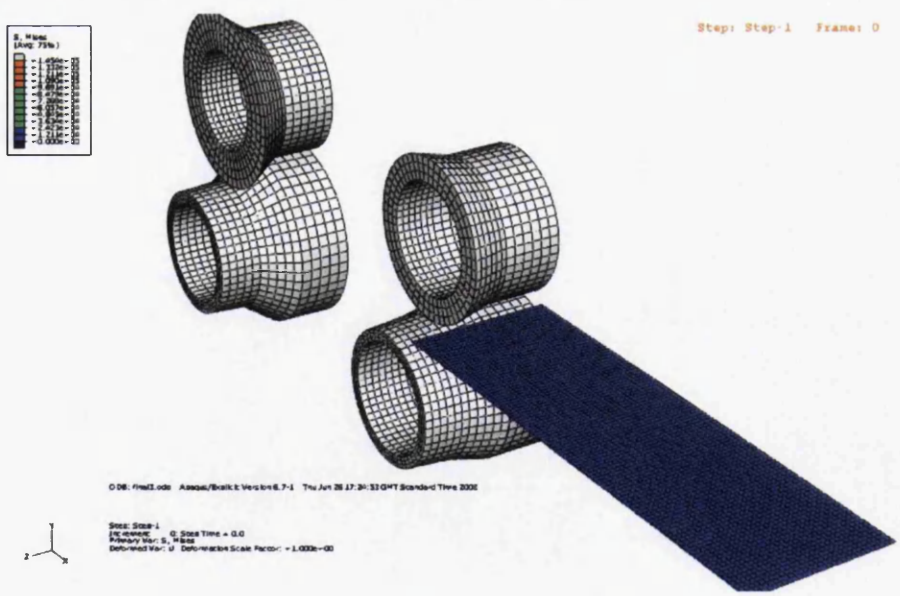


Figure 5.2: Final model geometry.

Rolls Stand 1 & 2		Sheet	
Diameter - min	152 mm	Length	500 mm
Diameter - max	208 mm	Width	150 mm
		Thickness	0.9 mm

Table 5.1: Geometry dimensions

5.3 Boundary Conditions

Rolls

Boundary conditions were applied to one reference point in the centre of the upper and lower rolls (Figure 5.3). The rolls were restrained as follows:

- Displacement – Set to (0, 0, 0), to maintain the rolls in a fixed position.
- Angular velocity – Set to (0, 0, 6.28) upper rolls and (0, 0, -6.28) lower rolls.

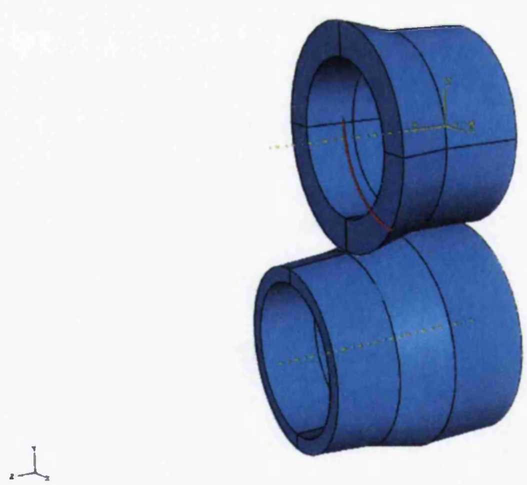


Figure 5.3: Roll boundary conditions

Sheet

As the model was simulating the inboard side of the geometry the sheet required boundary conditions to restrain its movement about the centre-line. The centre-line edge of the sheet was restrained in (x, 0, 0) for displacement and in (0, 0, 0) for rotation.

The sheet was given an initial velocity of 20mm/sec to initiate contact with the rolls in step 1.

The size of the final model created for analysis was as follows:

Number of elements:	14700
Number of nodes:	21747
Total number of model variables:	65253

5.4 Results

5.4.1 Stand No.1

The simulation proves that the rolls pull the sheet through the stand causing it to deform as predicted. The level of material deformation in this stand is relatively low to produce a shallow profile. As a consequence of this, the stress distribution in the sheet can be seen (Figure 5.4) to be increased at the bend radii of the profile, where higher stress levels were would be expected.

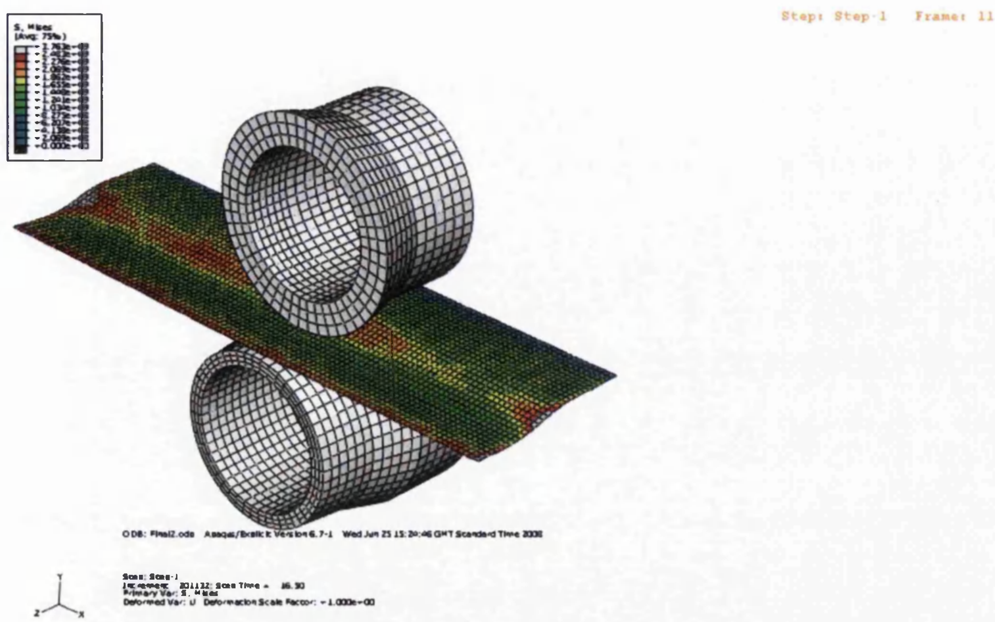


Figure 5.4: Stand No.1 – Profile mid section

As the sheet exits the stand it can be seen in Figure 5.5, that the profile shape is maintained and the stress decreases.

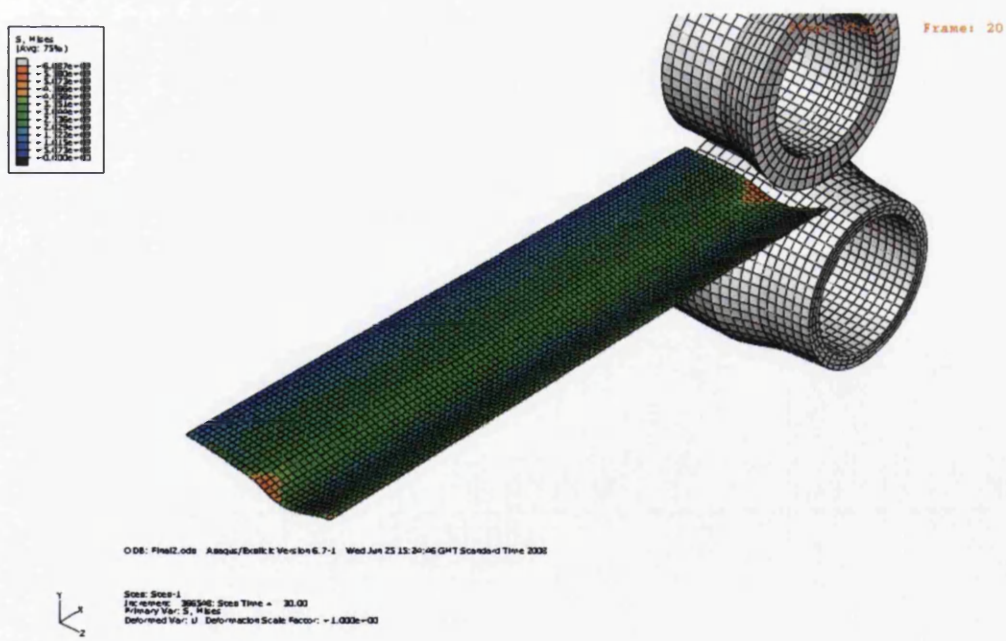


Figure 5.5: Sheet exit from stand No.1

The strain results in Figure 5.6 show the longitudinal and horizontal strain components at specified nodes on the surface of the leading edge of the sheet. Nodes 9301 (Centre-line, outboard edge), node 9346 (Centre of sheet) and 9391 (inboard, unrestrained edge) were picked in the same horizontal plane. The strain is plotted against time, which in this case is 30 sec which gave a total of 20 frames or steps.

The graph shows that the longitudinal strain is insignificant as it remains at zero for the duration of the simulation.

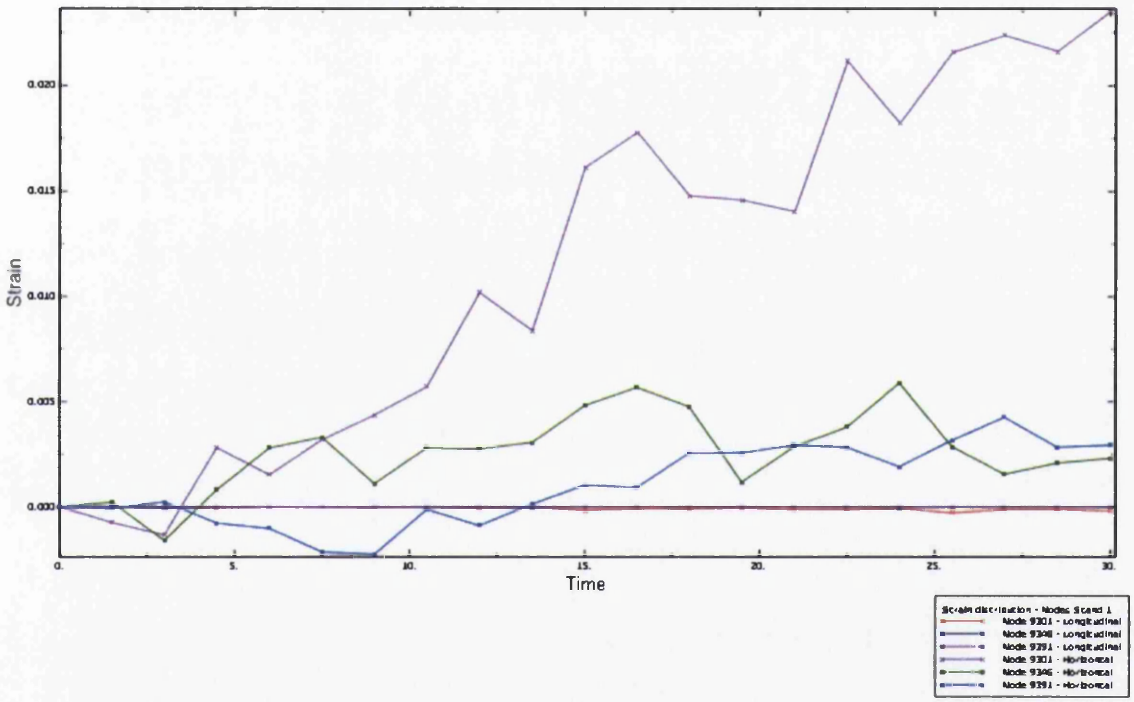


Figure 5.6: Strain distribution at specified nodes on the leading edge of the sheet on exit of stand No.1.

It can be seen that the strain is highest at node 9301 where the sheet is restrained in the rolls. This could be due to compression as seen in previous simulations where the sheet suffered from element compression at the restrained centre-line. The resultant strain at node 9346 is lower than experienced at node 9301 despite being positioned in the section of the sheet which would experience the highest amount of element deformation. Finally, the lowest strain can be seen at node 9391. This particular area of the sheet experiences the least amount of deformation due to compression or tension as it is unrestrained, hence the low resultant strain seen.

5.4.2 Transition between Stand No.1 & 2

The shallow profile created in stand No.1, transitions into stand No.2 without any complications, despite the large sheet deformation taking place (see Figure 5.7). The potential for complications to exist here were high due to the difference in the roll profiles between Stand 1 & 2, this can be seen by the upper rolls in Figure 5.7.

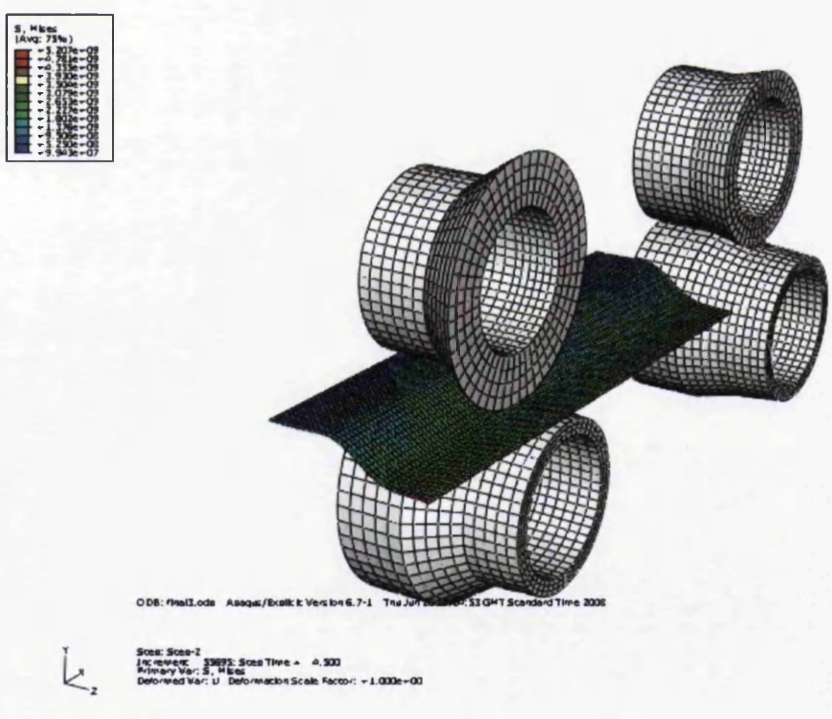


Figure 5.7: Sheet transition between stands No.1 & 2

However, due the centre edge of the sheet being restrained in the (y, z) axis the result is as predicted and the sheet is guided correctly into Stand No.2.

5.4.3 Stand No.2

The final sheet profile can be seen on the exit of stand No.2 (Figure 5.8). The stress distribution shows that the centre-line elements experience minimal stress due to not being in contact with the rolls. The model was created assuming symmetry in the roll and sheet geometry, as a result the sheet needed to be restrained on the centre-line edge and to enable a satisfactory transition through the rolls was restrained in the (y, z) axis. In reality the strip would be unrestrained at the centre-line and would be free to contact the rolls.

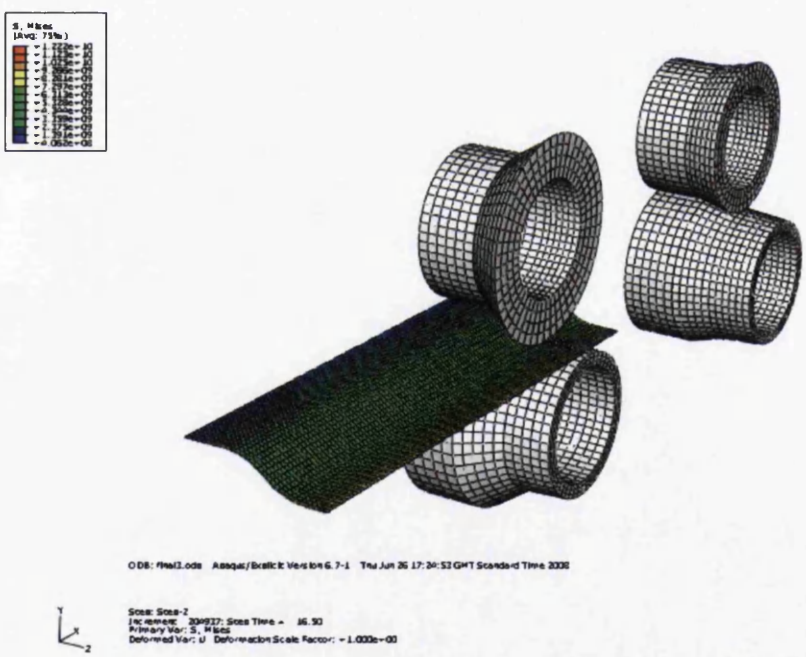


Figure 5.8: Sheet exit from stand No.2

The stress gradually increases horizontally as the strip gains contact with the rolls, however, when compared to the stress observed in stand No.1 it can be seen that the level is reduced. The reason for this lower stress distribution will be due to the deformation experienced in stand No.1. The deformation experienced to produce the profile is divided between both stands and as a result the stress caused during contact is much lower than if only a single stand were used.

The simulation proves that the sheet profile is maintained as the contact with the rolls is removed on exit of stand No.2. The resultant profile is discussed in Chapter 6.

The strain results in Figure 5.9 show the longitudinal and horizontal strain components at nodes 9301, 9346 and 9391 as in Figure 5.6 for Stand No.1.

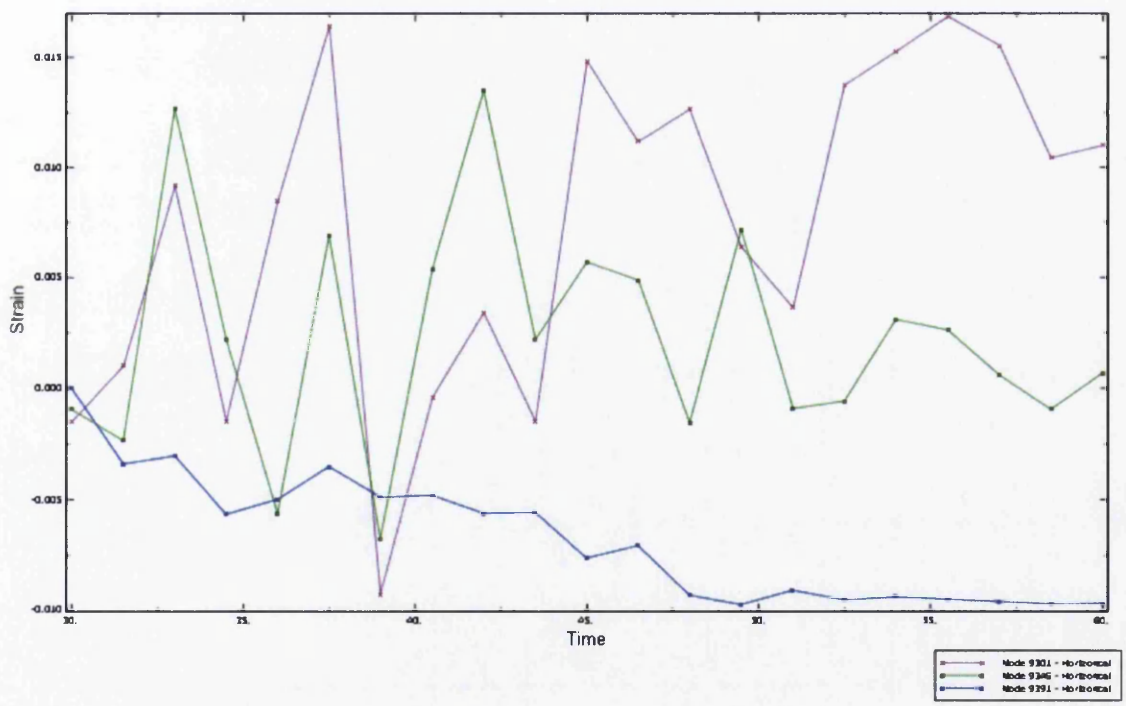


Figure 5.9: Strain distribution at specified nodes on the leading edge of the sheet on exit of stand No.2.

The deformation experienced in Stand No.2 is greater than that in Stand No.1 and this clearly shown in this graph. The Strain either compressive or tensile is significantly increased at nodes 9301 and 9346. This can be explained by the increased deformation in the centre of the sheet whereas node 9391 experiences less deformation.

CHAPTER 6: PLANT TRIAL RESULTS & DISCUSSION

6.1 Introduction

In this chapter the profiling trial preparation is discussed, leading onto a detailed explanation of the trial procedure and results from using the Celtic roll forming line at CP&P, Tewkesbury. The section also discusses the results from strip mechanical testing at Corus works, Shotton.

6.2 Profiling Trial

Following the decommissioning of the Celtic line from CP&P, Ammanford in 2006, the line was recommissioned at CP&P in Tewkesbury and the trial took place in July 2007.

6.2.1 Rationale

The trial was an essential part of the research as its purpose was to take dimensions from the strip during the roll forming stages which could be used for validation purposes against the computer model.

6.2.2 Aim

The aim of the trial was to collect strip profile data from roll stands No.1-3. The measurements taken were to be used to recreate a 2D representation of the profile to validate the 3D FE model.

6.2.3 Method

Following a presentation to the engineers at the plant, a plan was developed on how to conduct the trial. It was essential to gain a profile picture of the strip following each roll stand before entering the next stand.

The trial focused on the first three roll forming stands which form the centre 120mm profile in the strip, shown in Figure 6.1, below:

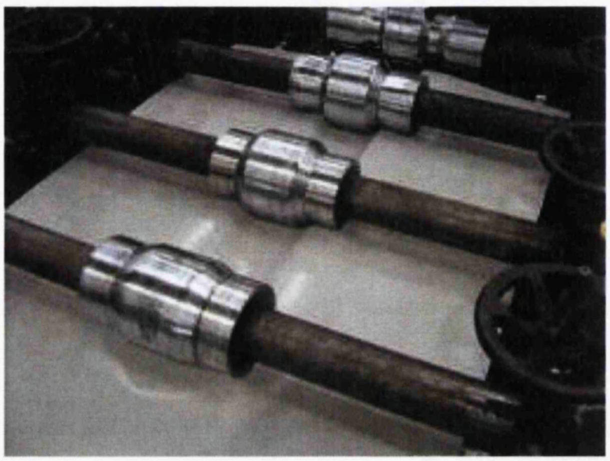


Figure 6.1: Celtic roll stands No.1-3.

Roll stands No.1 & 2 form the profile whilst the No.3 over-bends the strip to eliminate spring back from occurring, this can be seen in the 2D geometry drawings in Appendix C. Roll stand No.4 to 18 then repeats the process and so on, creating the finished profile.

6.2.4 Strip profile in Rolls

The strip was transported and profiled through the first three stands as shown in Figure 6.1, before the line was stopped. This revealed the profile in the strip after each stand, starting with a shallow profile between stands No.1-2 and finishing with a deep 32mm prominent profile between stands 3-4.

Measurements were carefully taken from the profile using a ruler, Vernier caliper and an angle measurer, as shown in Figure 6.2 (Results can be found in Appendix C).

Figure 6.2: Recording the strip profile.

6.2.5 Strip profile out of rolls

Once measurements of the profile were taken with the strip in the rolls, sections of the strip were cut from between the stands, i.e. between stands 1-2, 2-3 and 3-4. The sections were cut using a combination of two methods.

Figure 6.3, shows cutting the strip using a circular saw. This was used in areas in close proximity to the rolls and for cutting the profile in order not to damage the strip or compromise the profile shape.

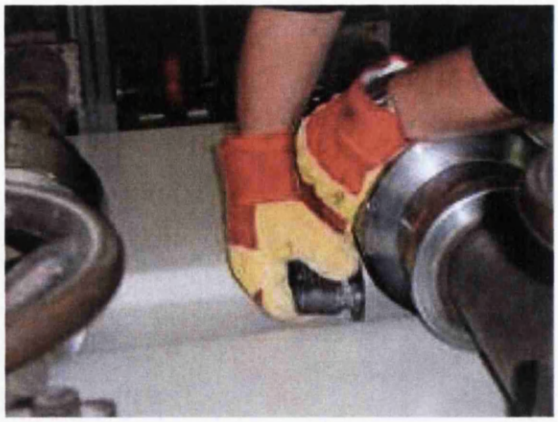


Figure 6.3: Cutting the strip with a circular saw.

The pneumatic cutter, as shown in Figure 6.4, was used for the flanges where precision was not as important. This process was much faster than using the circular saw but as a consequence was more likely to damage the strip. However, this was acceptable as measurements here would not affect the validation.

Figure 6.4: Cutting using a pneumatic cutter.

All three sections were cut from the inboard edge to the outboard edge and re-measured for comparison (results are discussed in Section 6.4.2).

Once removed from the line, the profile of each section was again recorded. The purpose of the two sets of results i.e. profile measurements whilst in rolls and profile measurements whilst out of rolls was in order to gain an idea of the spring-back of the strip once the tensile forces from the production line had been removed.

The profile measurements were used to create a 2D representation of the strip both whilst in/out of the rolls, which can be found in Figure 6.8.

6.2.6 Mechanical Testing Samples

On completion of the trial, the sections were taken for further testing. The aim was to test the mechanical properties of the strip at each stage in the process, therefore a sample was cut from the centre-line of each section extracted from the line (approximately 617mm) shown in Figure 6.5. In order to meet the testing criteria the samples had to measure a minimum of 250 x 25 mm.

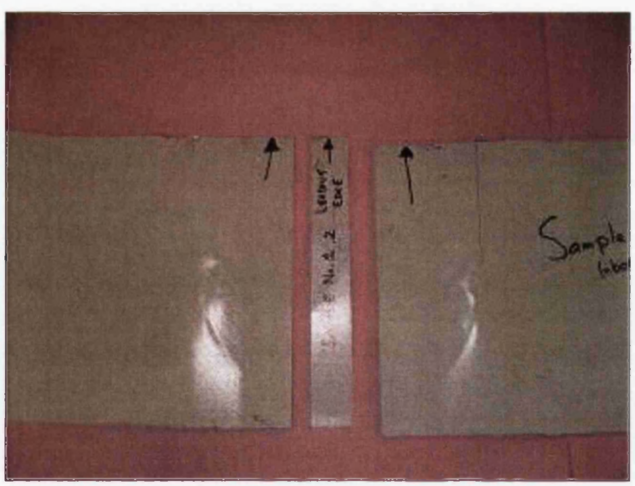


Figure 6.5: Centre-line test sample from line sample No.1.

6.2.7 Strip Properties

The properties for the coil used for the trial were obtained, including the mechanical properties taken from the strip at Shotton works, strip dimensions and chemical composition of the coil (Table 6.1):

HPS200 - S220GD+ZA Gauge:0.675 mm / Width:1235 mm			
Coil Mechanical Properties (Shotton)			
Yield Strength		406 N/mm^2	
Tensile Strength		432 N/mm^2	
Elongation		27 %	
Cast Analysis for batch K91877IJ			
Carbon	0.0390 %	Molybdenum	0.0010 %
Silicon	0.0020 %	Nickel	0.0210 %
Manganese	0.2300 %	Aluminium	0.0480 %
Phosphorus	0.0120 %	Cobalt	0.0100 %
Sulphur	0.0150 %	Copper	0.0200 %
Nitrogen	0.0053 %	Niobium	0.0010 %
Tin	0.0030 %	Vanadium	0.0010 %
Soluble Al	0.0450 %		

Table 6.1: Mechanical properties and batch chemistry limits for the steel grade.

6.2.8 Mechanical Testing results of samples

The original plan was to take three test samples from each section to send for mechanical testing, as shown in Figure 6.6. This would have provided three sets mechanical properties for the inboard, centre-line and outboard positions of each section extracted from the line. However, sections of the strip proved difficult to extract due to the spacing between the rolls. The rolls are positioned 450mm apart from centre to centre, which leaves a gap of around 280mm. As a result the length of each section was not uniform and in many cases the length fell below the 250mm minimum standard, specified by Corus Shotton.

As a result of the variation in profile length only the centre-line samples were sent for testing.

Figure 6.6: Samples cut from strip section No.1, including the centre-line section used for testing.

On completion of the trial 3 samples were taken for tensile testing at Shotton. The steel coil properties can be found in Appendix D. Table 6.2 shows a comparison between the mechanical properties between the samples taken during the trial with the properties gained from the initial coil test at Corus at Shotton works, several months before:

Sample	Width (mm)	Gauge (mm)	Yield Stress (N/mm^2)	0.2% Proof Stress (N/mm^2)	UTS (N/mm^2)	Uni Elong	Total Elong	YPE	n
Shotton	N/A	0.675	406	432	-	-	27	-	-
1	20.24	0.635	384	369	427	12	15	-	0.16
2	20.14	0.631	391	-	397	12	14	-	-
3	20.15	0.610	393	399	433	16	17	9.20	0.19

Table 6.2: Mechanical property results from tensile testing.

The results of the tensile testing are as predicted. However, it can be seen that the yield strength of the material tested following the trial is slightly lower than the yield of the coil test taken at Shotton. The results from the trial specimens show that the sample gauge reduces from the initial coil sample to the sample No.3 by 0.065mm.

Despite the yield strength of the samples being lower than that of the coil sample, the stress increases between each sample the further it moves through the line. This was predicted to a certain degree due to the forming process.

It can also be seen that the strain hardening exponent (n-value) increases between samples No.1-3.

The variation of the mechanical properties of each sample and that of the difference with the initial coil testing results were as predicted with nothing unusual seen and are therefore acceptable.

6.3 Trial Results.

6.3.1 Profile in Production line

On completion of the production line trial the profile dimensions were used to create a 2D diagram, shown in Figure 6.7. The diagram shows the resultant profile measured from the line after each of the 3 stages conducted during the trial, whilst the sheet was in held in the rolls.

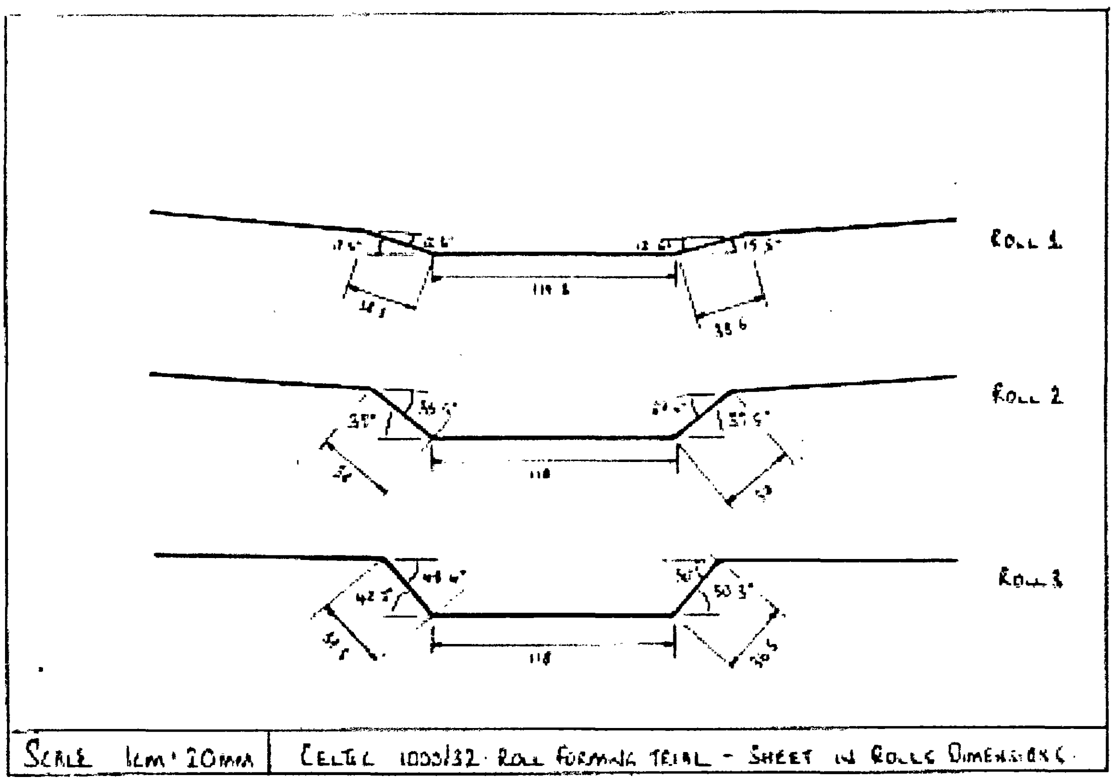


Figure 6.7: Resultant profile whilst in the production line.

These results can be compared to the final strip geometry as seen in Appendix C. It can be seen that the profile shown for roll 3 (Figure 6.7), is an accurate representation of the centre profile, shown in the Corus 1000/32 profile cross section diagram in the Appendix C.

6.3.2 Profile extracted from production line

The sheet profile was taken whilst the sheet was held in the stands, which is represented in Figure 6.8, as a black line. The profile was then re-measured post extraction from the stand, shown as a red line in figure 6.8.

The profiles show that the deformation in stand No.1 is small, creating a shallow profile. Stand No.2 creates the final profile depth of 32mm and roll stand No.3 over-bends the sheet sufficiently to create the final profile.

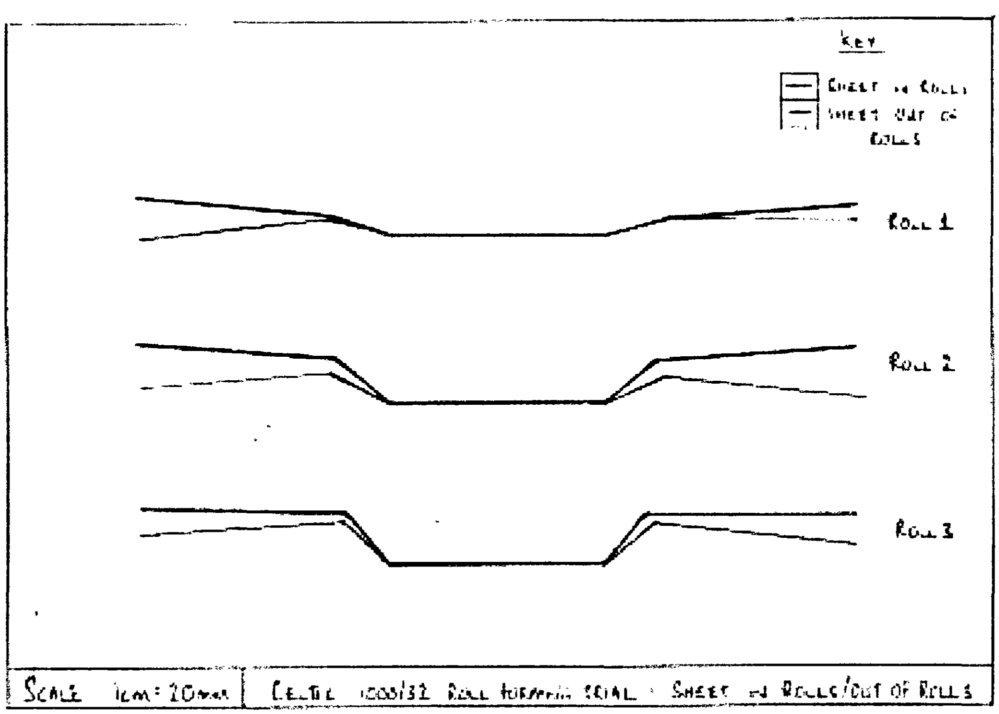


Figure 6.8: Celtic line resultant profile, taken whilst in and out of rolls.

However, it can be seen that there is a significant difference in the shape of the profile, when held in the stands and once removed from the stands, represented in figure 6.8, above. The red profile shows the material unsupported once removed from the line. Initial observations would suggest that the difference between the profiles (in/out of rolls) is purely due to spring-back. Spring-back (as explained in Section 2.4.2) is the elastic recovery of the profile during deformation after rolling forces have been removed. Material recovery of this magnitude is common in roll forming and therefore predicted in this trial. To compensate for spring-back the profile is continuously over-bent throughout the production line process to achieve the desired radius. However, as this trial was focused on the centre profile only and the remainder 4 profiles which make up the 1000/32 cross section were not formed in the strip, then it can be assumed that a proportion of what appears to be spring-back is actually caused due to the fact that the profile is not supported on either side, the weight of the steel causing deflection on what could be described as floppy HPS200 product. This in mind, the profile was turned upside down and was seen to sit flat on the worktop surface, representing the 1000/32 profile shown in Appendix C.

It can therefore be assumed that a despite a certain amount of spring-back existing that would be naturally predicted in this process, over-bending that would occur in the remainder of the Celtic line roll stands would reduce if not eliminate the spring-back seen in this trial producing the resultant 1000/32 profile.

6.4 Validation of model

To validate the computer model, it was necessary to make a comparison between the results gained from the simulation (see Chapter 5) with the line trial results explained in this section.

To do this the profile generated by the model was represented in graph format, in order to both make a comparison between the profiles at each stage of the process and to enable input of the line trial profile dimensions for comparison.

6.4.1 Computer Model profile results – Stand No.1

Co-ordinates of nodes within the centre-line of the strip cross-section within the computer model were recorded and plotted. The strip profile generated by stand No.1 in the model can be seen Figure 6.9.

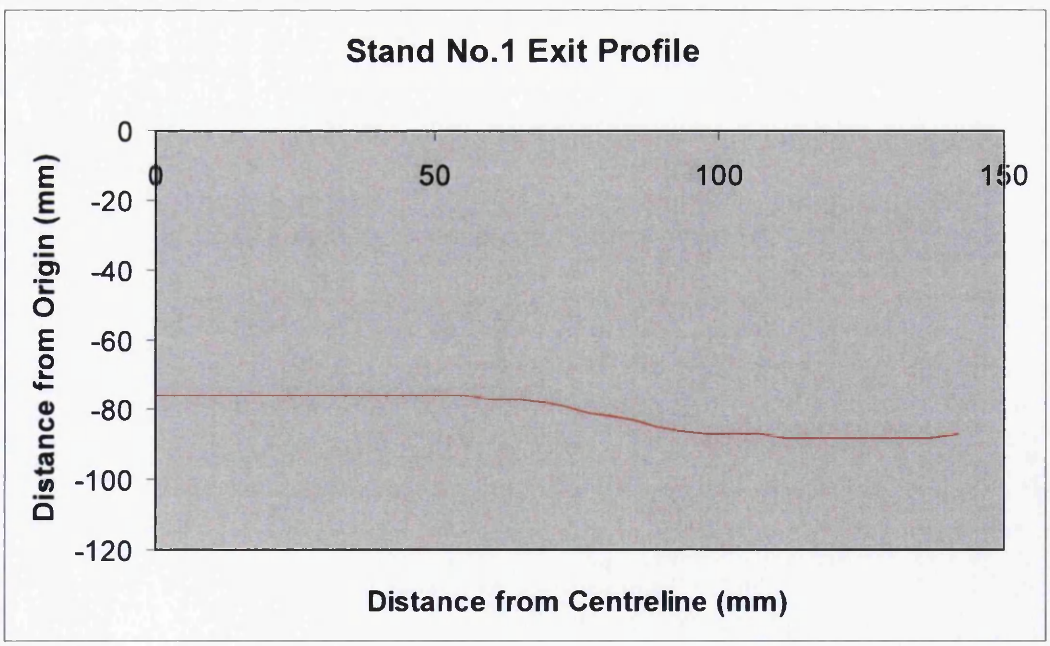


Figure 6.9: Model profile at exit of stand No.1

This represents the cross section of the sheet as if it were viewed from the exit of stand No.1. It can also be seen that for simplicity when plotting the profile results the profile orientation is upside down, compared to how the strip is formed in the production line. This can be compared to the resultant profile drawn in figure 6.8.

The sheet originally measured 150 mm, following the deformation in roll stand No.1 it can be seen that this has reduced to a resultant span of 146 mm. This is as expected due to the slope of the profile side wall and as a result a further reduction on the width was predicted following stand No.2, as the profile would become deeper, reducing the strip span.
The depth of the model profile at this stage, following stand No.1 profiling is 18mm.

6.4.2 Computer Model profile results – Stand No.2

The resultant profile following exit from roll stand No.2 in the computer model can be seen in Figure 6.10. As predicted the strip width is reduced further to 144mm, due to the increased depth of the profile.
The depth of the profile at this stage is 30.2mm, which is less than the expected final resultant profile depth of 32mm. This is discussed in the next Chapter.

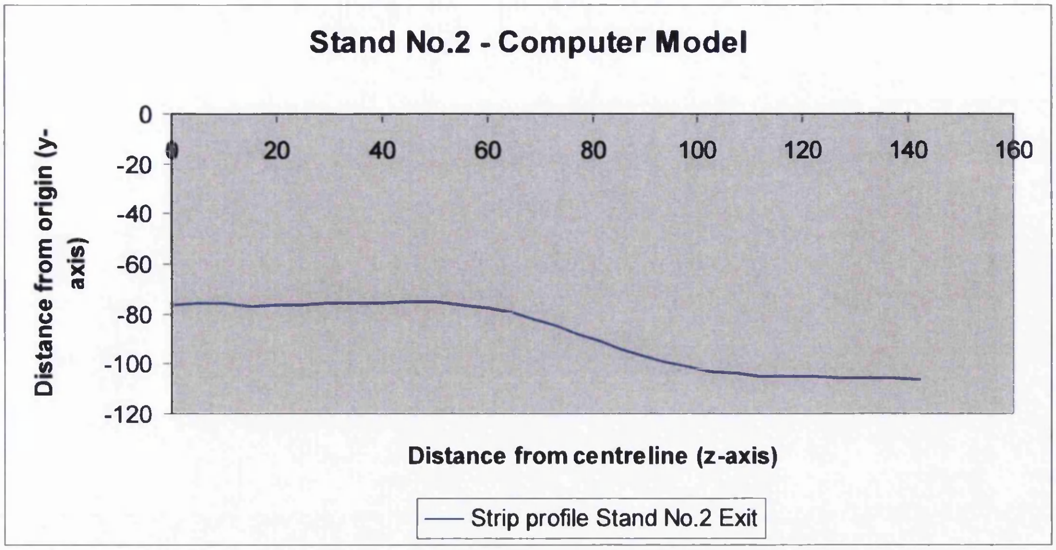


Figure 6.10: Model profile at exit of stand No.2.

It can be seen that the model profile is comparable to the profile shown in Figure 6.7 for roll 2. However, it can also be seen that the bend radii in the model profile are undefined. This is potentially due to the basic mesh used in the sheet geometry. The defined mesh is fine but constant through the width of the sheet and as a consequence the model deformation around the bend radii is unrealistic, as it is represented by a smooth curve opposed to a distinctive bend in the strip.

A solution to this problem would be to partition the sheet and create a very fine mesh longitudinally where the rolls contact and profile the sheet. This would increase the accuracy of the deformation and create a more defined bend in the model.

6.4.3 Computer Model profile results – Stand No.1 & 2

Figure 6.11, shows the sheet cross-section comparison following stand No.1 and No.2. The model profile of the sheet on exit of stand No.2 is again comparable to the profile taken during the line trial.

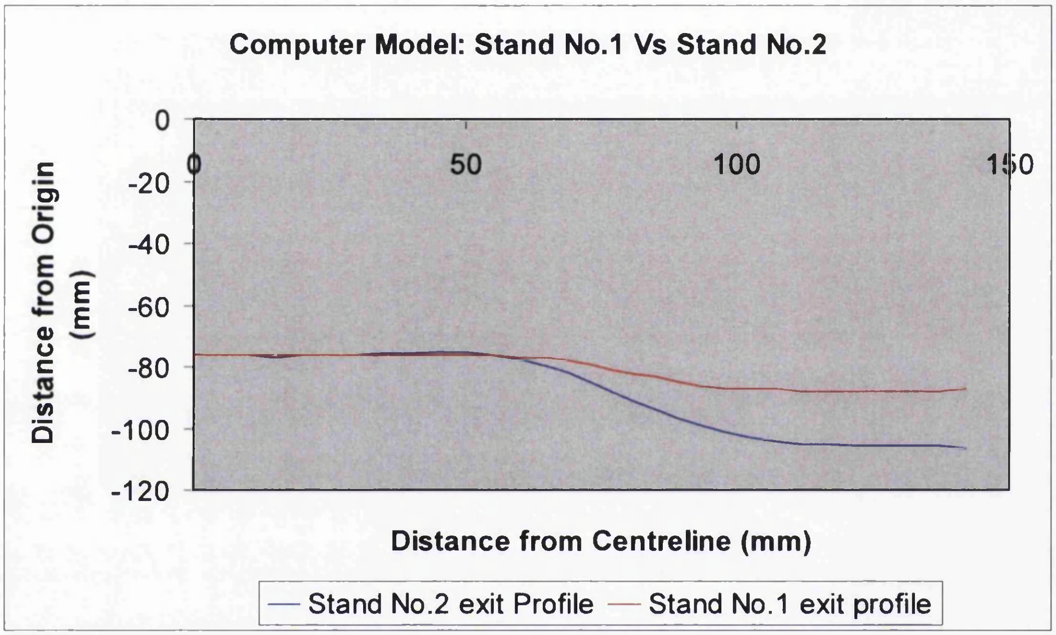


Figure 6.11: Model sheet profile at exit of stand No.1 compared with sheet profile at exit of stand No.2.

However, it can be seen that the profile bends are undefined as in Figure 6.10, which would be a result of the meshing technique used. This is inaccurate when compared to the sheet profile in Figure 6.8, but could be rectified with a more complex sheet mesh as explained above.

6.4.4 Computer Model Vs Production Line

The computer model of the strip profile in Stand No.1 is compared to the strip profile gained from the production line trial in Figure 6.12.

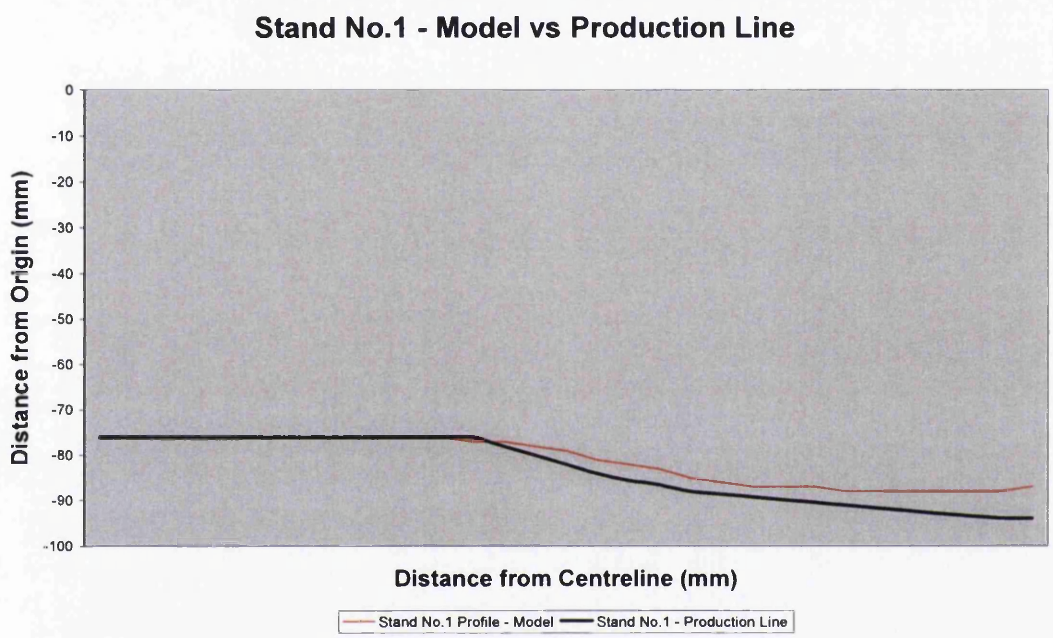


Figure 6.12: Stand No.1 – Model Vs Production Line

The model profile (shown in red) despite not following the trial strip profile (black) exactly can be seen to be relatively accurate as they are comparable. However, as explained in Section 6.4.2, some accuracy is lost in the profile bends which could be improved.

The computer model and production line trial profiles for stand No.2 are compared in Figure 6.13. As with the results for stand No.1, both are comparable with good accuracy. However, some accuracy is diminished in the side wall section of the profile around the profile bends.

Despite this, the computer model can be deemed a success, as it realistically simulates the forming process of the steel strip and accurately provides a 3D representation for the strip following each roll stand.

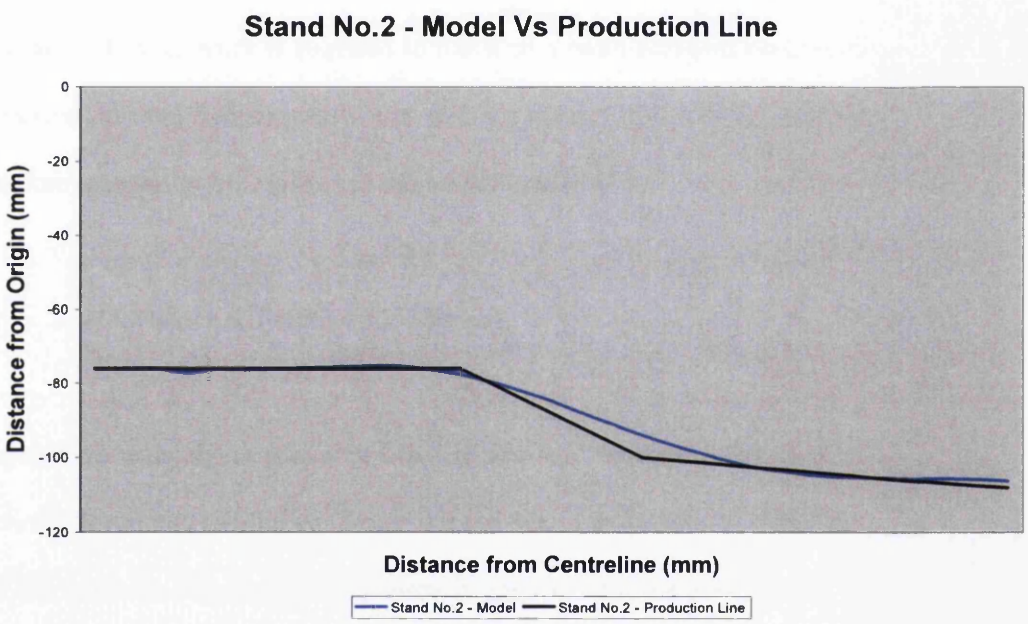


Figure 6.13: Stand No.2 – Model Vs Production line

CHAPTER 7: CONCLUSIONS & RECOMMENDATIONS

7.1 Conclusion summary

Profiling stands No.1 & 2 of the Celtic 1000/32 roll forming production line have been successfully modelled using parameters such as roll friction within ABAQUS FEM software. The computer model representation of the strip being formed is comparable to the results gained from the actual production line trial. However, accuracy is lost in the model due to the sheet mesh density and design. Therefore, to increase the accuracy of the simulation, further work is required to focus on a more complex sheet mesh for the model. Enhanced meshing techniques would enhance the definition of the strip profile bend radii, therefore increasing the realism of the model to reality.

7.2 Roll Contact & Friction Coefficient

The study and analysis performed in Chapter 4 to research the use of rotating rolls and friction proved extremely beneficial. We can see in this model that the use of rotating rolls and friction can be executed successfully for roll forming analysis. In this model it was determined that with the size of the profiling rolls a rotation velocity of 6.28 rad/sec was required in order to give a strip velocity comparable to the actual production line of around 39 metres per minute. However, as the model was a roll/material contact simulation it was essential to accurately replicate the correct friction experienced in the actual production line. The complication here was due to a number of variables. Firstly, rotational friction coefficients are complex due to the fact that the rolls are constantly rotating, certain rolls may differ in size and shape and therefore it is likely that the friction value would be constantly fluctuating throughout the production line. Secondly, it is also probable that as the material is profiled in the line that the rolls and strip heat up thus changing the friction value between the rolls and the strip. Thirdly, the Colorcoat finish on the HPS200 product has a rubbery finish, which is somewhat different on both the top and bottom surfaces. Therefore, it is extremely probable that the friction coefficient on the top and bottom surfaces would be different, which was impossible to replicate in the computer model. Therefore, due to the fact that both the rolling friction and the HPS200 friction were unknown, a friction value for steel on steel contact was used. Despite this, the friction coefficient was changed from 0.3 to 0.57 in models completed in chapter 4. These tests concluded that the difference between the friction values had little or no influence on the performance of the simulation. Therefore, this was fixed at 0.3 for the final Celtic model. An initial velocity of 20mm/sec was applied during the model to allow for initial strip/roll contact. This strip velocity was removed in step No.2 of the simulation as the rolls began to form the strip and gain traction with the material.

In conclusion, due to the successful results gained from the model, the roll speed and friction coefficient used for the analysis were deemed satisfactory for this type of simulation.

7.3 Validation of the model

The results shown in chapter 6 prove that the computer model profile created for both roll stands No.1 & 2 of the Celtic production line are comparable to the profiles gained during the trial. This is demonstrated in Figure 7.1, showing a 3D representation of the profile similarity.

However, the model profiles from stand No.1 & 2 also highlight that a simple mesh causes inaccuracy in such areas of the profile bend radii. One solution to this problem could be to redesign the mesh to enhance its structure and complexity where required, this is explained in Section 7.5.

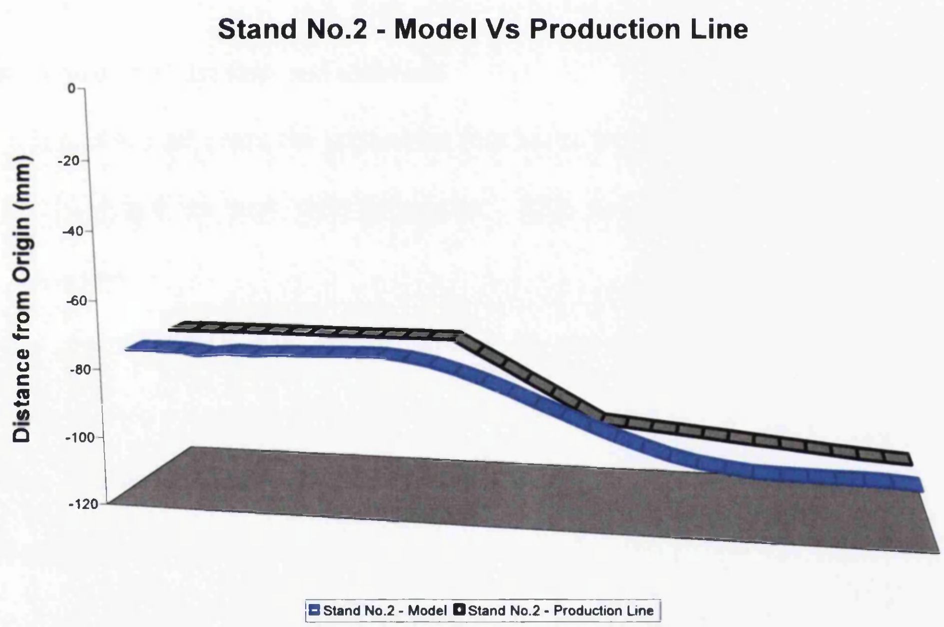


Figure 7.1: Exit of Stand No.2 – 3D representation of Model Vs Production Line

Therefore, in conclusion, the validation of the simulation model proves that a Celtic line profile can be successfully modelled using ABAQUS with parameters such as friction and rotating rolls to transport the sheet.

The accuracy of the simulation is satisfactory for this particular application. However, if higher accuracy was required, then it could be increased by using a more complex meshing technique and density. For example, this would increase the accuracy in simulations where large material deformation is expected.

7.4 Benefits and Cost savings

As outlined in Section 1.3, the long term goal of this research was to create the ability to predict the performance of new steel grades used for roll forming without the requirement to use production line time and materials.

To trial a new steel grade the production line has to be stopped and the roll setup changed to accommodate the new steel properties. This can also lead to material waste and increased cost.

This computer model has proved success in simulating 2 stands of a roll forming production line of a simple HPS 200, 1000/32 profile. Therefore, could be used to simulate various other steel grades within the same model and determine their suitability. For example the steel strength could be easily increased in the model in order to determine the highest strength steel which could be used by the same production line before encountering material defect problems such as cracking.

Despite not being used during this study to assist Corus business units, the model was promoted as a potential tool for future use to CP&P and Kingspan. Therefore, could be used to help predict performance of new grades or even investigate the cause of defects being encountered within a production line. The benefits of such a tool could result in cost reduction of production line time to trial new steel grades and also minimise material waste.

7.5 Recommendations

This study has presented evidence that ABAQUS can successfully simulate the roll forming process with parameters such as friction and rotating rolls applied in the model.

However, this thesis does not discuss all model parameters in depth and as a result further work to investigate these parameters would be beneficial, especially to help increase the accuracy of the model already created. Further work would need to focus on the following:

- Rolling Friction

The friction coefficient for the actual production line could be determined. As discussed in Section 7.2, analysis during initial research of this study proved that there was limited impact on simulation results with a change in friction coefficient. However, only steel on steel contact friction coefficient were used and therefore more research is required in the potential values of rolling friction with a product such as HPS 200. The friction coefficient could then be updated with the computer model.

It would also be beneficial to determine if the friction coefficient can be varied within a computer model, for example, as the material passes through different roll stands. For the purpose of this study, the friction coefficient was constant.

- Sheet mesh

As discussed in Section 6.4, the sheet mesh for this simulation was basic and even though the results were satisfactory, the results could be made more accurate in future simulations.

This would require the strip to be partitioned and the mesh density varied throughout the cross section. A high density mesh in sections of the strip that are to be profiled would dramatically increase the bending accuracy of the material in the simulation and would make the resultant profile more comparable to the production line profile. Areas of the strip that are not profiled can maintain a lower density mesh to reduce the quantity of elements and nodes within the mesh to help reduce analysis computational time.

- Element type

This study focused on using C3D8R element within the mesh, as it is a proven method for roll forming contact simulations. However, further work could be carried out to investigate various element types and their influence on the performance of the simulation.

REFERENCES

Beddoes J., 'Principles of metal manufacturing processes', Arnold publications, 1999, pp142 - 147.

Bernard E.S. & Bridge R.Q, 'Tests of profiled steel decks with flat-hat stiffeners', Journal of structural engineering, Vol 121, 1995, pp 1175-1182.

Bernard E.S.& Bridge R.Q, 'Design methods for profiled steel decks with intermediate stiffeners', Journal of constructional steel research, Vol 38, 1996, pp 61-88.

Bernard E.S. & Bridge R.Q, 'Tests of profiled steel decks with v-stiffeners', Journal of structural engineering, Vol 119, 1993, pp 2277-2293.

Corus panels and profiles (CP&P), 'Composite floor decks', Customer brochure, Corus 2002, p01.

Corus Staal, 'Steel processing brochure', Corus 2001.

Dasarthy C., 'Processing of uncoated sheet steels', engineering doctorate materials course notes, 2003, pp 01-06.

Dieter G., 'Mechanical metallurgy', SI metric edition, McGraw-Hill publishing, 1998, pp 287-677.

Fagan M.J., 'Finite element analysis- theory and practice', Longman, 1992, pp 01-235.

Hibbitt Karlsson & Sorenson, 'Explicit Users Manual', ABAQUS 6.3, Vol 1, Inc, 2002, 7.6.1 pp 01-07.

Hibbitt Karlsson & Sorenson, 'Explicit Users Manual', ABAQUS 6.3, Vol 1, Inc, 2002, 2.3.4 pp 01-06.

Hibbitt Karlsson & Sorenson, 'Explicit Users Manual', Vol 1, ABAQUS 6.3 , Inc, 2002, 7.5.1 pp 01-12.

Hibbitt Karlsson & Sorenson,'Getting started with ABAQUS/Standard', ABAQUS 6.3 , Inc, 2002, pp 01-02.

Laging W. & Peeters R., 'Validation of the 3D Roll forming simulation of an open profile', Corus RD & T, June 2003, p 03.

Laging W., 'Catalogue of defects in roll forming products', PAC, Dec 2000.

Lawson R.M., 'Testing of profiled decking', Journal of constructional research, 1989.

Leslie C.W., 'The physical metallurgy of steels', Hemisphere publishing, 1981, pp 07 - 297.

McMurray H.N., 'Coated steel products', Engineering doctorate materials course notes, 2003, pp 275-280.

Peeters R., '3D modelling of the roll forming process', Internal report, Nov 2001, p 02-73.

Selves N.W., 'Performance of beams', Journal of structural engineering, 1999.

Website References:

ABAQUS products website, http://www.abaqus.com/products/products_overview.html.

ABAQUS website, industry solutions, Corus example, http://www.abaqus.com/solutions/sol_industry_corus.html.

Corus Panels and Profiles website, Corus emissions 1999, http://www.corusgroup.com/en/news/news/2000.htm

Key to Steel, 'Engineering stress-strain curve', http://www.key-to-steel.com/Articles/art43.htm.

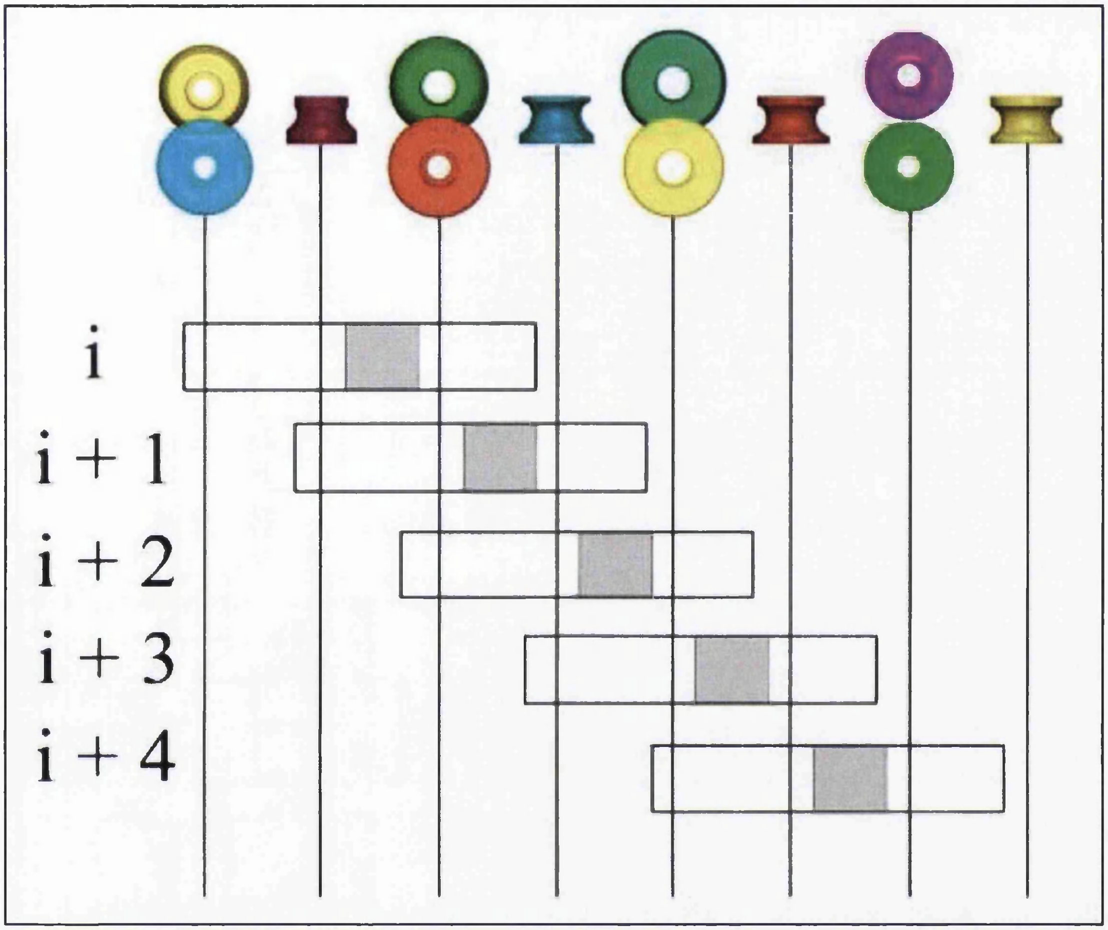
Key to Steel, 'Tensile strength', http://www.key-to-steel.com/Articles/art43.htm.

Kingspan products, flat panels - http://www.kingspanpanels.com/uk/prod_selector/wall/index.htm

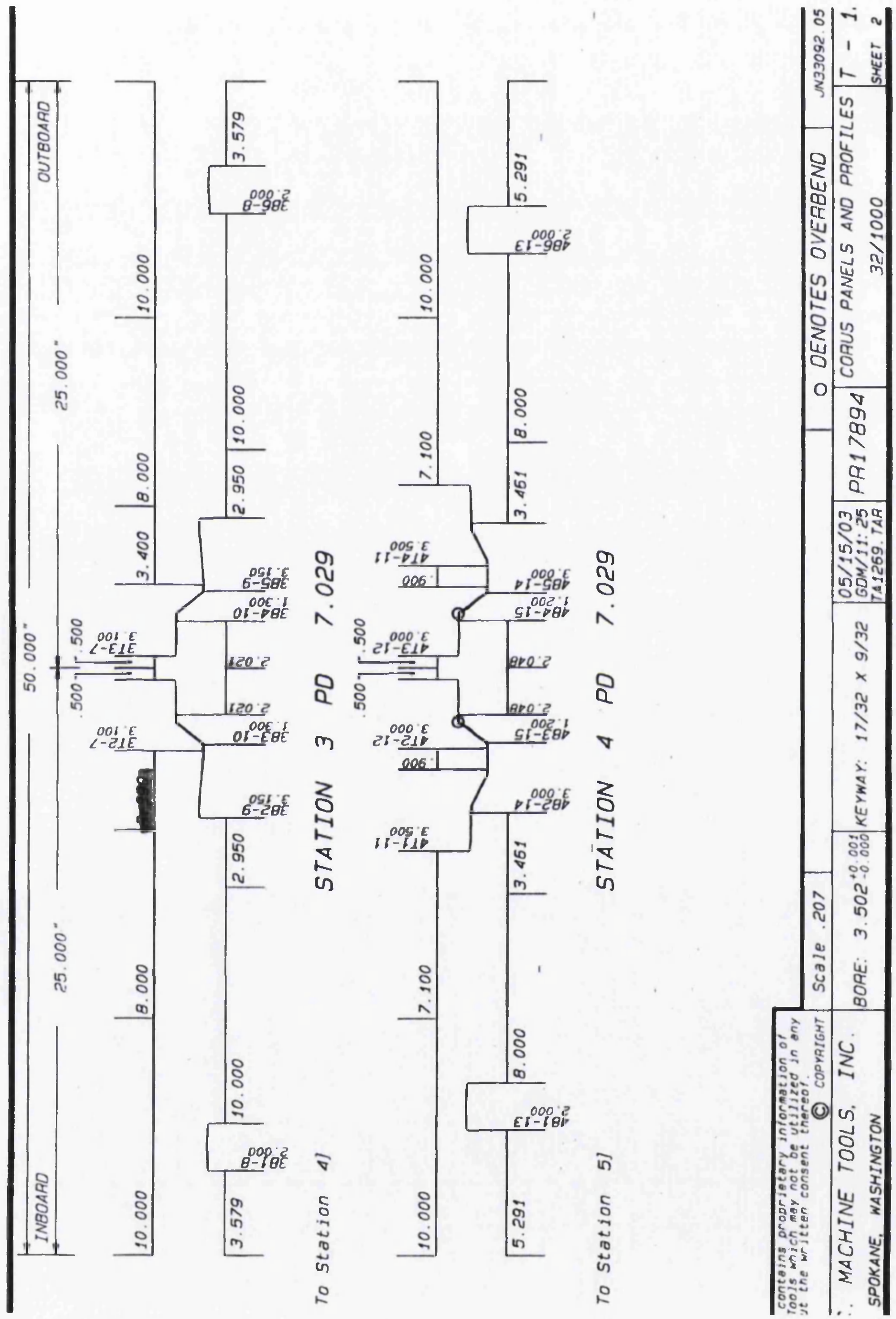
Mechanical Engineer magazine, Corus article-

http://www.memagazine.org/backissues/aug03/departments/computing/computing.html

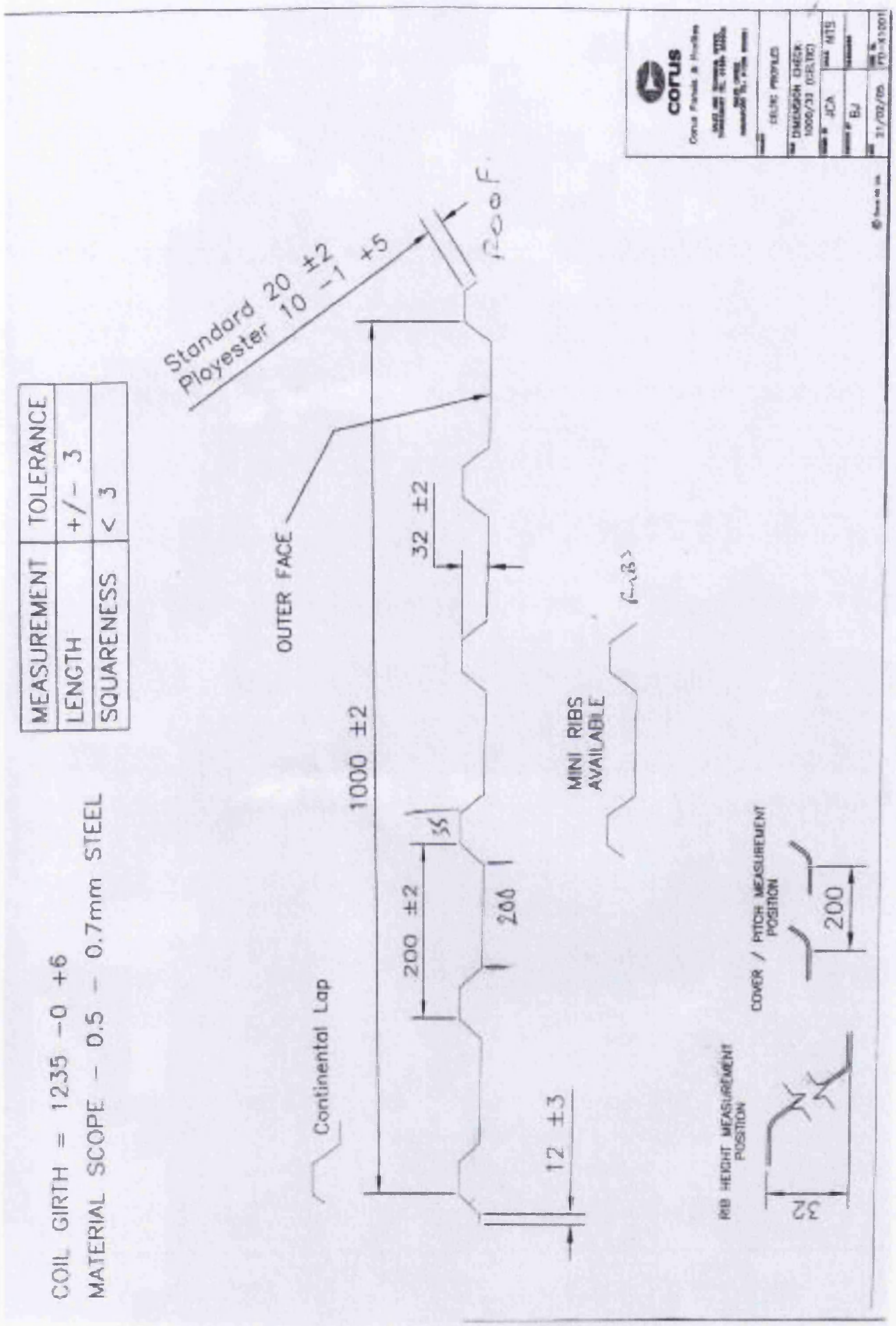
APPENDIX A – Length of Sheet



APPENDIX B – Roll Stand Geometry



APPENDIX C – Celtic Line 1000/32 Geometry



APPENDIX C – Coil Data