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MODELLING OF FLEXIBLE ROLL FORMING

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To My Parents

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ABBREVIATIONS

2-D	: Two Dimensional
3-D	: Three Dimensional
ASME	: American Society For Mechanical Engineers
ASTM	: American Society For Testing and Materials
BS	: British Standards
CAD	: Computer Aided Design.
CAM	: Computer Aided Manufacturing
DIN	: Deutsche Industrie Norm
FEM	: Finite Element Method
ISO	: International Organization For Standardization
LNL	: Length of Neutral Line
PtU	: Institut für Produktionstechnik und Umformmaschinen
RC	: Rockwell Hardness
TAN	: Tangent

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LIST OF SYMBOL

a_b	: Amount of widening in cross-section
a_l	: Length of the transition region
a_x	: Length of a region of profile that is straight with varied cross-section
b	: Height of the arc region
c	: Height of the line region
C	: Length of the bending zone/ A chain parameter of a mechanism
d	: Length of the arc region
D	: Dilatation rate
D_{max}	: Maximum diameter of the roll
e	: Length of the line region
G	: A chain parameter of a mechanism
h	: Leg height
H	: Height of the edge wave
I	: Unit for expressing the edge wave shape criteria
J	: Web width
k	: Non-dimensional coefficient
K	: Strength coefficient
l	: Total length of the profile
L	: A chain parameter of a mechanism
M	: A chain parameter of a mechanism
n	: Strain hardening exponent
Oq	: Offset quantity to find the unfolding shape
$O_{Temporary}$	: A temporary offset quantity to reach the tool path
P	: Peak to peak repeat distance of edge waviness
r	: Radius of the arc regions in the user defined end profile
R	: Inner radius of bending zone, a chain parameter of a mechanism
Rc	: Radius of central line
R_i	: Inner radius of profile
RiO	: The proportion of the inner radius to wall thickness
Ro	: Radius of the rolls
Ro_{max}	: Maximum radius of the roll
s	: Length of a region of profile without cross section variation
S	: Distance from the roll center to the central line when touching / A chain parameter of a mechanism
ß	: Bending angle of the leg according to the station
t	: Wall thickness of profile
w	: Wall thickness on the leg
x	: The amount of elevation that must compensate the rotating roll
X_0	: Initial cross-sectional position
ΔB	: Amount of dilatation
δ	: Slope of arc and line in translation / Max. rotation angle for the rolls
σ	: True stress value

MODELLING OF FLEXIBLE ROLL FORMING

ABSTRACT

In this thesis, the required parameters to realize the finite element analysis of roll forming of a U channel with varying cross-section were investigated. Most significant factors affecting the consistency of shape dimensions were inspected. In order to acquire a constant leg height at the end of cross-section variation, the tool path of the rolls as well as the unfolding sheet metal must be defined wisely. An appropriate rotation definition is also supposed to be specified by referencing the determined tool path.

Following the introduction of necessary theories, a case study was commenced with an assumed user definition that has arbitrary dimensions for a cross-section varying profile. The end shape of the profile was referenced as the initial point. Thereafter, the appropriate precut unfolding shape was calculated by respecting the deformation originated dilatation. The profile was separated into groups to define the regions that are affected from the dilatation during deformation. As the unfolding shape and the tool path for the rolls were specified, the rotational definition was also determined by calculations aiming to keep the perpendicularity with the specified tool path. The position of the rotational center point was also a significant parameter, since the rotation movement depends on its location. Also, a relationship with roll size and the flexible profile geometry is created to set a maximum roll size limitation.

The feasibility of the flexible roll forming in commercial finite element software was inspected. Determining the arrangement of the rolls and setting additional flattener rolls to the system was also significant. Besides, the availability of finite element software to assign up to six degree of freedoms was investigated and succeeded. The results of the simulation were discussed and the dimension consistency was achieved with good precision and successful material properties.

ESNEK ROLL FORM İŞLEMİ İLE PROFİL İMALATININ MODELLENMESİ

ÖZET

Bu yüksek lisans tezinde, esnek roll form işlemi ile şekillendirilen bir profilin sonlu elemanlar yöntemi ile analiz edilebilmesi için önem taşımakta olan parametrelerin teorik ve deneysel olarak tespit edilmesi amaçlanmıştır. Şeklin boyutlarının kabul edilebilir olması için önem taşıyan faktörler incelenmiştir. Endeki kesit değişimi ile oluşan deformasyon sonucunda profilin bacak boyunun uzunluk boyunca eşit kalması isteniyorsa, çözülmüş metal sac şeklinin ve hadde takım yolunun doğru tanıtılması gerekmektedir. Tanıtılacak olan takım yolunu referans alarak da rotasyon hareketinin tanımlanması yapılır.

Gerekli teorilerin tanıtılmasının ardından, kullanıcı tarafından tanımlandığı varsayılan ve boyutları isteğe göre verilmiş ve enine kesit değişimine uğrayan bir vaka çalışması gerçekleştirilmiştir. Kullanıcının tanıttığı son haldeki profil başlangıç noktası olarak kabul edilmiştir. Ardından deformasyon sırasında oluşan enine uzama hesaplanarak, prosesten önce kesilmiş olması gereken çözülmüş sacın boyutları hesaplanır. Deformasyon sırasında hangi kısımların enine yöndeki uzamadan etkilendiğini anlıyabilmek için profil gruplara ayrılırak hesaplamalar gerçekleştirilir. Çözülmüş sac boyutları ve uygun takım yolu belirlendikten sonra, dönme hareketi tanımlanmalıdır. Dönme hareketi, belirlenmiş olan takım yolundan çıkarılarak, aralarındaki diklik durumunu her geometri evresinde korumak gerekmektedir. Dönme hareketinde merkez noktası büyük önem taşıdığından ötürü, bu noktanın nerede duracağı sonuçtaki boyutları etkileyecek kadar önemlidir. Bunun dışında, tanımlanan profil şekli ile hadde boyutu arasında bir ilişki kurularak, hadde için bir azami boyut sınırı kısıtlaması getirilmiştir.

Esnek profil şekillendirme yönteminin bir ticari sonlu elemanlar yöntemi programına uygulanabilirliginin incelemesi yapılmıştır. Haddelerin sistemde dizilimi ve gerekli olduğu taktirde düzleyici haddelerin yerleştirilmesi durumu da bu çalışmada işlenmiştir. Ayrıca, mevcud programın haddelere altı serbestlik derecesine kadar izin verip vermediği de araştırılmış ve sonucunda başarılı olunmuştur. Simulasyonun sonuçları değerlendirilmiş ve yüksek boyut uyumunun yanında malzeme özelliklerinin de iyi olduğu görülmüştür.

1. INTRODUCTION

1.1. Problem Statement

Cold formed long sheet parts with constant cross section are used almost in every area of industry. Especially in automotive and construction industries, beam shaped, open-ended or closed steel profiles without varying cross-sections can be produced **[1]**.

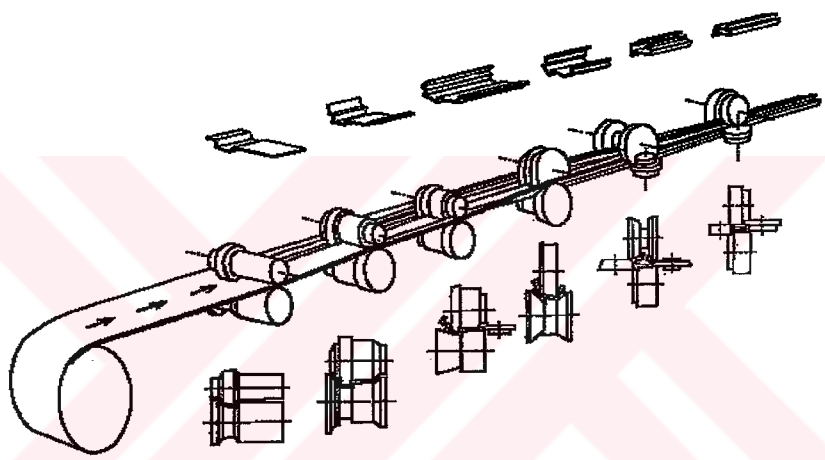


Figure 1.1: Roll forming

Roll Forming has more significance in comparison with other techniques to manufacture a cold profile with constant cross-section. In this technique, a great output quantity per time can be attained and consequently a profitable economical efficiency can be achieved due to the continuous bending action. The length of the profile is selectable and independent from tool geometry **[2]**. Roll forming is in challenge with "Folding" and "Die Bending" techniques on the production of the components with constant cross-section. These techniques are qualified because of their flexibility, especially when small batch sizes are required to be produced. While the shape spectrum with roll forming is almost unlimited, with folding and die bending relatively simple shapes can be produced **[7]**.

The most important technical advantages of the roll formed components against other techniques are the purposed work hardening and very good surface properties. Naturally coated and enameled sheets can be processed without any harm on the surface. Other bending techniques such as "Sliding draw bending", have also an important meaning in industrial applications at present [7].

In the other applications of technology, especially in the development of new vehicle concepts, the lightweight aspect is a central criterion to determine the necessary material and the selection of the proper manufacturing process [4]. On one hand the intelligent material combinations with new materials and new joining techniques, on the other hand new profiling technology can be taken in consideration and be evaluated during the conceptual design. Hence, the manufacturability of the load-adaptable and light-weight components becomes an important qualification [3].

The technological demands to lengthwise-oriented components changed radically in the course of ever-growing impact of good formed and designed, material conditioned light-weight construction. Today the profiles with reduced weight and good design are required in lightweight construction. So that, the high strength and the high stability characteristics with light weight are becoming the primary solicitation, which pushes the industry to apply high-strength materials in combination with reduced wall-thickness. In addition to these material design parameters, the shape-design of profiles has also a big importance to produce light components, which leads to strengthened applications of profiles with cross-sections, that exhibits an optimized correlation between weight and mechanical profile properties [7].

Their insertion is applied by individual design of the profile cross-sections, which constitutes a step to the concept "flexible forming". Beside the expanded design flexibility, a hardening avail can be reached up to a level of 25% with the same weight, by the components that has better load (stress) adapted cross-section properties according to the components with constant cross-section.

The cross-section of the components that are being produced with common techniques is however constant through the lengthwise direction. The economical production techniques fail so far to get a varying cross-section through the

longitudinal axis. Such cross-sections are being manufactured cost-intensively either by multi-level processes or by multi-parts [7].

Despite the expensive manufacturing possibilities, there is a wide application area of rod-shaped components with varying cross-sections. Their usage area can be substantially expandable by new manufacturing techniques.

The main application areas are:

- Vehicle construction
- Machine or mechanical system construction
- Building industry
- Furniture industry



Figure 1.2: Some profile concepts with varying cross-sections [21]

In automobile industry, especially in bus, omnibus, commercial vehicle constructions, longitudinal structure components are needed, which are currently joined with a separate connection or knot member [7]. Thus, reduction in the weight and also in cost for the automobile body work should be reached.

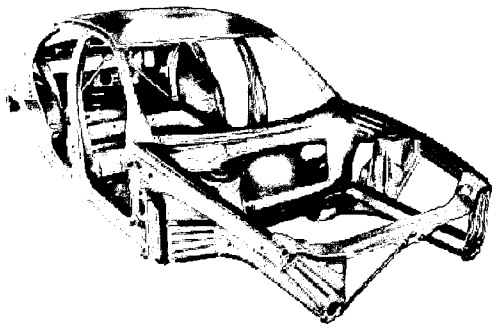


Figure 1.3: Lightweight construction of automobile bodywork **[15]**

Therefore, the interest in thin-walled, open channels or closed structural profiles is very large. Such profiles can be characterized, on one hand by the consistent, uniform wall thickness; on the other hand they show a varying cross-section over the length. Due to varying cross-sections some possibilities appear for load-adapting structure parts, like saving the weight and taking out the joining elements from the main part. The other components of steel-space-frame design are being manufactured with other multi-level techniques like deep-drawing or bending operations with many steps **[7]**.

Such process chains, with intense set-up times and huge capital investments, prove to be disadvantageous not only because of their low productivity, but also because of the constraints they place on meeting each customer's requirements. Profile-shaped components with geometrically similar shapes within a product family arise in the course of the diversification of product lines. Structural components from utility vehicles serve as an example of one such product family (Figure 1.4). The different shapes of these structural components result from differences in wheel base and acceptable total weight **[11]**.

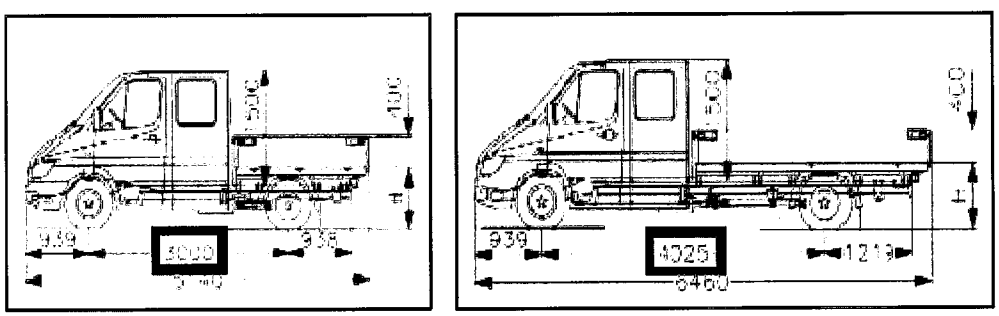


Figure 1.4: Light trucks with different wheel bases **[11]**

From the perspective of lightweight construction, longitudinal beams and cross-beams in automotive technology are designed to be load-optimized. This inevitably leads the components to be produced with variable cross sections in the lengthwise direction. Likewise, the package in automobiles requires components with increasing geometrical complexity. In numerous other applications apart from automotive technology, the use of open and closed profiles with variable cross sections along the longitudinal axis is equally conceivable and consequently, carries significant potential for production technology **[11]**.

Furthermore, varying cross-sectional profiles are required to be produced reaching three degree of freedoms. This restriction can cause also some design constraints that affect the flexibility of the profile design. So that, a production technology can be developed, achieving up to 6 degrees of freedom in the whole system. However, before producing such a technology, simulation and experiments are supposed to be executed. An appropriate FEM Software must be inspected in order to check the capability of the most convenient software to reach up to 6 degrees of freedom on the roll kinematical move.

Systematic and economical acknowledgment of the possible flexible roll forming is not yet available and being researched by many institutes that have different purposes to use it. There are already pilot systems that have two degree of freedoms for the roll movement. Simulating the flexible roll forming with detailed descriptions hasn't been explained in detail yet. The most preferred CAD-CAM Software programs also don't have any flexible roll forming simulation module for the designers, who demand more flexible design issues in cold-profiles.

1.2. Objectives

Most of the objectives of this thesis appeared during the study of FEM simulation inspections for the flexible roll forming process. The definitions of the necessary parameters are also set as a goal of this study since they combine to achieve the correct result. The objectives of this thesis are:

1) Modelling a flexible form that has varying cross-section by determining a pre-cut shape acting on the assumption that user defined a complex U Channel.

2) Definition a contour-way (tool path) of the rolls to follow during the deformation, achieving a constant leg height on the profile at the end of process by considering the sheet-metal dilatation during the complex deformation.

3) Determination of a correct rotation definition that will depend on the defined contour-way by keeping the perpendicularity with tool path in each deformation stage.

4) Exploration of a commercial FEM Software to achieve flexible roll kinematics, expanding the flexibility of the rolls in the process up to six degrees of freedom considering the application of any arbitrary complex profile shape, setting restrictions for the definition to the roll size or shape definition to achieve flexible roll forming process.

5) Evaluation of parameters to execute the nonliniear finite element analysis of the flexible roll forming, determination of the position of the roll stations and deformation steps.

6) Simplification of the necessary parameters in the computer environment in order to level off the way of a possible software module.

1.3. Approach

The main goal of this study is the development of a method and determination of its correct parameters to achieve flexible form that has varying cross-section. A U channel has been developed and studied, which would be a key for the further flexible roll forming projects. The CAD model of the desired shape is generated to foresee a preview of the profile and to receive an impression how the tool path should be defined. The experiments are carried out using a commercial "finite element software" that has nonlinear characteristic to reflect the real roll-forming manufacturing environment and to provide elastic-plastic conditions. The approximate methods are investigated with numerous simulations to optimize the required parameters. The starting point is assumed to be any software user definition for a channel that has varying cross-section and necessitates complex roll advance.

During the trials to achieve the correct tool path, it is observed that many parameters affect the contour-way and the leg height at the end profile is a result of the defined tool-path and the rotational path. The rotational path is thought to be advancing always perpendicular to the tool-path. Thus, a definition of the rotational path is derived from the tool path definition mathematically.

The explored parameters of the whole concept are deformation steps (no of stations), positioning of rolls, relationship between the applied rolls and geometry of the profile, meshing method of the sheet metal, determination of the pre-cut shape, correlation between pre-cut shape and the correct tool path that rolls will follow in 3-dimensional dimensions, rotational path, determination of the rotational center point and definition of boundary conditions to receive the correct result.

The ultimate goal is to explore the feasibility of the flexible roll forming in computer environment, which should contain the 3-D kinematics of the rolls and gives the correct results by using up to six degree of freedom flexibility. The conventional roll forming products always had a profile-web, which has a constant cross-section over the length. Although there were some studies to vary the cross sections, it couldn't be simulated nor produced with the rolls that are able to move with 6 degree of freedoms (3 translational displacements and 3 rotational displacements), which gives the designer a real flexibility of designing the profiles in any industry area.

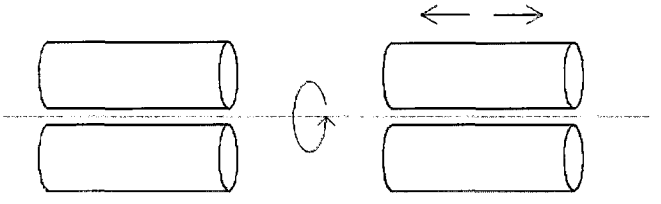


Figure 1.5: Rotational and translational degree of freedoms on x-axis

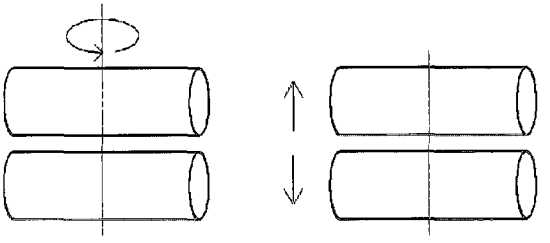


Figure 1.6: Rotational and translational degree of freedoms on y-axis

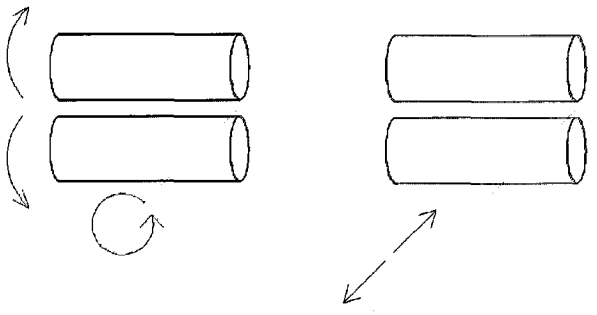


Figure 1.7: Rotational and translational degree of freedoms on z-axis

The theoretic definitions are declared before beginning the simulation and the required parameters are determined. Theoretic explanations are expanded to produce the leg height equal all along the leg-line. The theories are tried to be associated with the mathematical explanations to prove the accuracy of their existence. The mathematical expressions are thought to be helpful during the creation of a flexible roll forming software module. In order to adapt a Flexible Roll Forming Module to the main Roll Forming software (COPRA® RF), all the studies were made to simplify the steps and to attain a user friendly computer environment. At the beginning, defining the whole simulation and setting the parameters were laborious, tedious and long. Some procedure files are coded, which accelerates the definition and brings more time to the user. The complicated theories shouldn't be dealt with during the building of a new simulation. Therefore, a simplified definition of the whole progress is developed, which could be easily turned into a module only by programming and compiling in C++ environment.

The simulation is carried out and the results are evaluated in different aspects. The geometrical aspect of the final profile is the most important issue among the results. After evaluating the final shape, stress, strain and deformation hardening results, the factors affecting the process are verified.

1.4. Content of the Thesis

This thesis consists of six chapters. After this brief introduction, the second chapter gives summarized information on conventional roll forming technology. The roll forming design issues, the appropriate materials, its application in industry and its

advantages and disadvantages are described. The common roll forming problems are also mentioned. Then the technical situation for the complex shaped profiles and some patent attempts to produce these kinds of profiles are summarized.

In the third chapter, the significance of some design parameters is discussed. The geometry of defined pattern shape is also explained. The number of deformation steps (the number of the stations) is determined. The type of the rolls in the stations to achieve complex profile cross-sections is also discussed. The classical calibration methods are also mentioned and the choice of calibration method for the flexible roll forming is determined with emphasizing the reasons.

In the fourth chapter, a complete case study for simulating a flexible form is explained in detail. The all parameters, theories and applications are described here in order: The assumed arbitrary user definition dimensions are set as the starting point. These dimensions are also set as the target of the studies and tried to be achieved also at the end of simulation. Determination of the pre-cut shape according to the user definitions, calculation of the dilatation values of deformation in the complex shapes, definition of the contour-way depending on the dilatation values and pre-cut shape, determination of the rotational path according to the contour-way, specification of the rotational center point for each station, restrictions for the roll size or for the shape geometry with the defined dimensions, specification of the deformation steps and the arrangement of the rolls and the all necessary information to build a flexible roll forming simulation.

In the fifth chapter, required simulation parameters are given. The significant methods, which make the simulation possible, are explained in this chapter. The contact properties of the rigid bodies and the deformable body are discussed.

In the sixth chapter, the obtained results are declared. The shape geometry is measured and compared with the user definitions, if it fits and fulfils the expectations. Other results like stress, strain and deformation hardening are also observed and evaluated, whether they improve a flamboyant failure. The tolerance limitations are determined and the corrugations are investigated, if they represent a certain roll forming failure. Additionally, the recommendations for a further project on the same

subject are manifested. The focus points and the actions, which shall be considered in the future, are discussed. The further tasks for both mechanical engineers and software engineers are specified.

2. ROLL FORMING

Roll forming is a continuous metal forming process using sheet, strip or coiled stock. This process bends or forms these unfinished materials into the shapes of essentially identical cross-section by feeding the metal between successive pairs of rolls that gradually shape it until the desired cross section is completed. The process adds both rigidity and strength to the roll formed metal. The thickness of the metal does not change except for a slight thinning of the material at the bend radii. In many cases, roll forming eliminates multiple stage production, sub-assembly and finishing operations.

Roll forming permits consistent adherence to close tolerances, producing shapes and dimensions to fit an application. By eliminating the need for secondary operations such as notching and deburring, production speed is increased and assembly costs are reduced. Roll formed material generally has a structural strength advantage over other processes. Hollow or semi-hollow shapes can be produced with thinner walls than competing processes.

Roll Forming is the most economical choice for many companies that look to streamline their production and reduce overall cost in medium to high volume production. The high-speed continuous nature of roll forming is especially beneficial for large volumes. An experienced designer will incorporate a number of secondary operations in one line. Savings are realized through the need for fewer component parts, fewer post-production operations and reduced manufacturing cost **[9]**.

Many shapes are roll formed without much problem. Although not all shapes may appear to be suitable for roll forming, it is worth considering this process in the evaluation. In many cases an experienced roll former can provide alternate designs to fit the needs. All industries can benefit from the flexibility of roll forming. Many companies that use roll formers do so, because they require consistent adherence to close tolerances.

Roll formed shapes can be economically produced from an almost limitless variety of stock coated or uncoated eliminating the need for secondary finishing operations. Uniformity assures precise fit and simplifies production, speeds assembly and minimizes rejects.

2.1. Roll Forming Techniques

There are two methods commonly used when shaped parts are rolled formed. They are the:

- Pre-cut or cut-to-length roll forming,
- The post-cut roll forming.

The selection of the best roll forming process is normally based on the difficulty of the cross section and the production length required by the end-user specifications **[9]**.

2.1.1. Pre-cut Roll Forming

The material to be roll formed is cut-to-length before being fed into the roll forming machine. Normally, this process includes both a stacking and feeding system that moves the metal blanks into the roll forming machine running at a fixed speed (normally between 15 to 75 meter per minute), and a post production conveying and stacking system. This roll forming technique is typically used for lower volume parts. It is also used when notching can't be easily handled in a post-cut line.
Tool cost is economical for the pre-cut roll forming process since cutting requires only an end notch die or flat shear die. However, end flare is more obvious and side roll tooling idler is needed to obtain a high-quality finished shape **[9]**.

2.1.2. Post-Cut Roll Forming

The most efficient, consistent and least problematic process is the post-cut roll forming method. It is the most widely used roll forming process.

The post-cut roll forming process requires:

- an uncoiler
- a roll forming machine

- a cut-out machine (flying cut-off shear press), and
- a run-out table.

Post-cut roll forming can be supplemented by a variety of secondary, or auxiliary, operations including:

- pre-notching
- punching
- embossing
- marking
- trimming
- welding
- curving
- die forming

When used in conjunction with post-cut roll forming, these operations can eliminate the need for stand-alone secondary operations providing a complete or net shape profile. The cost of tooling, and the tooling changeover time for post-cut roll forming, are greater than for the pre-cut method, but are usually more than offset by the other advantages [9].

2.2. Roll Form Design Issues

The most successful and problem-free roll forming operations involve shapes that are previously designed under the assumption they will be shaped through roll forming. Metal sections that have been routinely produced in the past by press braking, stamping or extruding can be effectively and profitably switched to the roll forming process. The end-user or roll former must be aware of eight key roll forming considerations:

- Cross section depth
- Blind corners
- Symmetry of roll forming design
- Length of the leg
- Radius of the bend

- Notches/punched holes
- Width of the section
- Length of the part

2.2.1. Cross-section Depth

End-users of the roll forming process should avoid forming pieces with extreme depth in a cross section. The movement of the metal around the arc of the bend is much greater in a deep piece, so the stress produced on that piece during roll forming is much greater and that produces stress on the formed piece's edges.

2.2.2. Blind Corners

A blind corner can be defined as a bend that can't be handled by direct roll contact. Blind corners eliminate the precise control of sectional dimensions unless the corner is reachable by slides or other forming rolls. Blind corners should be designed out before roll forming a part.

2.2.3. Symmetry of Roll Forming Design

Non-symmetrical sections are often roll formed without problems, but the section that is symmetrical to its vertical centerline creates equal forming pressure being applied to each edge of the metal as it is roll formed. Symmetrical pieces reduce metal stress since the roll forming pressure is equal.

2.2.4. Length of the Leg

A good rule of thumb is the leg length should be three times the thickness of the material. Shorter legs do not allow the rolls to properly form the leg resulting in nipping the edge of the material that will produce an undesirable wave along the finished part's edges.

2.2.5. Radius of the Bend

Sharper radius creation can be produced by roll forming than by any other conventional metal forming methods. Generally, the bend radius should be equal to, or greater than, the material thickness. Smaller radius creation can often result in fracturing at the bends due to the thinning of the metal that does occur at the bend radius only.

2.2.6. Notches / Punched Holes

The pre-punched holes or notches should be kept away from bend lines or material edges. The part holes should be placed at least three to five times the material thickness past the bend radius. Slight distortions in the size and shape of the notches/holes during forming are very possible and should be considered as a normal probability of the process. If the number of passes your material makes through the roll former increases, the occurrence of hole distortion will be reduced.

2.2.7. Width of the Section

Wide sections with wide flat areas are difficult to form and hide imperfections like curvy edges or lack of centre flatness. Roll forming can't remove flaws inherent in the coil or surface imperfections in wide flat areas. However, roll forming can try to conceal them or disguise them in the roll formed cross-section.

2.2.8. Length of the Part

Facilitating cut-off that will minimize part distortion should be taken into consideration. In the designing for cut-off, the shortest length for pre-cut parts is no less than twice the horizontal centre distance between two roll forming stations.

2.3. Roll forming Advantages and Limitations

2.3.1. Advantages

Roll forming offers a number of distinct advantages over other metal fabricating methods. Advantages include:

- The initial cost of a roll forming line is no more, and often less, than the cost of a standard stamping line or progressive die operation.
- Production speeds of 5-55 meters per minute can be attained but 30-54 meters per minute is a reasonable average for most current equipment.
- Roll forming is a high volume process that makes uniform and accurately dimensioned parts.
- Parts are produced with little handling, minimizing labor costs and needing only the coils to be loaded at the starting end of the machine and removal of

finished parts at the other end. This process can usually be handled with a minimal number of operators.

- Roll forming can also be used for low-volume production because setup or changeover time for new parts is not long.
- Maintenance costs are generally low. The form rolls can produce several million millimeters of product before problems occur when properly maintained.
- The roll forming process is easily combined with other operations and processes to automatically form a considerable range of metal parts.

2.3.2. Limitations

A few limitations also exist. Roll forming limitations include:

- Experienced roll design engineers must design those rolls exclusively for complex shape forming.
- Complicated tubular shapes, and some closed shapes, may need mandrels to form the shape accurately.
- Variation in cross-section cannot be achieved yet with the roll kinematics for complex designs.
- Delicate, breakable, machine parts may need recurrent replacement during high volume production runs.

2.4. Materials that can be Roll Formed

Almost any material that can tolerate bending to a desired radius can be roll formed. The more ductile a material is, the better it will roll form. The roll forming process can handle ferrous, nonferrous, hot rolled, cold rolled, polished, plated, or pre-painted metals producing excellent results [9].

Materials as thin as 0.15 mm and as thick as 19 mm can be roll formed. Material pieces as narrow as 3.2 mm and as wide as 1830 mm, or more, can be roll formed, depending on the vendor's machinery.

The length of the finished roll formed part is only restricted by the length that can be functionally handled after the finished part exits the roll forming machine.

Sometimes, several sections can be formed from a single strip or several strips can be fed concurrently and united to produce a combined section. There is only one absolute material requirement for composite forming. The material must be capable of being formed at room temperature to the desired radius. Roll Forming is suitable for almost all metals. Some of the most common are;

- Galvanized steel
- Stainless steel
- Carbon steel
- Brass
- Copper
- Zinc
- Titanium
- Many other materials

Unlike other processes roll forming is also ideal for various metals that have been painted or coated.

2.5. Tolerance Expectations

Typically, four tolerances are critical to successful roll forming operations. These include dimensional cross-sectional, length tolerances, angular, and material straightness.

2.5.1. Dimensional Cross-sectional Tolerances

Dimensional cross-sectional tolerances from ±0.3 to ±0.8 mm can be achieved with roll forming equipment. If tighter tolerances are required the roll former must buy materials that can hold the increased tolerances.

2.5.2. Length and Angular Tolerances

Length tolerances are totally dependent on the thickness of the material, the length of the part, the speed of the roll forming line, the quality of the equipment, its condition, and the type of measuring and cut-off system used by the roll former. Angular tolerances of ±1° are typical in the roll forming process. In the roll design 1° tolerance should be appointed to the roll on the bending side.

2.5.3. Material Straightness

Material straightness is another tolerance consideration. Factors that establish material straightness include camber, curve or sweep, bow, and twist. The terms camber, curve, and bow are many times interchanged when describing material straightness, but they actually have slightly different meanings. A formed part's horizontal and vertical planes are determined by their position in the roll forming process.

2.6. Quality and Accuracy

Two situations that may negatively impact the quality and accuracy of roll-formed sections are springback and end flare.

2.6.1. Springback

Springback occurs when the material to be formed has not been stressed past its elastic limit. Springback can be engineered out during tool design by overforming the material beyond its anticipated final shape.

2.6.2. End Flare

End flare is the deformation at the ends of a roll formed part. End flare can be eliminated or at least reduced through using proper roll forming tool design.

2.7. Common Roll-forming Applications

Roll forming, as a metal fabricating process, is used in many diverse industries to produce a variety of shapes and products. Roll forming is a desirable process since it adds both strength and rigidity to lightweight materials **[9]**. Some industries that frequently use roll-formed products include application on:

Table 2.1: Roll forming application areas **[9]**

• Automotive • Truck • Building construction commercial and residential • Highway construction • Office furniture • Home appliances and products	• Medical • Marine • Agricultural • Rail • Aircraft • Heating ventilation and air conditioning (HVAC)

2.8. Roll Forming Tooling

2.8.1. Forming Rolls

The rolls are the tools that form the moving through the roll forming machine. The number of passes the material makes depends on the complexity of the part and the properties of the material to be formed.

2.8.2. Flower Design

The creation of the flower is the first step to be undertaken in the design of roll tooling. The flower is the station-by-station overlay of progressive section contours starting with the metal strip and ending with the required component profile. The two major considerations in designing the flower are:

- a smooth material flow from first pass to the last pass, and
- utmost control over fixed dimensions while roll forming.

2.8.3. Tool Material

A number of standard materials are used to manufacture the roll forming rolls. The type and shape of material being rolled and the quality of parts being produced are key factors in the selection of the roll material.

The most extensively used material used in manufacturing rolls is an oil-hardened tool steel that has been hardened to RC 57-60. For excellent tool longevity, tool manufacturers should use a high-carbon, high-chrome tool steel, hardened to RC 60.

Cast aluminum-bronze is a good choice forming deep sections that have sliding motion since it possesses good frictional qualities. Roll forming vendors should chrome-plate their rolls if they need to sustain a highly polished finish or prevent painted surfaces from being damaged **[9]**.

2.8.4. Operating Parameters

The roll forming operation increasingly forms material as it passes from one forming station to another. The changeable parameters in a roll forming operation include power requirement, speed and type of lubricant used. These parameters are determined by width, thickness, and type of material, complexity of cross section, coating on material, and the accuracy required **[9]**.

Auxiliary operations such as pre-punching, embossing, curving, coiling and cut-off incorporated in the roll forming line, also influence the parameters at which a roll former must operate.

2.9. Common Roll Forming Problems

2.9.1. Twist

Twist is the rotation of two opposing edges in opposite directions. During typical twist deformation, the edges of the sheet are stretched, while the material that closer to the bend axis undergoes the compression. Twist in a formed part is generally the result of excessive forming pressures along the longitudinal radii.

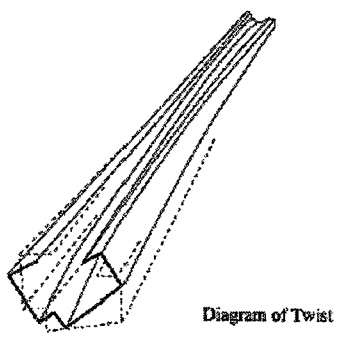


Figure 2.1: Illustration of twist **[9]**

Table 2.2: Factors that affect twist failure **[9]**

Factors	Causes / Cures
Tooling Set-up	▪ Balancing roll gaps or uneven roll gaps cause twisting. ▪ Increasing roll gap in area where twisting occurs. ▪ Reducing the degree of forming in several stands sequentially reducing the deformation imparted through several stands will reduce the peak forces, allowing a smoother strain distribution and less likelihood of twisting.
Panel Design	▪ Symmetrical panels should run without twist issues. Unsymmetrical panels are most susceptible to twist.
Material	▪ Changes in gauge across the width of the incoming material can induce twist, especially if the edges are thicker than the center. The edges will undergo more deformation than the center and twisting can result. ▪ Incoming material shape in the form of an edge wave (edge of the sheet longer than the adjacent area) can propagate itself as twist. Forming that works material on this elongated edge can result in unbalanced strains from side-to-side. Ordered material shape quality standards should be well known and defined.
Heat	▪ Heat expansion of the tooling from the forming process can reduce the roll gaps originally set, resulting in twist. If the panel runs okay at start-up and subsequently twist appears, check the roll gaps for heat expansion. The use of a lubricant can reduce temperature increase during forming. ▪ Sharp corners are a source of localized heat expansion, which can be minimized by lubrication. However, in many cases it is desirable to maintain the sharpest corner possible. This must be balanced with the roll gaps and ultimate forming pressures to minimize twisting issues.
Cut-off	▪ Improperly timed panel cut-off dies can cause cut-off drag resulting in panel deformation, which appears as twist.
Roll Pick-up	▪ Galvanized or coating pickup on the tooling can reduce the roll gap resulting in uneven deformation, and heat build-up. Clean the rolls periodically to remove any pickup to assure conformance to designed tolerances. ▪ The use of a lubricant can reduce or eliminate roll pickup.

2.9.2. Edge Wave

Edge wave is the result of the edge of the panel having been elongated with respect to the rest of the panel. Incoming shape criteria are generally expressed in terms of I units. I units are numerical designations that applied to the height and the peak-to-peak repeat of the wave.

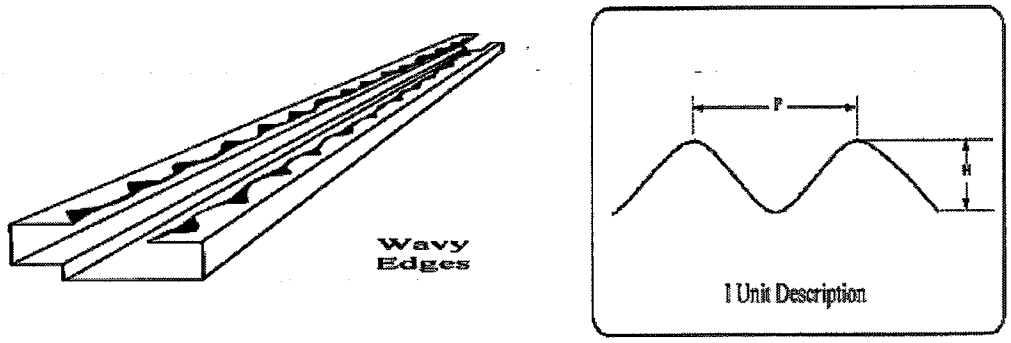
The I unit value is calculated as follows

$I = [(JI \times \text{height of the wave} / (2 \times \text{the distance between the peaks are})]^2 \times 100{,}000$

$$I = (JI \,.\, H / 2.P)^2 \, X \, 100{,}000 \qquad \textbf{(2-1)}$$

Table 2.3: Factors that affect edge waviness **[9]**

Factors	Causes / Cures
Leg Length	▪ Waves can occur because the distance from the edge to the first bend is too great, or the metal is too thin. A bend adjacent to the edge can alleviate an edge wave problem. Typically, bends at the edges should be at least 3-6 times the material thickness in distance from the edge.
Horizontal	▪ When a bend close to the edge is not possible, the operator may be able to minimize the distance condition by increasing the horizontal distance at the stands where the edge wave appears.
Lubrication	▪ The addition of a lubricant and/or raising the top rolls a little can often reduce or eliminate edge wave.
Material Shape	▪ The incoming edge shape criteria should be specified; incoming shape criteria is generally expressed in terms of I units. An I unit is the dimensionless number which signifies the amount of full center or edge wave based on the height of the wave and the length of the repeating wave.



A B

Figure 2.2: A-) Illustration of wavy edges on a profile B-) Definition of the parameters in the formula 2.1 **[9]**

2.9.3. Sweep or Camber

Sweep or camber is the deviation from a straight line in the horizontal plane of a finished panel along the length

Table 2.4: Factors that affect the sweep failure **[9]**

Factors	**Causes / Cures**
Material	▪ Sweep, or camber, can be the result of incoming material issues. Width and camber tolerances needed to develop a dimensionally accurate part must be specified for the incoming material.
Tooling	▪ Camber/sweep problems can also be the result of excessive roll gap tightness.
Alignment	▪ Shoulder alignment, spaces and roll design should all be carefully scrutinized to minimize sweep issues.

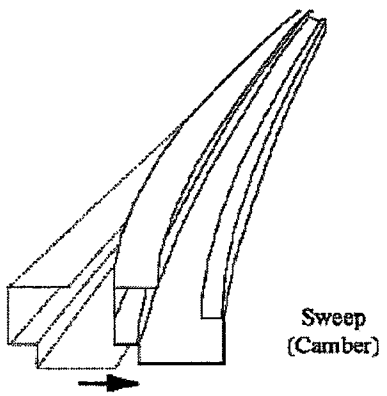


Figure 2.3: Illustration of sweep failure **[9]**

2.9.4. Flare

End flare is the distortion that appears at the ends of a panel in the width direction. End flare is the result of the stress induced in the material as a result of the bending operation.

Table 2.5: Factors that affect the flare failure **[9]**

Factors	Causes / Cures
Number of Passes	▪ If the number of passes are too few, that is, too much forming is being done per stand for a given part configuration, flare can result. Extra roll passes can minimize end flare.
Pre-punched Holes	▪ Avoid pre-punched edges at the cut-off zone.
Material	▪ More ductile materials can reduce flare
Tooling	▪ There is little an operator can do to the rolls themselves; however, operator must ensure that the roll former is adjusted correctly.
Side Rolls	▪ Flare can sometimes be fixed by "pushing" the sides inward at the exit end of the line with idling side rolls.
Part Straightener	▪ Occasionally, the only recourse is to add a part straightener at the end of the roll-forming line.

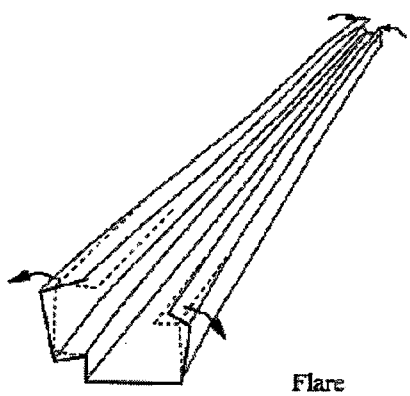


Figure 2.4: Illustration of flare failure **[9]**

2.9.5. Bow

Bow is the deviation from a straight line in the vertical direction. Bow can be either cross bow, across the panel width, or longitudinal bow, along the length of the panel.

Table 2.6: Factors that affect bow failure **[9]**

Factors	Causes / Cures
Tooling	▪ Rolls that are not adjusted properly can cause bow. Specifically, overtightening the rolls to the point of coining the metal on single or multiple web configurations can result in large amounts of bow.
Pass Line Height	▪ Bow can also result from uneven pass line height. Check the pass line height and adjust.
Material	▪ Bow can be the result of incoming material issues such as shape or gauge variation.
Part Straightener	▪ Ultimately, some parts may require a straightener at the end of the line to correct for designed bow.

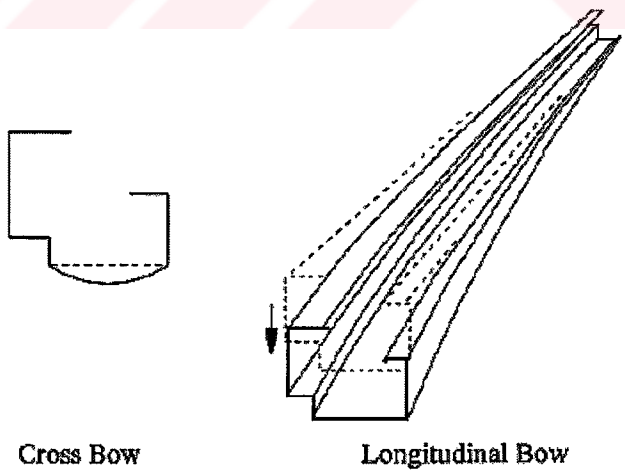


Figure 2.5: Illustration of the bow failure **[9]**

2.9.6. Oil Canning

Oil canning is generally considered as simply an elastic phenomenon resulting from stresses induced during forming panels that are wide and have only their edges formed. Operators have several descriptions for this imperfection: full center, pocket wave, loose metal, panel buckling and oil canning. Oil canning is hard to measure in a finished panel although it can readily be seen in appropriate light **[9]**.

Table 3.7: Factors that affect oil canning failure **[9]**

Factors	Causes / Cures
Flat/Free Span Area	▪ The general rule of thumb is that flat areas over 10-15 mm in width are susceptible to oil canning.
Tooling Set-up	▪ Correct tooling setup can significantly reduce oil canning, but will probably not eliminate it entirely.
Large Free Span	▪ On panels where there is a large, flat unformed area, it is vital that the tooling be designed and adjusted properly to reduce the degree of oil canning which will be inherent in profiles with large free span area(s). As the free span to thickness ratio increases, the likelihood of oil canning also increases.
Panel Length	▪ Oil canning can be present in wide free span profiles at one length and disappear if the same profile is produced at a shorter length.
Strain Localization	▪ It is generally considered that tooling/material which allows a localization of strain at the bend points of the radii will produce panels less susceptible to oil canning. This approach has been effective in reducing oil canning in panels with large free span areas such as standing seam roof, or architectural panel.
Material	▪ As the edge wave criteria, the amount of oil canning is often described in I units. Properties such as gauge, flatness, friction and mechanical properties can significantly impact oil canning in a finished panel. Subsequently, coils of the same grade can perform differently based upon variability of these properties. Thicker/higher strength materials are more likely to resist the strains that are induced at the edge of a large free span, thereby resulting in less oil canning.

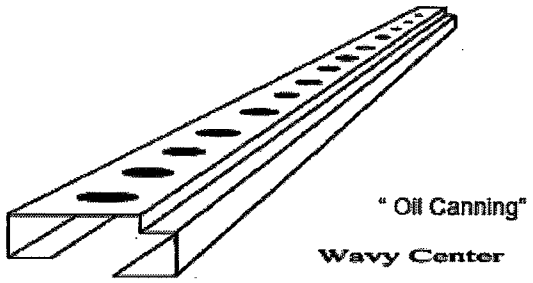


Figure 2.6: Illustration of oil canning failure **[9]**

At the end of the Flexible Roll forming study, these common problems will be respected and during the interpretation of the results these concepts will be taken into consideration in order to find the remedy.

2.10. Manufacturing of Components with Varying Cross-Sections

The rod-shaped components with varying cross-sections are being manufactured using a few different techniques, depending on part geometry and specific demands. Continuous techniques, such as Roll-Forming has not been applied yet in the industry for this purpose. Generally the production of such parts is achieved by multi-step draw-bending operations with machining steps that connected to the outlet side **[7]**.

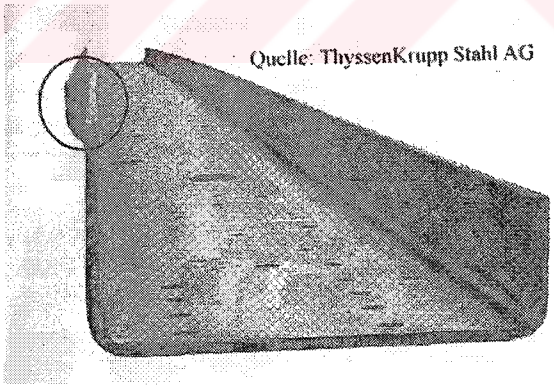


Figure 2.7: Varying cross-section with deep drawing method for a vehicle component **[7]**

This shape shows us an example from the industrial application of such a part with longitudinally varying cross-sections. At the beginning, this component produced conventionally by roll-forming process with a constant cross-section. Subsequently, it undergoes to the deep-drawing operation with the purpose to insert the difference of cross-section supplementary **[7]**.

Another commonly used alternative is the manufacturing of small pieces as welding components of multi-partial welding assembly. However, single segments with constant cross-section are usually produced with roll-forming.

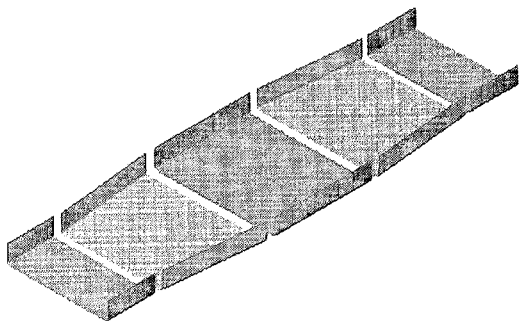


Figure 2.8: Welded components to achieve varying cross-section [7]

The flexible roll-forming has not any industrial application at present. However in the past some patent registrations were engaged with that theme, but no continuous manufacturing technique of components with variable cross-sections in the lengthwise direction were examined nor realized. At present some research projects and applications are being tested at PtU Darmstadt University in Germany, however the kinematical movement of the rolls is not enough to give the desired flexibility both in production and in simulation.

3. METHOD OF FLEXIBLE ROLL FORMING

The objective of this chapter is to present the design parameter. The roll design will be discussed to make the cross-section variation available. The implementation of the rolls is one of the concerns. The classical calibration methods are also mentioned and the choice of calibration method and its reasons are declared.

3.1. The Main Shape

A typical U-profile is selected for the investigation and the application of a method to analyze its specialties fundamentally. A profile consists of a web (base), two legs and two bending zones.

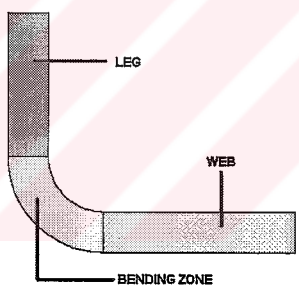
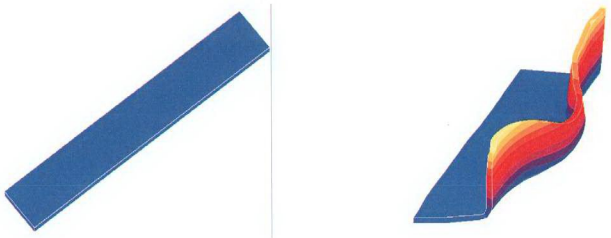


Figure 3.1: Main regions of a profile

In bending zone the highest strain hardening arises because of the localized intensive deformation. In profiling, the legs are formed in certain deformation steps. The cross-section variation associates with a change-over in the width of a web. The sheet-metal that is originated from the coil, has a constant width. Moreover, the leg length changes dependently with the predicted cross-section variation when there is no contour precutting **[18]**.



A B

Figure 3.2: Flexible Roll forming application without precutting (COPRA FEA RF, data M) A-) Straight sheet metal from the coil (300x40x2) B-) Flexible profile with varying leg height

Due to a cross-section variation by a widening (bulge out) in middle section of U profile, five main cross-section regions occur **[7]**. These are:

- Section with a constant starting width (front end)
- Profile bulge out : The ship width increases steadily, the section begins with the starting width and ends up with the maximum width
- Section with maximum constant ship width
- Profile necking: The ship width decreases steadily, the profile characteristic shows the same geometry with the profile bulge out section and the web ends up with the starting width.
- Section with constant ending width: It is equal to the starting width (back end)

As it can be realized, the leg height isn't equal in all areas and shows great difference depending on the cross-section variation. To produce a profile with a constant leg height, the amount bended sheet material that is processed during the cross-section variation must be compensated. That can be done with expanding the ship width in that section of the unfolded shape. A precutting action should give the desired shape to compensate that material loss. The critical point is the determination of the precut contour dimensions which leads us to the definition the tool path. The optimal leg must have no curvatures and the leg height must be constant or have low tolerance values along the profile length. The parameters that affect the leg height will be discussed in the forthcoming chapters.

3.2. Roll Design

First of all, one has to design the bending levels to achieve a U-Profile form with 90° symmetrical legs. The number of the bending stations that determines the bending levels is also a design parameter and it depends on the desired leg height. The angle steps in each station must be designed wisely to reach the 90°. The steps can be 3 to 6 steps depending on also other numerous process parameters.

The roll sequence has been selected into 3 angle steps purposing the general solution of the flexible roll forming and the exhibition of the pattern shape easily. Therefore the experiments could take shorter and the correct parameters could be discovered in a short time. The rolls in the bending stations will have 30°, 60° and 90° respectively. A varying web width is achieved self-evidently with displacement of the tools transverse to the driving direction. Conventional roll forming stations have a certain arrangement of the rolls to produce a U-profile **[7]**. Figure 3.3 shows the conventional U-profile design with three bending stations on the left side and a tooling system with separated profile sides and separated tools on the right side.

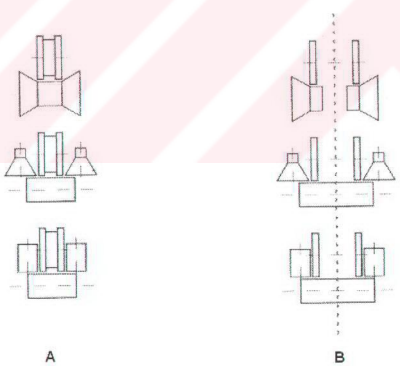


Figure 3.3: A-) Conventional U-profile design with three bending stations B-) a tooling system with separated profile sides and separated tools **[7]**

The determination of the ship width variation depends on the side rolls and top rolls in this pattern shape. The bottom roll is not a parameter to be designed in this shape because it has no effect on the variation of the cross-section. However in this classical

form, the arrangement of the rolls isn't appropriate to realize the widening of the web-width. The problem is the geometry and the position of the rolls. Figure 3.4 illustrates the process with certain roll arrangement during the 90° station. During the widening the profile legs touch the sides of the top rolls. The profile legs have skews and in the driving direction because of the insufficient support from the top rolls. The shape of the rolls is cylindrical and impedes the widening or the narrowing. Therefore, it proves that this arrangement isn't appropriate for the flexible roll forming and another design should be developed specially for this purpose.

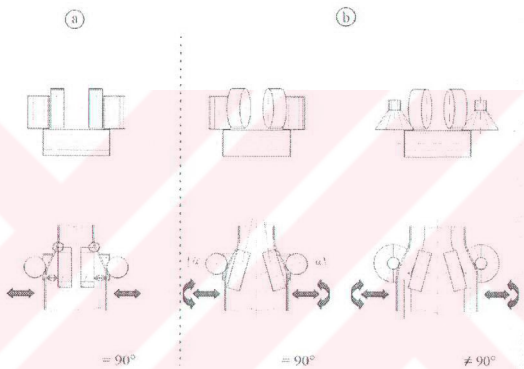


Figure 3.4: The application of wrong tooling and kinematical failure **[7]**

3.2.1. Implementation of the Rolls

The settlement of rolls is a significant concept that depends on the sheet geometry. In roll-design the parameters has be evaluated delicately. The rolls must be adapted to the calculated contour-way that will be followed. The size of a roll consists of three parameters; the diameter of the roll, the length of the roll and rounding radius on its edges. The selection of these parameters is an important issue and has vital effect on the result. As the rolls rotate in the simulation, a problem should appear about the size of rolls. If they are larger than a constant optimized value, they may collide with other section of the profile during the rotation, which damages already formed shape. Besides, the fillet-radius of the roll edges has an important role as we are trying to get

U-Profile. The radius of rolls determines the inner-radius of formed profile and it must coincide with the user definition for inner-radius.

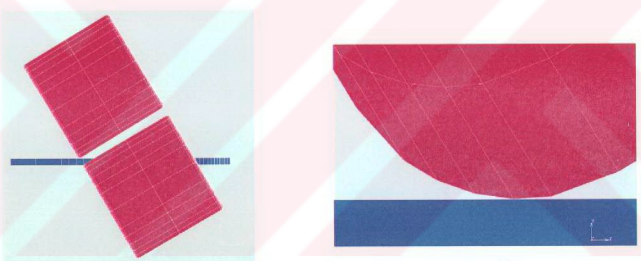
The deformation steps to get the 90° leg shape are decided to be in three steps. Hence, there are three folding roll-stations (30°, 60° and 90°) and three flattener roll-stations to be placed. In the last folding station there will be also bottom flattener. The positioning of the folding rolls is significant. As the contour-way described, all stations must follow the same contour-way independent from their folding angles.

Therefore, the exact point of the contact must be specified and afterwards the rolls must be positioned depending on that point. It is also a matter of importance which calibration method will be used. In this simulation constant-length method (Kreisbogen) is applied. So that, we are able to determine a touching point, which will be constant in every folding station. The touching point will be associated with the rotation point. Each folding station will have its appropriate center of rotation point. The rotation point specification will be explained. The touching point is determined depending on the last station. The important issue is the desired inner dimensions of the profile. So the touching point is the edge point of the base width in the cross-section. That means, it is determined from the user definition and it is on the edge of the base with, which is the web width excluding the inner radius. Thence, the touching point in the recent application will be 19mm far from symmetry plane along the cross-section because the web width is 20 mm and the planned roll fillet radius is 1mm. After designating the touching point, the rolls, which are touching the profile leg from the inner side, will follow this touching point starting from the unfolded sheet metal surface. Thus, the positioning and alignment of the rolls can be set from the very beginning in the unfolded shape just entering touching point and their folding angles **[17]**.

The rolls that touch profile from the inner side of the leg will be determined in first step, then the second outer side rolls can be defined by deriving the inner side roll. However, the inner side rolls should have an additional 1° folding angle than the desired folding angle, because this 1° tolerance difference will create a gap, which provides relaxation for the leg after the deformation. This relaxation diminishes the springback effect and prevents the sheet metal to jam between two rolls during

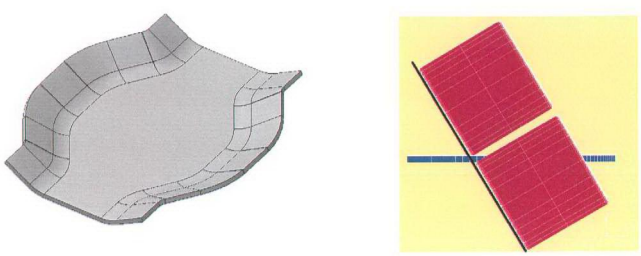
deformation. In the last station with 90° there will be no need for this relaxation. Therefore, the angles of the inner-side rolls will be 31°, 61° and 90° where the outer-side rolls will have 30°, 60° and 90° subsequently. The arrangement of the rolls could also be done with the main roll forming Software COPRA® RF FEA (data M) since the desired flexible roll forming module will work under this program **[17]**.

There is also an important theme that should be implemented during the roll positioning. In each station the rolls must also be positioned with each other. The reason for that adjustment is to enhance the roll contact to the sheet metal. This adjustment is aimed for the outer-side rolls by moving them to downwards position in order to seize the sheet metal better from the bottom. This adjustment is not obligatory, should be applied, if the fillet radius of the roll is great. In the recent application, there is no need for that since the fillet radius is 1mm. The folding station with 30° degrees the arrangement is shown in Figure 3.5.



A B

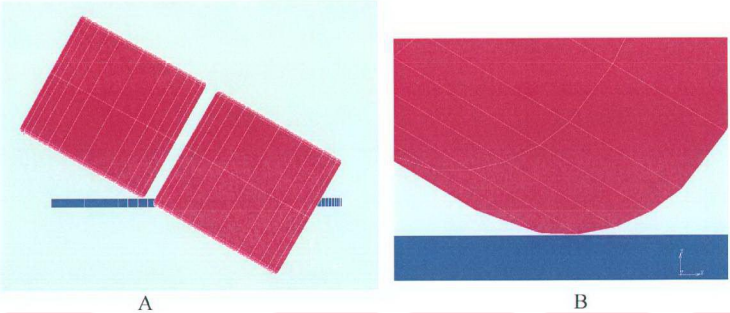
Figure 3.5: A-) 30° folding station B-) Touching point (COPRA FEA RF data M)



A B

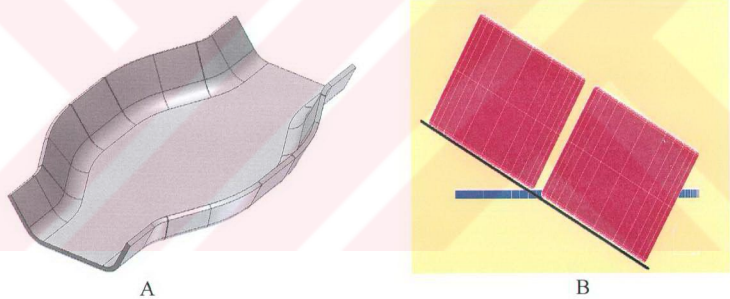
Figure 3.6: A-) The estimated deformed shape B-) The adjustment of the rolls with each other (COPRA FEA RF, data M)

The folding station with 60 degrees will have the following arrangement:



A B

Figure 3.7: A-) 60° folding station B-) Touching point (COPRA FEA RF, data M)

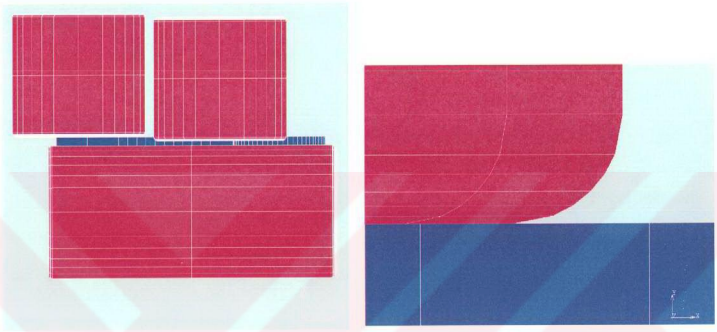


A B

Figure 3.8: A-) The estimated deformed shape B-) The adjustment of the rolls with each other (COPRA FEA RF, data M)

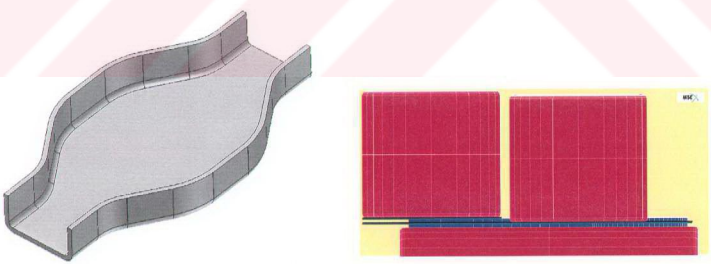
The last folding station with the 90° degrees should have the adjustment on all accounts. Furthermore, the rolls in the last station shouldn't have the same position on the vertical axis because the contact of the outer-side roll won't be enough to reach until very bottom of the profile. In order to enhance the contact the outer side roll is moved downwards on the vertical axis. The amount of the displacement should be selected as the half amount of the wall-thickness of the profile. This amount is depended on the fillet-radius of the roll and as the case may be, it should be increased.

The height of the rolls should also be decided depending on the last station and should cover the leg without difficulty. The displacement in the last station the fillet-radius dimensions should be taken into consideration during the determination of the roll length. In the current application the roll height is selected as 28 mm where the leg height will be 20 mm. The folding station arrangement with 90° degrees is shown in Figure 3.9.



A B

Figure 3.9: A-) 90° folding station B-) Touching point (COPRA FEA RF, data M)



A B

Figure 3.10: A-) The estimated deformed shape B-) The adjustment of the rolls with each other (COPRA FEA RF, data M)

3.3. Calibrating Methods

The calibration method depends on the section to be formed. In practice, "constant length of neutral line" or "constant radius" calibrating methods are the most common ones. However, some roll forming processes require more advanced methods. The inner radius R_i, the bend angle and the length of neutral line LNL describe each bend.

There are five main calibrating methods:

- Constant radius
- Constant length of neutral line
- Track holding profiling
- Angle/radius profiling
- Tube profiling/power bending

3.3.1. Constant Radius Method

This calibration method uses a constant radius among all forming steps. This means that the material has to be taken from the inner, the outer or from both legs. By the term legs, we understand the unbent neighbor entities. When unfolding starts from the final section, this process is inverted. The material may be distributed to the inner, the outer or to both legs. The entities created during this process are called the length compensation pieces. The default distribution of the length compensation pieces is 50% to the outer leg and 50% to the inner leg. The inner leg is the leg, which is closer to the section forming point. The length of the length compensation pieces depends on the calculated neutral line. Depending on the bending angle, material strain has to be considered. Therefore the theoretical strip width, which equals the length of the neutral line, is smaller than the actual centre line of the final section. The length compensation pieces may also be positioned in the middle of a bend; this is, however, very rarely made use of **[14]**.

Advantages and the disadvantages are:

- Advantages: low spring back rate
- Disadvantages: bending areas tend to be cornered

- Restrictions: a bend cannot be folded with this method if the neighbour entities are also bends

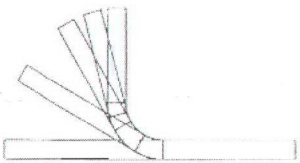


Figure 3.11: Constant radius method

Characteristics of the constant radius method are:

- Inner radius: constant
- Bend angle: variable
- Length of neutral line: variable
- Length compensation: yes

3.3.2. Constant Length of Neutral Line Method

If used, the calculated length of the neutral line remains constant throughout all passes, the inner radius is automatically being calculated depending on the unfolding angle of the bend. Material strain is considered during all forming steps. No length compensation pieces are created during the unfolding process. Optionally, straight entities may be folded by using that calibrating method **[14]**.

Advantages and disadvantages of this calibrating method:

- Advantages: bending areas are not cornered
- Disadvantages: higher spring back rate

Characteristics of the constant length of neutral line method:

- Inner radius: variable
- Bend angle: variable
- Length of neutral line: constant
- Length compensation: no

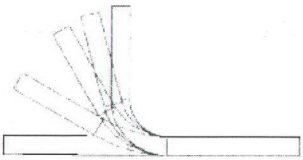


Figure 3.12: Constant length method

3.3.3. Track Holding Method

This method is a variant of the constant radius method. Just as with the constant radius method, the radius remains constant during all forming steps. The only difference is that the length compensation pieces are not defined by the user but calculated by computer automatically. Calculation results in a constant intersection point of the inner line of inner and outer leg. This calculation method is only valid for bending angles between 1° and 90° **[14]**.

Advantages and disadvantages of this calibrating method:

- Advantages: high accuracy of dimensions
- Disadvantages: difficult machine set-up

Characteristics of the constant length of the track holding method:

- Inner radius: constant
- Bend angle: variable
- Length of neutral line: variable
- Length compensation: yes

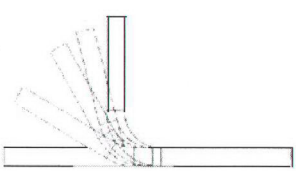


Figure 3.13: Track holding Method

3.3.4. Angle/Radius Method

It may be necessary to not only modify the angle of a bend, but also the inner radius. Examples are Dutch bends with a bend angle of 180° and an inner radius of 0mm. For a proper layout of this area it is necessary to find the correct pre-shape. For example, it would not be possible to start forming from flat with an inner radius of 0mm. When modifying the angle as well as the inner radius the length of neutral line has to be recalculated. The applied strip width calculation method is added as an attribute to the bend in proper software. Thus it is possible to recalculate the length of neutral line for the bend with the same conditions **[14]**.

The length compensation pieces can be taken from the inner or the outer leg. The length compensation pieces may be positive or negative depending on the modification. If, e.g., the angle is not modified and the radius increases, they will be negative. If the radius decreases, they will be positive **[14]**.

The adjacent entities increase or decrease respectively. The default distribution of the length compensation pieces is 50% to the outer leg and 50% to the inner leg. The inner leg is the leg, which is closer to the section forming point. The length compensation pieces can also be positioned in the middle of a bend.

- Advantages: less restrictions than the above described methods: angle as well as radius can be varied
- Disadvantages: the length of the neutral line has to be recalculated. This may give rise to little deviations within the flower. Pre-requisite is that the calculated strip width remains constant.
- Restrictions: length compensation pieces cannot be taken from adjacent entities, if these are bends.

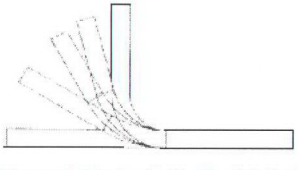


Figure 3.14: Angle/Radius Method

Characteristics of the angle/radius method:

- Inner radius: variable
- Bend angle: variable
- Length of neutral line: variable
- Length compensation: yes

3.4. The Selection of the Calibrating Method

The two of the possible calibrating methods are discussed because they were the most convenient methods among the other methods. "The constant length method" and "The track holding method" is compared with the COPRA® RF Software. The track holding method keeps up advancing a certain amount of further deformation in the cross-section direction in every station. Because of the complex shape and the complex rolling process flow, the track holding method caused apparent shape disruptions. In order to form the bending radii, a gradual deformation according to the constant length method with constant distance is needed. That means the position of the rolls don't change and a certain touch point will be determined for each station. This application gives the advantage to define one constant contour-way for each station.

4. MODELLING OF FLEXIBLE ROLL FORMING

4.1. Initial Situation

Flexible roll forming manufacturing technique offers the manufacturer the ability to design a profile with variable cross-sections on the longitudinal axis. Previous applications were without any cross-section variation and had a constant shape through the longitudinal axis. The number of rolls' degree of freedoms over different axes is also a concern of the flexible roll forming and must be developed and verified. The necessary knowledge can be comprehended by simulating the flexible roll forming in a FEM Software. There are plenty of parameters that must be taken into account during the simulation. This paper exhibits the general "Flexible Roll Forming" simulation stages with explaining the importance of the parameters and the studies that has been executed during the exploration of the parameters. As the FEM Software package, MSC.Marc program has been chosen because of its relying nonlinear analyze properties. The initial situation is evaluated from the user definition stage considering that user has no relation and knowledge over the technical issues and he starts from drawing a flexible form in a 3D or 2D CAD environment designating the demanded shape dimensions.

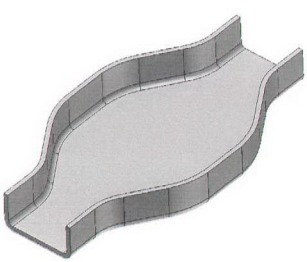


Figure 4.1: The 3D form of the Flexible Form that designed in Autodesk Inventor environment

On the course of definition the user is supposed to define the starting U-profile dimensions and the desired ship geometry that determines widening rate and the length of the profile. The 3D form can be produced by defining the U profile at first. Then the rest of the shape will be created by the "Sweep" feature in order to define a contour-way. The contour-way defined here is just the request of the shape from the user. The scientific contour-way that will be taken into consideration in the FEM stage is different than this contour-way; however, they are related with each other.

The U-profile below is the initial cross-section of the defined shape. The shape can also be drawn in 2D software by defining the necessary dimensions.

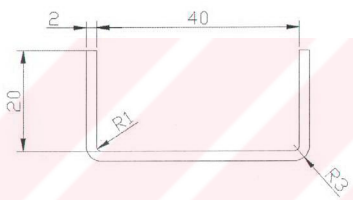


Figure 4.2: U-Profile that represents the initial cross-section

The shape below is the overview of the profile with necessary dimensions defined by the user. The inner side of the leg is the reference of the dimensions. It is also the user described contour-way to acquire the 3D shape in CAD software.

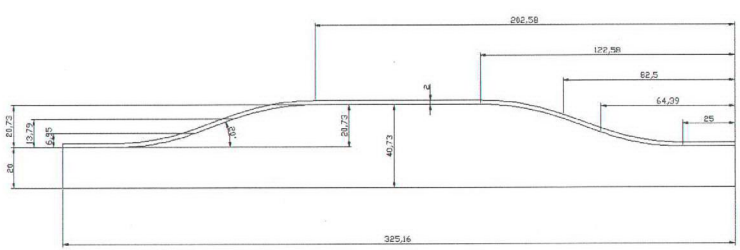


Figure 4.3: Dimensions of the assumed user definition for the flexible profile

The user is also supposed to define the desired leg height. The demanded leg height here is 20 mm and the desired widening is 20.73 mm. The geometry of the widening

region consists of three main parts; two arcs and one line (Figure 4.4). The dimensions of these sections are also designated to show the borders. It is assumed that user defined two arc sections equal with 20° degrees slope and the line must be tangential to the arcs. In order to provide the equal tangency between the line and the arcs, the slope of the line must be identical. On the point where they merge, the both slopes must be equal. Therefore;

$$y_{arc} = (x-x_c)^2 + (y-y_c)^2 = r^2 \quad \textbf{(4-1)}$$

$$y'_{arc} = y'_{Arc} = -x*(r^2-x^2)^{-0.5} = \text{The slope of the arc on a certain point} \quad \textbf{(4-2)}$$

$$y_{line} = dx + f \quad \textbf{(4-3)}$$

$$y'_{line} = d = y'_{Arc} = -x*(r^2-x^2)^{-0.5} = \text{The slope of the line} \quad \textbf{(4-4)}$$

Thus, the convergence point and the slope of the line can be found, even if no CAD application is used.

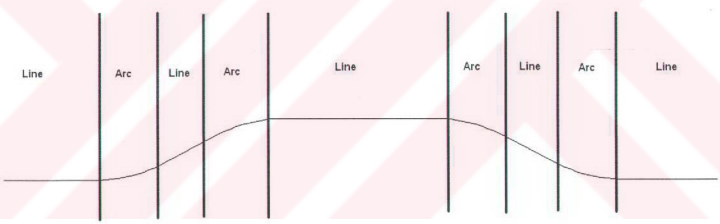


Figure 4.4: The main regions of defined flexible form

In order to grade the widening ranges and to compare the results a factor, named flexibility factor, can be set. This factor is the proportion of the widening rate to the widening length. The flexibility factor here is;

$$F_{flex} = \text{Widening rate} / \text{Widening length} = 20.73 / (122.58 - 25) = 0.212 \quad \textbf{(4-5)}$$

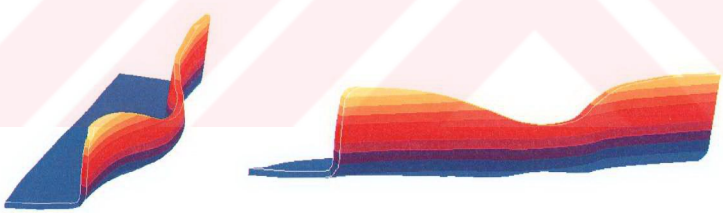
The user determines the flexible forming factor as he/she makes the design of desired shape. Therefore, in some cases some restrictions will appear depending on the shape,

if the user desires an exaggerated or a difficult shape. This theme will be also related with the design of rolls and will be mentioned in that chapter.

4.2. Interpretation of the User Data from the Geometric Base

The geometric definition starts from the unfolded shape of the sheet metal acquire final shape. The production also proceeds in this order. Thus, a relationship between the user demands and the simulation of the process must be created. In software terms however, the user demand is the initial position so that the software needs can be ascertained. The focal point here is to make relation between the end of the process and the beginning of the process, which means the relationship between the initial unfolded shape for the simulation and the initial formed shape for the user.

The industry needs are also a concern of this theme as the U-profiles must have constant leg height. Depending on the application the leg height of the U-profiles gains importance. If the leg height consistency is not necessary, a straight unfolded sheet metal (even from coil) can also be produced with flexible roll forming resulting in severely disrupted leg height as shown in Figure 4.5 **[18]**.



A B

Figure 4.5: A-) Front view of flexible profile without precutting B-) Right view of flexible profile without precutting (COPRA FEA RF, data M)

However, the concern of this study is to produce a flexible form (channel width) with a constant leg height. For that purpose the unfolded sheet metal must be cut before forming. The pre-cut shape depends on the user input for the desired shape. After completing the shape definition, the input data becomes also another input data for the definition of the pre-cut shape.

Advancing from the user definitions to the pre-cut definition requires some additional procedure including the calculation of the dilatation and reconstructing the pre-cut shape in the CAD environment depending on those values.

The reason why the dilatation is supposed to be calculated is to find the correct contour-way in FEM stage, which is determined by the pre-cut shape dimensions. The relationship between user definitions, pre-cut geometry and the contour-way of the rolls can be thought as a circulation. In this circulation the dilation values of the unfolding (or forming) must be taken into consideration. Otherwise the correct contour-way can't be defined, which causes a disrupted leg height and disrupted dimension at the end of the production or simulation.

There several calculation methods for strip-width dilatation during the forming. In these methods the amount of dilatation is calculated. This dilatation amount can be used either in unfolding processes or forming processes by either subtracting or adding it. In particular, there are six main calculating methods; they are DIN 6935 method, Proksa method, Bogojawlenskij method, Oehler method and the standard formula method. Among these methods, DIN 6935 is selected because of its reliable results that are observed to correspond with real results and achieve the closest approximation in the common roll forming processes. However, it must be taken into account that the flexible roll forming process is not a common roll forming process and this calculation may not match with the real result **[18]**.

In the DIN 6935 method the dilatation amount for a certain bending circular arc is represented as delta B (ΔB). It is calculated with a non-dimensional coefficient "k" that depends on the RiO, which is the proportion of the inner radius to the gauge (wall thickness) **[14]**

RiO = Inner radius / gauge (wall thickness) **(4-6)**

$0 \leq k \leq 1$

delta B = ΔB = [Bending angle / 360°] x Π x gauge x (1-k) **(4-7)**

$RiO > 5$	then, $k = 1$
$0.05 < RiO \leq 5$	then $k = 0.65 + [0.5 \times \log (RiO)]$
$0 \leq RiO \leq 0.05$	then $k = 0$

The length of the strip width in the user definition is referenced as the center line, which is the presentation of a line between outer and inner side of the formed U-Profile **[14]**.

h = Leg height

J = Web width

C = Length of the bending zone

$C = 2 \times \pi \times Rc \times [\text{Bending Angle} / 360°]$ **(4-8)**

$\text{Central Line} = h + J + C$ **(4-9)**

So the Strip width of the unfolded shape will be;

$\text{Length of the unfolded shape} = \text{Central Line} - \Delta b$ **(4-10)**

In this manner the dilatation of the shape according to the user definitions can be calculated. In order to simplify the calculation a symmetry axis is assumed in the middle of the web.

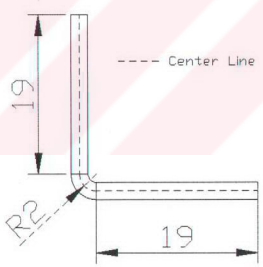


Figure 4.6: Illustration of the profile central line from front view (cross-section)

Thus, a and b values of the equation are clear. The length of the circular arc will be:

$c = 2 \times \pi \times Rc \times [\text{Bending angle} / 360°] = 2 \times \pi \times 2 \times 0.25$ **(4-11)**

$c = \pi = 3.1416$

$\text{Central Line} = 19 + 19 + 3.1416 = 41.1416 \text{ mm}$ **(4-12)**

$\text{delta B} = \Delta B = [\text{Bending angle} / 360°] \times \pi \times \text{gauge} \times (1-k)$ **(4-13)**

$\Delta B = 0.25 \times \Pi \times 2 \times (1-k)$

RiO = inner radius / gauge = $1 / 2 = 0.5 \rightarrow k = 0.65 + [0.5 \times \log (RiO)]$ **(4-14)**

$k = 0.65 + [0.5 \times \log (0.5)] \rightarrow k = 0.499$

$\Delta B = 0.7862$

In order to find the unfolded strip width, the dilatation value is subtracted from the central line **[14]**.

Strip width = Central Line - $\Delta B = 40.3554$ mm **(4-15)**

Considering the symmetry axis the total strip width will be two times this value. It is assumed that the same actions take place in both circular arcs. Than the total strip width will be 80.7108 mm. However, this strip value represents only the initial cross-section unfolding process. In the flexible form there are several regions containing the complex widening and narrowing sections.

It is assumed that the amount of dilatation is same in every bending zone. By means of this assumption it can be claimed that the dilatation effect in the cross-section direction can be taken as ΔB in each bending zone. Channel contour can be defined with an algorithm as shown in Table 4.1 (geometric definitions are in Figure 4.7).

Table 4.1 : Shape function of user definition **[7]**

$$x_1 := \begin{cases} x_0 + r - \sqrt{r^2 - (z-s)^2} & \text{if } s \le z < (s+d) \\ \left[\frac{c}{e}\cdot(z-s-d) + x_0 + b\right] & \text{if } (s+d) \le z < (s+d+e) \\ \left[\sqrt{r^2 - (a_1+s-z)^2} + x_0 + a_b - r\right] & \text{if } (s+d+e) \le z < (s+a_1) \\ (x_0 + a_b) & \text{if } (s+a_1) \le z < (s+a_1+a_z) \\ \left[(x_0 + a_b) - r + \sqrt{r^2 - (z-s-a_1-a_z)^2}\right] & \text{if } (s+a_1+a_z) \le z < (s+a_1+a_z+d) \\ \left[-\frac{c}{e}\cdot(z-s-a_1-a_z-d) + x_0 + b + c\right] & \text{if } (s+a_1+a_z+d) \le z < (1-t-d) \\ \left[x_0 + r - \sqrt{r^2 - (1-t-x)^2}\right] & \text{if } (1-t-d) \le z < (1-t) \\ x_0 & \text{otherwise} \end{cases}$$

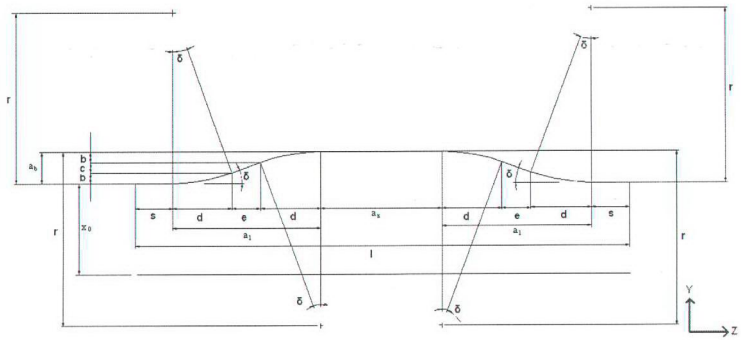


Figure 4.7: Definitions of parameters in the shape function in Table 4.1

This definition belongs to the user defined flexible shape. This definition has also some restrictions such as assuming both widening and narrowing distances and their angles identical. It is supposed to be flexible also and the user should be able to define any narrowing or any widening rate. However, assuming that the user defined the same narrowing and widening rates, the possibility to define the pre-cut shape is evaluated.

Defining the unfolded shape (here the pre-cut shape) in a profile with constant cross-section is the subtraction of the dilatation amount from the central line, which is carried out during the explanation of the dilatation calculation. The cross-section plane must be considered during the calculations and the dilatation during unfolding takes place in only one direction just on x-axis, which is shown in Figure 4.8. Except the widening and the narrowing region of the flexible form the calculation is also the same in the constant linear regions. However, the transition regions make the pre-cut shape definition more difficult. The dilatation takes place this time also in one direction however as a component of two dimensions which is illustrated in figures 4.9 and 4.10.

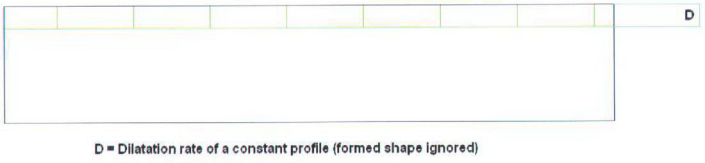


Figure 4.8: Illustration of dilatation rate of a profile with constant cross-section

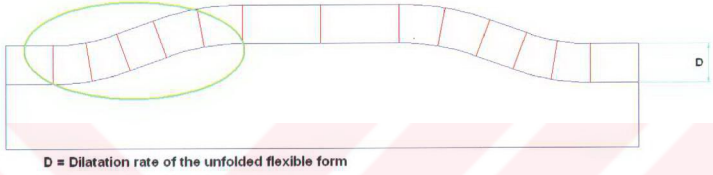


Figure 4.9: Illustration of dilatation rate of a profile with varying cross-section

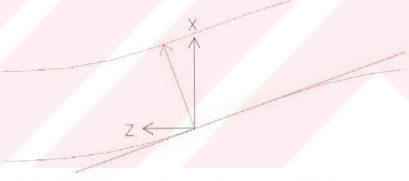


Figure 4.10: The direction of the dilatation during the forming on the transaction region

In flexible form the dilatation advances in a two dimensional direction, which means the dilatation direction is not constant. While the rolls advance straightly on the constant profile, they proceed in many dimensions and rotate in order to complete the forming of the desired shape.

The pre-cut shape is defined by taking a normal to the tangential of the current arc or of the current line. This normal determines the direction of the dilatation. Referring this direction, the appropriate distance values should be added. Thus, the calculated pre-cut geometry would be determined. The widening and the narrowing sections

should be divided into numerous planes. Each plane is a representation of direction for strip width values that is calculated by the explained method. This theory is valid as long as the rolls advance perpendicular to leg surface of profile.

It is worth to remind that the dilatation values are assumed to be equal in every section. So that, the dilatation distance must be kept during the pre-cut definition. After determining the number and the position of the points on the user-defined shape, taking their tangents, finding their normal (progress direction) the calculated strip width values should be applied referring the normal direction (Figure 4.11). The new achieved points will constitute the pre-cut shape after this process.

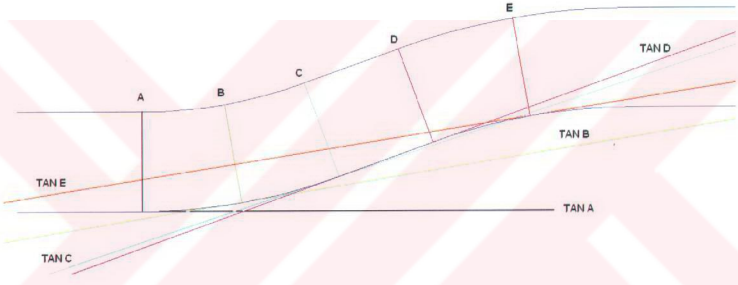


Figure 4.11: Determination of dilatation by normal lines that are derived from the tangent lines of certain points on the first shape without dilatation

This approach is realized by defining a complex function that is derived from the shape function. The user definition provides the input of the function. The function calculates the dilatation ratio and then it should assign the tangential lines and their normal and eventually adding the values and find the pre-cut shape. This complex function would also not be appropriate for each shape and maybe required to be redefined. However, there is also another possibility to achieve the pre-cut shape. The mentioned function above is also the identical function of the "offset" feature in CAD software. If user defines the starting shape in a CAD environment, taking advantage of this feature would simplify the pre-cut shape definition. The dilatation amount is still to be calculated and then the offset amount must be set correctly.

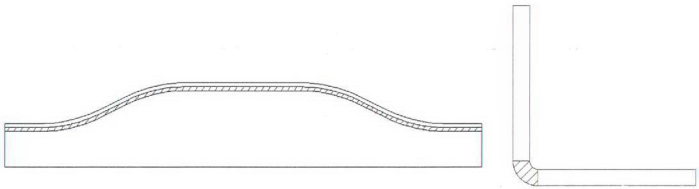


Figure 4.12: A-) Illustration of bending zone from top view B-) from front view

In order to take advantage of the cad application, the web dimensions should be taken into account (Figure 4.13). The reason is that; the base is the only unformed part of the profile and there is no dilatation caused by forming. The forming action and its consequences take place in the bending zone. Thus, the offset quantity will be calculated from the bending part and the desired leg height. The offset quantity for one side of the symmetrical profile will be:

$$Oq = \text{Central line} - \Delta B - \text{Web width} = \text{Length of the arc} + \text{Leg height} - \Delta B \quad \textbf{(4-16)}$$

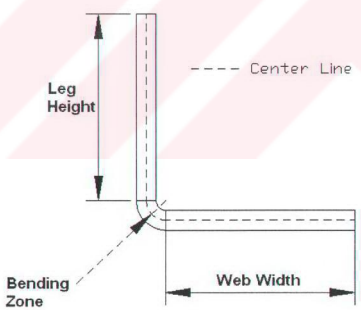
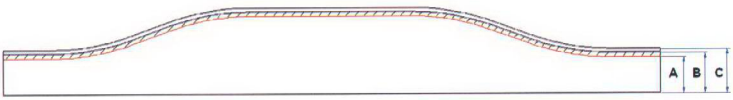


Figure 4.13: Segmentation of a profile cross-section

Eventually, from the user defined profile, the web width definitions are offset with the appropriate quantity to find the pre-cut shape definition (Figure 4.16). Web-width concept here is assumed as the unformed base of the profile excluding the ending zone so the inner radius (Figure 4.14).



A = Web Width excluding the inner radius (Base width)
B = Web Width including the inner radius and bending zone
C = Ship Width (including the wall thickness, bending zone)

Figure 4.14: Illustration of used technical terms of flexible profile section along the width A-) Web width excluding the inner radius (Base width) B-) Web width including the inner radius namely the bending zone C-) Ship width including the wall thickness and bending zone

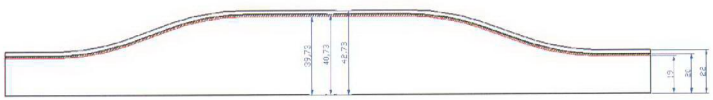


Figure 4.15: Illustration of dimensions of profile sections along the width in the user definition

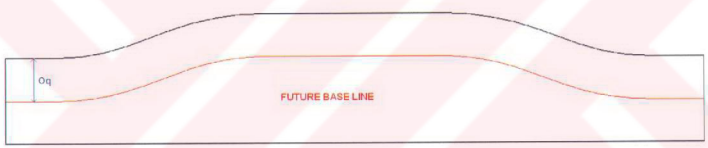


Figure 4.16: Determination of the precut unfolding shape by referencing the base line with appropriate offset quantity

The offset quantity in the example shape will be;

$$Oq = 41.1416\ mm - 0.7862 - 19mm = 21.3554mm \quad \textbf{(4-17)}$$

The sum of the base width with the offset quantity must give the calculated strip width in order to prove, if the offset method is correct.

$$\text{Calculated strip width} = 40.3554\ mm \quad \textbf{(4-18)}$$

$$\text{Offset quantity} + \text{base width} = 19 + 21.3554 = 40.3554mm \quad \textbf{(4-19)}$$

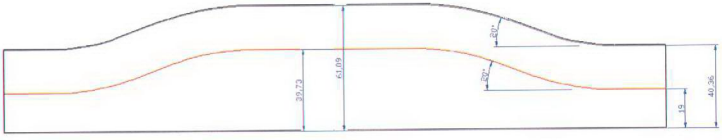


Figure 4.17: Specified precut unfolding shape

Consequently the pre-cut shape is acquired by the offset definition. However, the quantity of offset has some restrictions. Offset has a direction to advance and if this advance is towards the center of one the arcs, then some precautions must be taken. Since in the defined shape the radius values are changed as offset executed, the offset quantity must not exceed one of the radius quantities that has its arc center towards the offset action. Otherwise, the usage of the offset would not serve as the correct action to find the shape parameters like unfolding shape and also to find the trajectory of the rolls.

$$Oq < R_{profile} \tag{4-20}$$

Furthermore, for better precision, it is advised that the offset quantity should not exceed half value of the radius, if the center of the arc lies on the offset direction.

$$Oq \leq (R_{profile} / 2) \tag{4-21}$$

4.3. Determination of the Correct Contour-way (Tool Path)

As the calculated pre-cut shape attained, it should be exhibited in a CAD application. It is assumed that AutoCAD is the appropriate CAD application to demonstrate the pre-cut shape. The definition process should also be simplified if the user defines the desired shape in AutoCAD environment. After completing the pre-cut shape, a contour way is supposed to be defined. This contour-way will be the tool path of the flexible rolls, which will form the pre-cut metal. The contour way definition is required for the finite element program and will be adapted for each roll station and will be used in the definition of the roll motion. It is the most important parameter and must be defined delicately.

There are parameters that effect the contour-way definition. These parameters are explained exclusively and they should be taken into account during the calculation. After the correct definition of the contour-way on the pre-cut shape, contour-way adaptation for the rolls will be carried out according to the roll positions on their stations. Due to the calibrating method that will be explained in following section the same contour-way can be used in each roll station by adapting it according to station distances. The user defined shape at the beginning must be achieved again at the end of the FEM simulation.

Fundamentally, the procedure defining the contour-way definition is very similar with the pre-cut definition. However, the reference of the contour-way will be the pre-cut itself this time. Besides, the calculation will be done in a reverse manner in comparison with the calculation of the pre-cut shape from the base width. The similar part is the assumption of the dilatation direction and taking the leg height and the dilatation values into account. The contour-way can also be extracted by the offset feature because it suits the same theory with the procedure of the pre-cut shape definition. The distances must also stay constant by taking the tangential guide lines in the tool-path definition. However, the offset quantity calculation is more complex, because it contains the roll positions, their advancing points and their detailed motion. The rotation motion of the rolls will also be defined completely depending on the contour-way.

During the definition of the contour-way there will be some assumptions like taking the rotation point at the middle of the future leg. Rotation point will determine the starting position of the contour-way, so it has an important effect.

The rolls will proceed by obeying the contour-way and will execute the forming simultaneously. Therefore, the dilatation must be included by in the calculation of the tool path. Thus, the pre-cut shape should be assumed as dilated. That means the length of the central line should be assumed as unfolded (Figure 4.18).

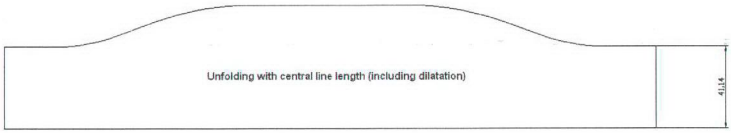


Figure 4.18: Assumption of dilatation on the unfolding shape by adding the dilatation quantity to dimensions by means of offset

This assumption gives the opportunity to calculate considering the situation at the end of the forming. This is a method for definition of the contour-way by counting the dilation before forming. In the reality there will be no shape like that on the unfolded shape because dilatation occurs during the forming and can be measured after the deformation. This is just an assumption to figure out how the contour-way can be built and which parameters are included.

There is also another parameter that affects the tool path definition. As we assumed that the rotation point is in the middle of the leg, as shown in Figure 4.19, the wall thickness becomes also a parameter to be taken into consideration. After the bending, the leg will be perpendicular to the base and the distance from the surface and the middle of the leg will become horizontal from the top view.

Since the last station determines the final shape, the contour-way should be defined referring to the dimensions and distances from the last station. So, as the wall thickness becomes horizontal, the distance of the rotation point along the wall thickness becomes also a parameter to consider. The half of the wall thickness behaves like a dilatation value because it is also an additional amount that becomes important after the deformation (Figure 4.20).

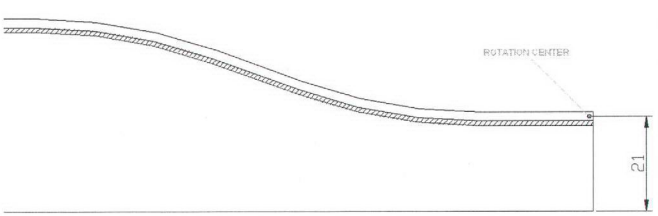
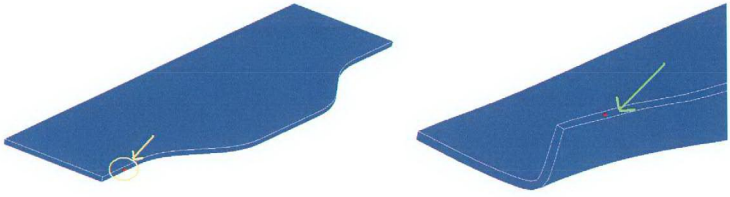


Figure 4.19: Illustration of rotational center location



A B

Figure 4.20: The importance of the wall thickness during the tool path calculation. A-) Location of the rotational center before deformation. B-) Location of the rotational center after deformation (COPRA FEA RF, data M)

The half amount of the wall thickness should be added to the assumed unfolding shape that is built to calculate the offset quantity. After this addition the offset quantity will be applied to this form. This application will give the advantage to count on the dilation and wall thickness effect for the tool path definition. After the addition of the wall thickness effect the assumed unfolding shape becomes 1mm further as the wall thickness is 2mm (Figure 4.21).



Figure 4.21 : Assumption the wall thickness effect on the unfolding shape by adding the half quantity of wall thickness to dimensions by means of offset.

Before explaining the final procedure to find the tool path, it is worth to remind that the calculation of the wall thickness depends on the offset quantity finding method. If the reference is taken in the middle of the future leg width, which starts 21 mm distant from the symmetrical plane, then the wall thickness is already counted and doesn't need to be respected as a dilatation. Because the user definitions specified that the web width (including inner radius) is 20 mm. So, this additional 1mm represents the wall thickness effect and the tool path should be referenced neglecting this effect

in the unreal unfolding form assumption. That means if the procedure is defined with such a method, the unfolding assumption in Figure 4.18 must be used, which adds only the dilatation value and represents the length of central line. However, should the distance from the symmetrical plane is taken 20 mm, which does not count the wall thickness effect, the unfolding form assumption in Figure 4.21 must be taken as the tool path defining reference to make the wall thickness effect count.

The offset quantity method is chosen the first mentioned method, at which the distance from the symmetrical plane is taken 21 mm, counting the wall thickness from very beginning of the process. Then the distance to reach the 21 mm position from the symmetrical plane from the strip-width (the real unfolding shape) outer edge should be found. This 21 mm distance represents the position of the future rolls. The middle of the leg represents also the middle of the rolls. The size of the rolls only affects the bending zone because their radius sets also the inner radius of the profile. So, the offset distance to reach 21 mm distance from the symmetry plan is;

$O_{Temporary}$ = Strip width – Aimed distance (the position of rotation point) **(4-22)**

$O_{Temporary}$ = 40.36 – 21 = 19.36mm

Afterwards, this temporary offset value must be applied to the assumed unfolding shape that includes dilation. The result will be the tool path as shown in Figure 4.22.

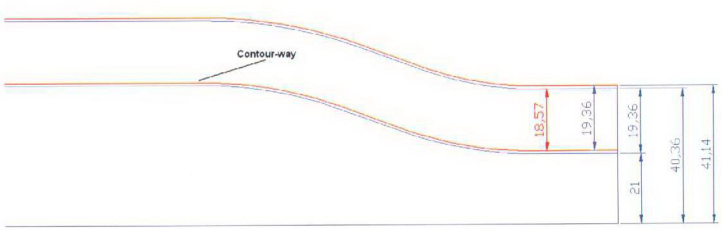


Figure 4.22: Specification of the contour-way for the rolls by determining a temporary offset quantity

However, the "definition" of the contour-way is found, its "position" isn't still correct. This method helps to find the correct form of the contour-way but the

position of it above won't give the correct result because this position counts the dilation from very beginning of the process. At the beginning we have the unfolded shape with the calculated strip width. Setting the contour-way in this position will cause shape disruptions in the web width at the end of forming. To overcome this problem the contour-way should be moved where the rolls will be placed.

Eventually, the contour-way will both be able to give the correct dimension in the web-width and count on the dilatation during the forming by reacting dependent on the dilated unfolding form assumption (Figure 4.23).

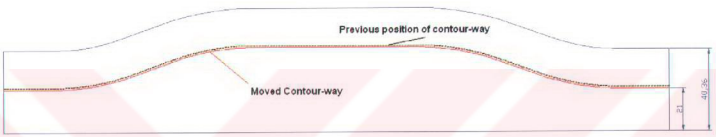


Figure 4.23: Displacement of the specified contour-way to the necessary position

In the user definition and the theory of the tool path calculation can be formulized to diminish the steps that has been explained until now. Supposing the process is just after the pre-cut definition, the contour-way can be defined by referencing the pre-cut shape outer edge. In Figure 4.22 the dimension 18.57 represents the distance between the calculated tool path and the pre-cut outer edge. By setting a relationship and formulizing this value, the tool path can be directly extracted from the pre-cut outer edge.

$O_{Temporary}$ = Strip width – Aimed distance (the position of rotation point) **(4-23)**

$O_{Tool\text{-}path} = O_{Temporary} - \Delta B$ **(4-24)**

Where, $O_{Tool\text{-}path}$ is the distance between the calculated tool path and the pre-cut outer edge. Thus, the definition of the correct contour-way form is completed. However, in order to complete contour-way definition phase the calculated form must be moved to the position where the rotational point of the rolls lie. The distance required to be moved is the dilatation rate ΔB. The direction of the moving process is towards the symmetrical plane or into the reverse direction of the dilatation. However it is moved

into the one dimension, not like the dilatation, along the cross-section. It should be emphasized that the moving shouldn't be mixed up with the offset.

After completing the pre-cut definition and accordingly the tool-path definition, the application in the fem software program should commence. The shape data should be kept in Autocad because they will be used during the data transfer from the Autocad to the MSC marc Mentat.

4.4. Transfer of Data and Calculated Geometry to the FEM Software

4.4.1. Data Transfer for Specified Precut Shape

The calculated values, forms and shapes must somehow be transferred to the FEM software base. Moreover, there are several methods to execute this process. The whole definition process could have been defined also directly in the FEM software by benefiting its CAD capabilities. However, the cad feature of the fem software is still insufficient for this purpose. Especially, the complex definitions that explained are not easy definitions to fulfill and must be executed with a professional software program **[19]**. Another method could be the formulization of the previous calculations and drawing the final shapes (the pre-cut shape and the contour-way) by a certain code like the described shape function in Table 4.1 on page 48. However, depending on the shape the formula must be everytime reconstructed. That should restrict the flexibility of the future software that will be written over this study. Hence, the calculated data should be kept in Autocad environment. Autocad is a professional CAD-software and can fulfill the expectations much better in comparison with the cad feature of the fem-software.

The transfer of the data should start with the transfer of the pre-cut shape from Autocad to FEM program. The import feature of fem software can also be handy but fem software caused problems during the conversion of the imported data curve into the nodes. Therefore, another method has been developed. The pre-cut shape should be divided into numerous points in order to take these points out as another data. The outer edge of the pre-cut shape is the vital part, so division of this part will be executed first. From the "Draw" menu, any user-defined curve can be divided into any number of points. The outer edge of the pre-cut shape should be thought as a

single part. Afterwards, the number of the divider points should be given. A small tip; single points must be given separately to the boundaries of the line **[18]**.

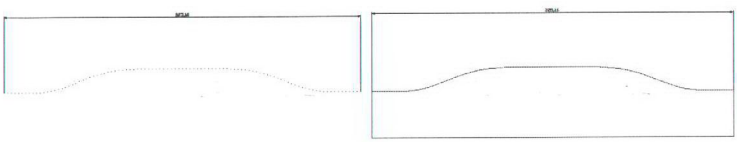


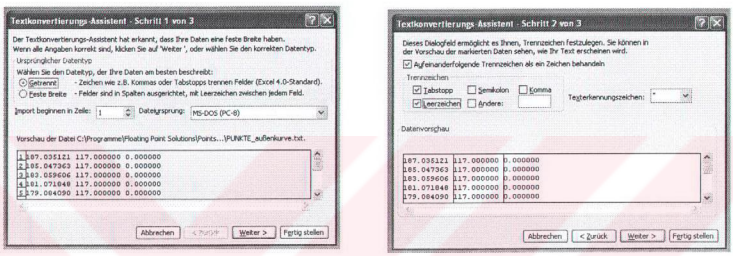
Figure 4.24: Extraction of the specified precut shape by means of data coordinate points A-) Extracted points B-) Reference shape in the Autocad

These data points represent a certain position in the coordinate system. These coordinate system values must be somehow extracted from the Autocad environment and must be written to a text data. A normal Autocad version doesn't include such feature. Hence, a software is applied that can function under the Autocad environment, which can fulfill this task. This software can also be developed with C++ because it is a simple program that ascertains the coordinates of the selected points and writes them to a text data. The name of the software is "Points export for Autocad". After loading the application the code "pointsout" starts the selection of the points. After saving the text data, it should be opened again in the Microsoft Excel. This process is needed because the definition in the Autocad is in two dimensions. In the FEM software the simulation will be executed in three-dimensional scale. Moreover, the defined position of the shape could be changed. The important issue is the attainment of the main pre-cut shape description and having the increments to define the shape. The positions and the axis can be changed in Excel. Nevertheless, the required codes that will be built the shape in the fem software can also be added in Excel environment regardless the number of the points **[18]**.

Before explaining the processes in the Excel, it is beneficial to remind that the number of points, divided from the outer edge of the pre-cut shape, determines how fine the mesh will be. Because every point is turned into a node and nodes will determine the mesh size. Therefore, the number of the divider points should be decided wisely.

A text data can be opened in the Excel environment. During the file opening some procedures must be followed. When the opening method is asked, the separated method must be selected.

Afterwards, on the menu that asks the parameters to be taken into account in the separating process, space feature must be selected. And finally in the last menu the formatting style should be accepted as the standard.



A B

Figure 4.25: Method to read a text file in Excel environment A-) Reading the separately B-) Designation of the spaces as separation sign

Thereby, the necessary coordinate points have been read by Excel. In the excel environment the order of the data points should be checked if there is an order disruption. Generally at the end of the code there should be one disruption because the boundaries of the curve were defined separately after dividing the curve in to points. Hence, the order should be disturbed. After adjusting the order, the coordinate axis and the starting position of the shape should be adjusted. For instance, the values in x-axis are moved to the z-axis because the planned advance direction in the fem software is the z-axis. Besides, the defined y-axis in Autocad is adjusted to x-axis to represent the cross-section direction. Furthermore, the calculated strip width value should be given in the Excel by adjusting the starting point on the cross-sectional axis and assigning the calculated strip width value to the starting node. The strip width value can also be defined by moving in the fem software. However assigning the correct axis is the most important issue. After the setting of the axis, the required FEM software code added before lines in each row. The required code for creating a node is achieved by adding writing "*add_nodes". The reason for that is to create a

procedure file for the FEM Software. Procedure files accelerate the process definition and give the user to automate the process. Otherwise each node value was supposed to be defined by hand. After making the FEM software read the procedure file, the following nodes are attained.

After moving this outer edge the strip width position (if it hasn't been done in Excel), the bottom side, represents the symmetry plane, is defined by removing the X-axis definitions from the outer edge values. This application assures the verticality of the nodes to each other, which becomes important during the definition of the elements over these defined nodes.



Figure 4.26 : Representation of procedure file result in FEM Software



Figure 4.27 : Representation of the boundary nodes that created by procedure files in FEM Software

4.4.2. Data Transfer for Meshing

Each defined node has a label that represents its order. These numbers should become handy, when the elements are desired to be defined also with the procedure files. "Renumber" feature in the FEM software makes these number to align in a logical order. After ascertaining the correct order of four nodes in order to create an element, one definition is entered to Excel at the beginning. Thereafter, the other rows can be derived by the Excel features (Table 4.2). Adding the necessary code to the head and

adding a special code "# | End of List" at the end of the rows will complete the elements definition. Eventually, the shape in Figure 4.28 occurs in the FEM Software **[18]**.

Table 4.2: A segment from element definition in Excel to define a procedure file

	A	B	C	D	E	F	G	H	I
1	*add_elements	1	2	101	100	# | End of List			
2	*add_elements	2	3	102	101	# | End of List			
3	*add_elements	3	4	103	102	# | End of List			
4	*add_elements	4	5	104	103	# | End of List			
5	*add_elements	5	6	105	104	# | End of List			
6	*add_elements	6	7	106	105	# | End of List			
7	*add_elements	7	8	107	106	# | End of List			
8	*add_elements	8	9	108	107	# | End of List			
9	*add_elements	9	10	109	108	# | End of List			
10	*add_elements	10	11	110	109	# | End of List			
11	*add_elements	11	12	111	110	# | End of List			
12	*add_elements	12	13	112	111	# | End of List			
13	*add_elements	13	14	113	112	# | End of List			
14	*add_elements	14	15	114	113	# | End of List			
15	*add_elements	15	16	115	114	# | End of List			
16	*add_elements	16	17	116	115	# | End of List			
17	*add_elements	17	18	117	116	# | End of List			
18	*add_elements	18	19	118	117	# | End of List			

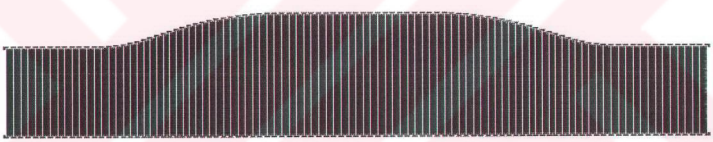


Figure 4.28 : Constitution of the elements by defined procedure file

Thence, the main elements and the meshes in z-axis are constructed. However, the remained elements and the meshes in the X-axis are still given by hand. These main elements must be subdivided into small elements. The meshes in the regions, which will host a possible roll-movement, should be finer than the others to realize an elaborate result. All elements should have their thickness equal to the thickness of the sheet metal. It means that there is only one mesh layer along the wall thickness. This can be realized by expanding the completed meshes with 2mm (wall thickness). After meshing, the half shape along 325.16 mm length contains total number of 1274 elements (Figure 4.29). The regions near to the middle of the profile (near to the symmetry plane) may have relatively coarser meshes, because they are only required just to check the corrugation (bulging) at the end of the process.

Thereby, the transfer of the pre-cut shape from the Autocad environment to the FEM Software is achieved. The method of transferring the tool-path is also very similar and it will be explained in the table definitions section. The next step should be the implementation of the rolls and the determination of the rotational point (center of rotation).

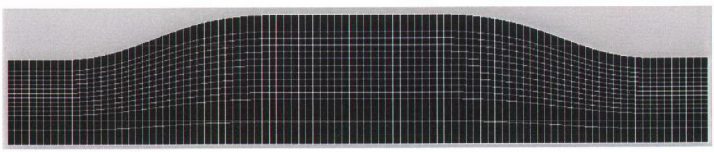


Figure 4.29 : The final meshing representation that is completed by hand after procedure file

4.5. Optimization of Rolls

The diameter of the rolls is related with the transition area between two straight cross-sections of profile. The greater angle of the transition is, the smaller the rolls should be. That means, as the transition area gets narrower in Z-axis direction or gets larger in X-axis direction, the rolls should be selected smaller than they are supposed to be, in order to prevent a possible collision. An exaggerated illustration in Figure 4.30 shows how the collision may take place, if the roll size isn't designed according to the defined shape.

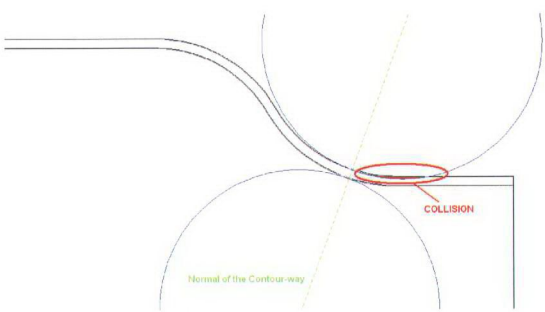


Figure 4.30 : Illustration of a possible collision between rolls and already deformed profile leg when the parameters are not defined within the limitations

It has been realized that without any restriction in the roll-size, there is always a danger of collision. If the concept is the software development of flexible roll forming, there should be formulization that sets the constrictions, while the user defining the roll size in the prospective software. The dimensions of the profile definition are also very important and they should determine the roll size. It can be also imagined that either rolls or the shape must be constant to be able optimize and prevent the collision. The possible shape can also be designed according to the possible roll sizes, if the rolls declared as the more important parameter. However, the optimization is executed referencing the actual shape of this study, assuming that the shape dimension precision is more important than the roll sizes. So the roll size becomes the parameter to be restricted.

The rolls must follow the contour-way and they rotate depending on the normal of the tangential to the contour-way. As they proceed the rotation will take place. As the rolls have the biggest rotation angle, the collision risk becomes supreme. Therefore, in order to assume the worst, it is presumed that the transition to the highest rotation angle should be neglected and it should be calculated, as if the highest rotation angle begins instantly after the straight line (Figure 4.31).

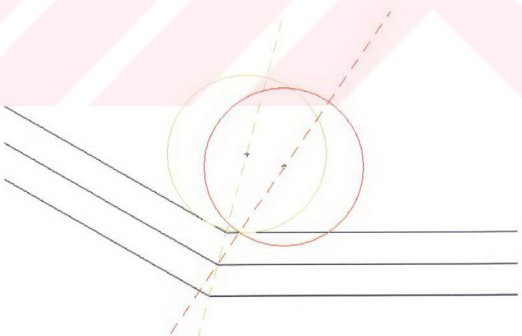


Figure 4.31 : Assumption of rotation without any longitudinal advance on the edge of cross sectional variation, which causes certain collision

The green colored roll is the first situation before rotation and the red colored roll is the presumed roll position neglecting the transition area and assuming the rotation happened without any proceed in the Z-axis direction (proceed direction of the rolls).

The aim here is to find the amount of sinking in order to construct a relationship between the roll-size and the shape. This figure can be illustrated as the following to build a logical explanation and to name the distances there.

The illustration of an optimization method is shown in Figure 4.32 with the necessary values. The middle (average) line is taken into account because the rotation center lies in the middle of the leg. The "x" value is the identical value of the sinking-rate. Because sinking happens due to the vertical displacement downwards, so the same displacement occurs also at the centers of the rolls. "S" is the distance between the first roll center and the rotational point on the middle line of the profile. "ß" is the maximum rotational angle that the rolls will reach.

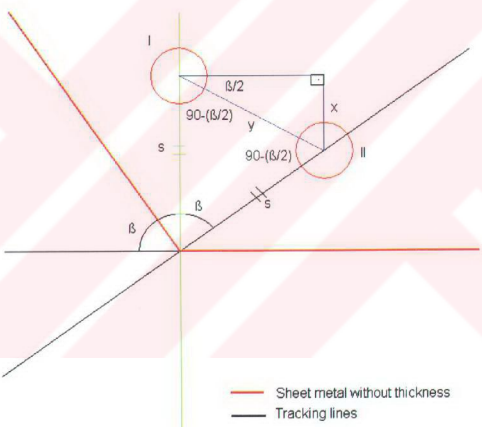


Figure 4.32 : Detailing the assumption of rotation without any longitudinal advance on the edge of cross sectional variation by referencing the central line of the sheet metal in order to optimize the roll size – shape definition relationship

The roll is assumed to be touching the surface at position I, displacement with rotation will cause collision. It is worth to remind that this collision happens by neglecting the time interval and the advancement of the rolls. If we compare two positions, it can be realized that in position II the roll sinks in X-axis downward direction colliding with surface. However, in the real action the rolls will move

further up to X-axis direction with rotation movement. To optimize the roll size or the distance that the rolls should take until they reach their maximum angle, this sinking rate must be taken into account. It should be thought that with the biggest roll or the shortest way the rolls should keep their position to prevent collision. That means the sinking amount in the figure above will lead us to determine the distance that is required to compensate with x-movement upwards, so that the roll position in the x-axis (vertical axis) can have the same level at position I and position II. In order to get that x value upwards with the constant slope, the distance in Z-axis direction shall be found. So that x-axis movement that is supposed to compensate the sinking shall be found. If these values are revealed, the maximum size of the rolls can be found.

So that the formulation will be;

Ro = radius of the roll
t = Profile thickness
x = the amount of elevation that must compensate the roll and prevent collision.
Ro_{max} = maximum radius of the roll
D_{max} = maximum diameter of the roll

$$S = Ro + (t/2) \quad \textbf{(4-25)}$$

$$y = 2 * s * \sin ß/2 \quad \textbf{(4-26)}$$

$$x / \sin ß/2 = y / \sin 90 \quad \textbf{(4-27)}$$

$$y = x / \sin ß/2 \quad \textbf{(4-28)}$$

$$x = 2 * s * \sin^2 ß/2 \quad \textbf{(4-29)}$$

$$x = 2 * [Ro + (t/2)] * \sin^2 ß/2 \quad \textbf{(4-30)}$$

$$Ro_{max} = [x / (2 * \sin^2 ß/2)] - t/2 \quad \textbf{(4-31)}$$

$$D_{max} = (x / \sin^2 ß/2) - t \quad \textbf{(4-32)}$$

After this the "x" definition that has been given by the user at the very beginning should be applied to this formula to learn the maximum amount of roll diameter that should be implemented to the process. It would be logical to select relatively smaller

roll-diameter than the value that obtained from this formula. The "x" definition is the distance on the x-axis in the transition region until the slope of the widening reaches its highest value (Figure 4.33).

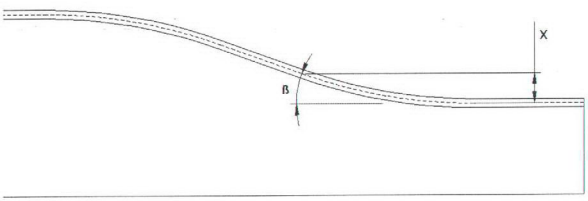


Figure 4.33 : Illustration of the x value on the profile

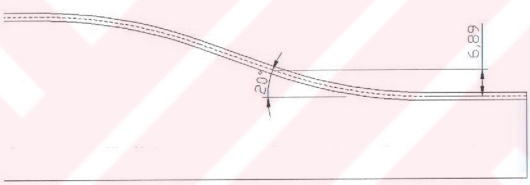


Figure 4.34 : Illustration of the x value on the user definition

So that the maximum roll radius in the user definition for the current design is;

$$Ro_{max} = [6.89 / 2 \sin^2 (10)] - 1 = 113.25 \text{ mm} \quad \textbf{(4-33)}$$

Therefore, the diameter allowance depending on the defined shape is pretty large and this allowance won't set a restriction for the current simulation since the roll diameter is chosen as "30 mm" for each rotating roll.

4.6. Determination of Rotational Point

The rotation point is the center of rotation position for the rotating rolls. It should be defined for each station separately. Its position in each station is a significant aspect because in order to reach a correct result the rotation process should proceed without

mistake and beside lots of parameters the position of the rotation point is also quite important.

During the definition of the rotation point the last station should be taken into account in order to find an optimized value. There are several parameters and these parameters should be explained relying on the coordinates. The point should be defined where the rolls are close to each other because the forming takes place on this location. Thus, the optimization on Z-axis (direction of proceed) is proved to be needless. The rotation will be executed on the Y-axis (vertical direction of cross-section), so that the defined point will show us the x-axis position of the rotation axis. Actually, the rolls will rotate around an axis, not around a point. Hence, the position change in y-axis (along the rotation axis) doesn't affect the result at all because all defined points will be on that axis and their effects will be same. Thus, the x-axis (cross-section direction) is the determinant of the center of rotation.

The rotation movement is factor that is depended on the arc, which hosts the rotation. The arc regions in the example shape represent these arcs (curves). Actually, in order to get the flawless result, the center of rotation point must lie, where the center of these arcs are. Since the current shape has two different arc-regions, there must be two different "center of rotation" locations that represent the centers of the arcs.

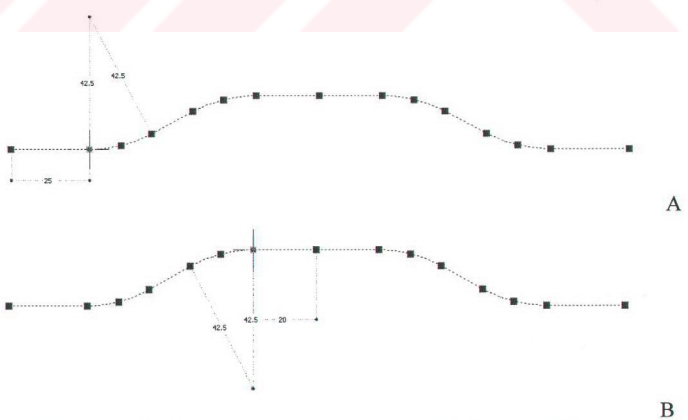


Figure 4.35 : A-)The illustration of rotation center of first arc B-) The illustration of rotation center of second arc

This theoretical explanation is the correct form to assign a center of rotation location. In order to reflect this theory to computer environment, the rotation point definition in the FEM software should be shifted during the simulation. However it is unfortunately not possible to simulate that rotation point movement in the computer environment with the current software. The center of rotation should have one constant location and it can't be moved independently from the contour-way definition that will be applied to it. Therefore these two different arc center locations must be optimized to degrade two different located points into one. So that, the optimization of the arc center points shows the middle point of the profile leg at the last station should be the optimized position and would give the best result with less deviation during the whole forming process. The optimization is executed by taking the average of two arc centers (Figure 4.36).

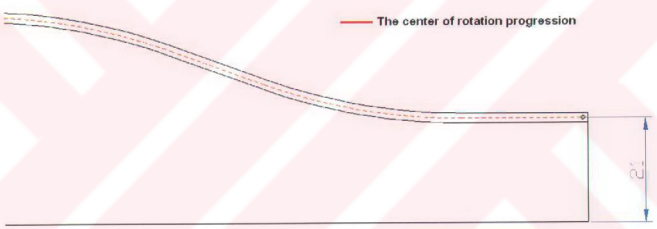


Figure 4.36: Progression of rotational center in during the process

In the following chapters it will be declared that the calculated contour-way will be applied to this optimized rotation point. However, it is always worth to remind that this point is only necessary for the rotation. For the progress of the rolls on the cross-sectional direction or on the longitudinal direction, the location of the rotation point is not important.

On the cross-sectional aspect, the attitude of the rotational point (the y-axis location) doesn't have an important role. However, in order to create a constant definition and also to determine the location in the other stations, the half amount of the leg length is chosen.

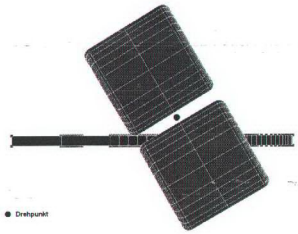


Figure 4.37: Illustration of rotational center in the first station with 30° (COPRA FEA RF, data M)

The reason for that is to provide equal rotation of the roll surfaces that touches the leg. When the rotation point is set in the middle of the leg height, the top and the bottom sides of the rolls would have the same amount of "rotational moment". Even if the rolls are much longer than the leg, this assignment of rotational point will provide the roll surfaces to have equal amount of moment of rotation on the bottom and the top contact points.

Although, the length of the rolls in the experiments was near the length of the leg height, creating a relationship between the rotation point and the rolls would perhaps be a mistake. If the user suggests using much longer rolls than the leg height, the top and bottom side of the rolls would have also the same amount of rotation moment but the effect of the roll to the leg height wouldn't be the same. Thus, the definition should be expanded and the relationship should be build between the leg height and the rotation point in order to provide same rotation moment effect on the top and bottom sides of the leg, independent from the height of the rolls.

Determining the rotational point should be automated for the forthcoming software module. A shortcut formula can be built by creating relationship with dimensions that are given by the user. The rotation point location can be assigned by assuming a triangle, and then by finding the necessary vertical and horizontal coordinate changes from the predefined touching point to the rotational point (Figure 4.38). However, it can be examined in two steps. From the assumed triangle the vertical displacement and a part of horizontal displacement can be found. After that, in order to find the rest of the horizontal displacement, the displacement caused by the fillet radius is

calculated. It is worth to remind that the assumed triangle is valid for the stations except the last station.

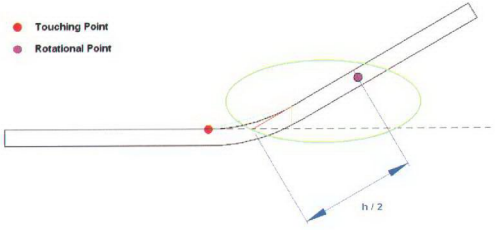


Figure 4.38: The illustration of the assumed triangle to find the middle point of leg

The rotation point would lie on the middle of the leg. In order to find the middle point of the leg with the x and y values, an illustration for the 30° and 60° bending station is created (Figure 4.39, Figure 4.42).

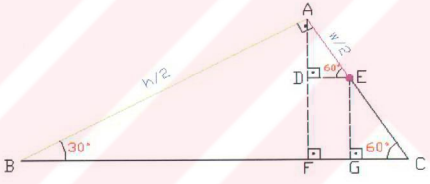


Figure 4.39: Representation of first assumed triangle to calculate the location of rotational center (point E) from the touching point in the first station

Here, "h" is the length of the leg and the "w" is the wall thickness. In order to find the coordinates of the middle point (showed by magenta point) according to the point B, the x-distance as [BG], and y-distance as [EG] must be calculated. For the bending angle ß = 30°, the formulization will be;

$$|BG| := \left(\frac{h}{2}\cdot\sin(90-ß)\right) + \left(\frac{w}{2}\cdot\sin(ß)\right) \quad \textbf{(4-34)}$$

$$|EG| := \left(\frac{h}{2}\cdot\sin(ß)\right) - \left(\frac{w}{2}\cdot\sin(90-ß)\right) \quad \textbf{(4-35)}$$

$$|BG| := \frac{\sqrt{3}h}{4} + \frac{w}{4} \tag{4-36}$$

$$|EG| := \frac{h}{4} - \frac{\sqrt{3}w}{4} \tag{4-37}$$

To find the rest horizontal displacement between the point B and the touching point, the calculation goes on determining the distances in the smaller triangle assumption (Figure 4.40 and Figure 4.41).

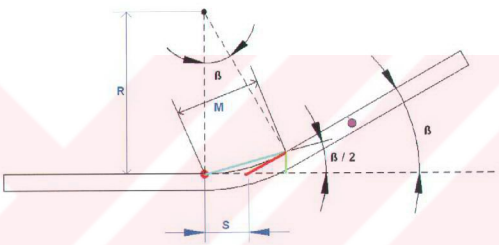


Figure 4.40: Illustration of the second assumed triangle to complete the calculation of the rotational center from the touching point by defining the x and y distances

In this step the radius amount of the fillet-radius becomes a parameter to count on. Here "S" is the rest amount of the horizontal displacement. In order to find the S value, the value M must be calculated.

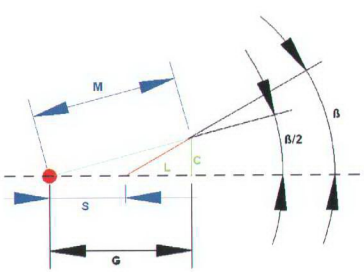


Figure 4.41: Detailed representation of second assumed triangle

Therefore;

$M = 2\ R.\ \sin(ß/2)$ **(4-38)**

$C = M.\ \sin(ß/2)$ **(4-39)**

$G = M.\ \sin(90 - ß/2)$ **(4-40)**

$L = C.\ \cot ß$ **(4-41)**

$S = G - L$ **(4-42)**

$S = M.\ \cos(ß/2) - C.\ \cot ß = 2.R.\sin(ß/2).\cos(ß/2) - 2.R.\sin^2(ß/2).\ \cot ß$ **(4-43)**

$S = R.\sin ß - R.\ (1-\cos ß).\cot ß$ **(4-44)**

$S = R.\sin ß - [R.\cot ß - R.\cot ß.\ \cos ß]$ **(4-45)**

$S = R.\sin ß - R.\cot ß + R.\cot ß.\ \mathrm{Cos}ß$ **(4-46)**

$S = R\ (\ \sin ß - \cot ß + \cot ß.\ \cos ß\ )$ **(4-47)**

$S = R\ (\ \sin^2 ß - \cos ß + \cos^2 ß) / \sin ß$ **(4-48)**

$S = R\ (1-\cos ß) / \sin ß$ **(4-49)**

So that; the horizontal displacement from the touching point to the rotation point will be;

$X{\cdot}Disp := |BG| + S$ **(4-50)**

$$X{\cdot}Disp := \left(\frac{h}{2}\cdot\sin(90 - ß)\right) + \left(\frac{w}{2}\cdot\sin(ß)\right) + \frac{R\cdot(1 - \cos ß)}{\sin(ß)} \quad \textbf{(4-51)}$$

$$Y{\cdot}Disp := \left(\frac{h}{2}\cdot\sin(ß)\right) - \left(\frac{w}{2}\cdot\sin(90 - ß)\right) \quad \textbf{(4-52)}$$

Eventually x and y displacement for the first station with 30°;

$$X{\cdot}Disp := \left(\frac{20}{2}\cdot\sin(60)\right) + \left(\frac{2}{2}\cdot\sin(30)\right) + \frac{1\cdot(1 - \cos 30)}{\sin(30)} \quad \textbf{(4-53)}$$

X Displacement = 9.428 mm

$$Y{\cdot}Disp := \left(\frac{20}{2}\cdot\sin(30)\right) - \left(\frac{2}{2}\cdot\sin(60)\right) \quad \textbf{(4-54)}$$

Y Displacement = 4.134 mm

The process can be repeated for each station; e.g. for bending angle with 60°;

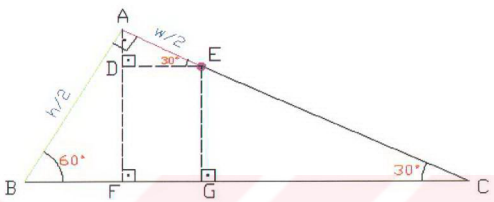


Figure 4.42: Illustration of first assumed triangle to calculate the location of rotational center (point E) from the touching point in the second station

$$X{\cdot}Disp := \left(\frac{h}{2}\cdot\sin(90-ß)\right) + \left(\frac{w}{2}\cdot\sin(ß)\right) + \frac{R{\cdot}(1-\cos ß)}{\sin(ß)} \quad \textbf{(4-55)}$$

$$X{\cdot}Disp := \left(\frac{20}{2}\cdot\sin(30)\right) + \left(\frac{2}{2}\cdot\sin(60)\right) + \frac{1{\cdot}(1-\cos(60))}{\sin(60)} \quad \textbf{(4-56)}$$

X Displacement = 6.443 mm

$$Y{\cdot}Disp := \left(\frac{h}{2}\cdot\sin(ß)\right) - \left(\frac{w}{2}\cdot\sin(90-ß)\right) \quad \textbf{(4-57)}$$

$$Y{\cdot}Disp := \left(\frac{20}{2}\cdot\sin(60)\right) - \left(\frac{2}{2}\cdot\sin(30)\right) \quad \textbf{(4-58)}$$

Y Displacement = 8.16 mm

Eventually, Figure 4.43 shows the rotational point at the last station.

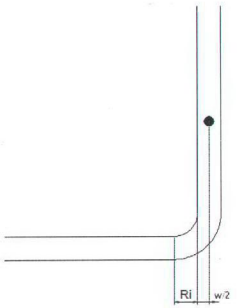


Figure 4.43: Representation of distance between the touching point and the middle point of the leg in the last station

$$X\text{·}Disp := R + \frac{w}{2} \quad \textbf{(4-59)}$$

$$Y\text{·}Disp := \frac{h}{2} \quad \textbf{(4-60)}$$

X Displacement = 2mm

Y Displacement = 10 mm

It is worth to remind that in each station the y displacement does not affect the rotation process because the rotation axis is the y-axis itself. However, to symbolize the middle point their formulations are also showed. The rotation axis is selected as y-axis because in the last station it is the normal to the base of the profile and represents the correct distance between two rolls. However, in the other stations except last station, the reason to have the y- axis as the rotation axis is different. Assuming the rotation movement, any deviations from the y- axis will result in collision between inner side roll and the profile base. Therefore, the y-axis is accepted as the rotation axis and it is assigned to the already designated rotational point.

The locations of the rotational points that determined here are belong to the coordinates of the X and Y- axis which are the cross-sectional and the vertical coordinates of the profile. The longitudinal position of these determined points will

be the middle of the stations. The stations shall have distances to each other and rotational points should have the same alignment in longitudinal direction with these stations.

After the theoretical explanations, the simulation settings should be defined. Elements and meshing, the implementation of the rolls and the insertion of the rotational points are assumed to be completed before advancing in the other themes.

4.7. The Rotation Process

During the rotation process the rolls both must pass the advancement of the contour way and must carry out the correct rotation movement. Therefore, a relationship must be built between the contour-way and the rotation activity. Theoretically the rolls should advance always perpendicular to the contour way during the rotation (Figure 4.44). So, the correct definition is achieved by the mathematical expressions. The fundamental contour way can be divided into small sections in order to make it easier to define these small sections with the mathematical formulas.

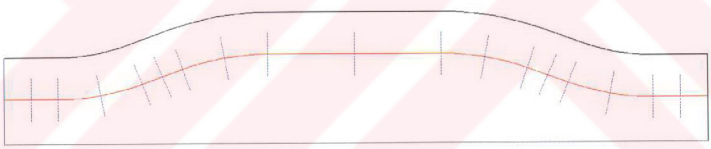


Figure 4.44: Representation of the rotation proceed in order to keep the perpendicularity with tool path

The most common formula of an arc is:

$$y_{arc} = (x-x_c)^2 + (y-y_c)^2 = r^2 \quad \textbf{(4-61)}$$

Where x_c and y_c are the center points of the arc center. The most common formula of a line is:

$$y_{Line} = dx + f \quad \textbf{(4-62)}$$

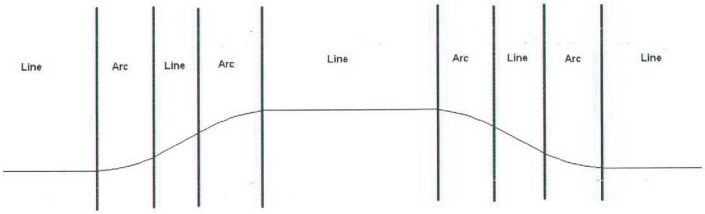


Figure 4.45: The main regions of defined flexible form

It is observed that the perpendicular accuracy is obtained by the derivation of the formulas. After derivation of the formulas, the necessary equations are acquired. By means of the equations the formulas can be extracted and the rotation graphic could be easily defined. The center point is assumed to be (0,0), in order to get an understandable illustration.

$$y'_{Arc} = -x*(r^2-x^2)^{-0.5} \quad \textbf{(4-63)}$$

$$y'_{Line} = d \quad \textbf{(4-64)}$$

According to the results the arc sections in the contour-way will be defined as line-parabola combination. Moreover, the line section in the contour-way will be defined as constant value. Finally the constant values in the contour-way will be respected as "zero" in the rotation graphic. The time steps will be arranged according to the contour-way and the action will start simultaneously. Besides, the value of the maximum angle will also be extracted from the contour-way. The arc section has a constant slope and consists of two arcs and one line subsection. The slope of the arcs and the line must be same in order to keep the tangency between each other. That gives the advantage to figure out the rotation angle, which is equal to the slope of the arcs and the line. Figure 4.46 shows the correct rotation graphic according that is extracted from the tool path.

The angle description should be done in the radian units to make the software work correctly. The definition is achieved by multiplying the angle value with the pi number and then dividing the result to 180°.

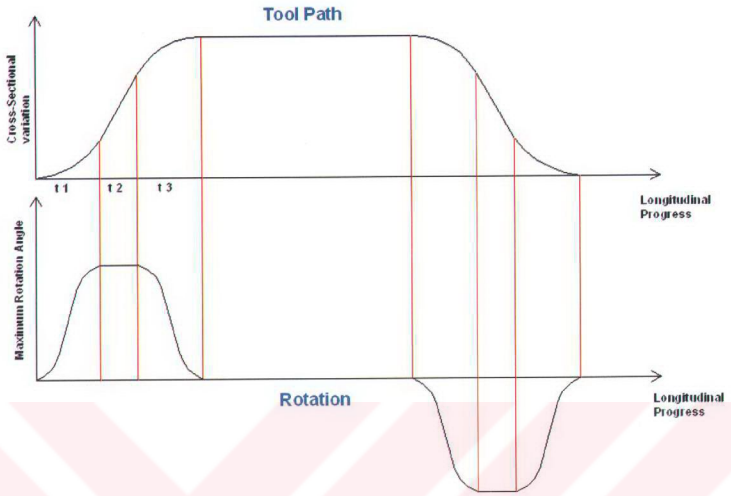


Figure 4.46: Derived rotational progress where the perpendicularity of rolls with the tool path is kept

Maximum rotation angle (radian) = [The slope of the arc (°) x (Π / 180°) **(4-65)**

Thence, the representation of the rotation movement should be defined like the pattern graphic above. According to the longitudinal locations of the rotational points this sample graphic should be derived and adapted to the real situation by shifting it in the X-axis (on the graphic). This graphic adaptation can be defined to the FEM Software by sinus curves. For instance, if the time step "t1" is 15 seconds, than the formula of the ascending section in the rotation graph will be defined by [y = 0.5* sin (Π*x/15)] sinus curve formulization.

5. FINITE ELEMENT ANALYSIS

5.1. Material Properties

In material selection, the values have been given to the Poisson's ratio as 0.3 and to modulus of elasticity (Young's Modulus) as 210000. The values are representing ST 37 steel type (ASTM A284 Steel, grade C), which is commonly being used in the industry (Figure 5.1). As the mechanical material type, isotropic type is selected to attain the correct result. In reality there are anisotropic materials also but since the goal of this work is to explore the correct manufacturing parameters, isotropic material type should be considered.

The plasticity properties of the material determine the strain hardening of the deformation seriously. The material should have the elastic-plastic properties to count the strain hardening. Yielding criteria will be "Von Misses criteria" and the "Piecewise linear method" will be selected as strain rate method. In nonlinear analysis the engineering stress-strain rate does not give the correct results. Thus, the true stress-strain formulations must be taken into account when defining the elastic-plastic material properties **[18]**.

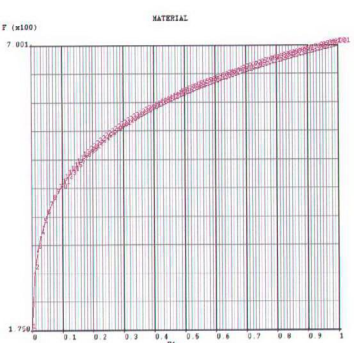


Figure 5.1 : True stress-strain curve with piecewise increasing strain intervals that is defined in COPRA FEA RF, data M

The formula of the stress is:

$$\sigma = K(\varepsilon + 0.001)^n \quad \textbf{(5-1)}$$

If we take the values from the material table

$$\sigma = 700 \,.\, (\varepsilon + 0.001)^{0.2} \quad \textbf{(5-2)}$$

5.2. Geometric Properties

The geometric properties of the sheet metal during the deformation must be described considering the non-linear simulation conditions. The sheet metal is considered as 3D Solid Body and applied to the elements. In this definition the dilatation of the sheet metal during the deformation should be constant. The dilatation occurs with respect to the Poisson's ratio; however the constancy of it should be indicated. That adjustment will bring equal dilatation values in assumed strain rates, which gives the better and correct result. The reason for applying these parameters is also the selected element type.

Truss, beam, plane stress, plane strain, axisymmetric, membrane, plate, and shell elements are based on theories that are limiting cases of the general continuum theory. Shell theory, for instance, requires the shell element to have a thickness. This thickness (although strictly speaking a part of the geometry) does not enter into the mesh generation phase. This data is entered through the geometric properties processor. Other element types have similar properties such as area for truss elements and moments of inertia and local axis systems for beam elements. For some element types, special options may be flagged in order to get more accurate results. For instance, the classical 4-node plane strain element is known to give a too stiff behavior if the element is subjected to bending. By selecting the assumed strain formulation, the element type is modified into a description with improved bending behavior. If for the same element the material behavior is nearly incompressible, also the constant dilatation formulation has to be selected. These special options are also defined in the geometric properties processor.

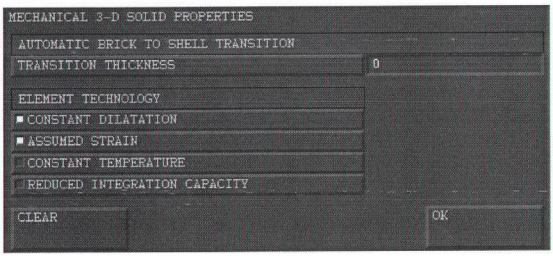


Figure 5.2: Definition of geometric properties

5.3. Elements

Elements consist of element edges and element faces and are defined by a sequence of nodes. The number of edges, faces and nodes depends on the element class. MSC.Marc Mentat employs a wide variety of element classes which are identified in Figure 5.3 below. When elements are drawn in wire-frame mode, the faces are indicated with a cross and the first edge is indicated with a half-arrowhead.

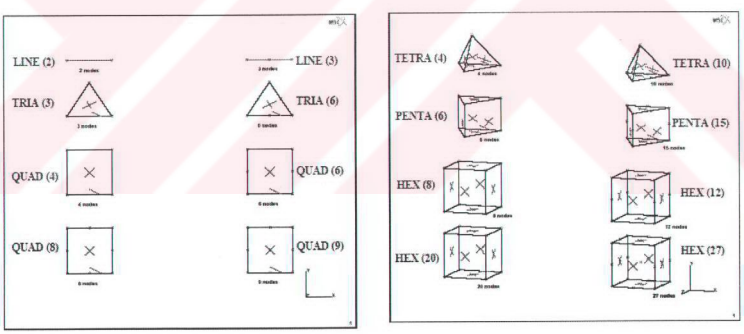


Figure 5.3: Various element classes

Since we have elements that have the thickness along the sheet metal thickness, it has been concluded that the application of the "mechanical 3D-Solid 8-noded – hexahedral volume element of Type 7 (full integration)" from the Marc element-library would be proper. Element type 7 is an eight-node, isoparametric, arbitrary hexahedral. As this element uses tri-linear interpolation functions, the strains tend to be constant throughout the element. This results in a poor representation of shear

behavior. The shear (or bending) characteristics can be improved by using alternative interpolation functions. Thus, the "assumed strain" procedure is flagged through the geometric properties option. This element is preferred over higher-order elements when used in a contact analysis. The stiffness of this element is formed using eight-point Gaussian integration.

For nearly incompressible behavior, including plasticity or creep, it is advantageous to use an alternative integration procedure. Thus, "constant dilatation" method, which eliminates potential element locking, is flagged through the geometry properties option. A mesh with hexahedral elements is generally more accurate and requires fewer elements than meshes that contain tetrahedral elements (Figure 5.4). For complex geometries, hexahedral meshes are easier to visualize and simple to edit than tetrahedral meshes.

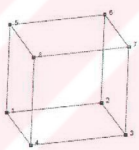


Figure 5.4: Selected element, three-dimensional, eight-node, isoparametric element (arbitrarily distorted brick)

MECHANICAL 3-D SOLID ELEMENT TYPES

	TETRA		HEX			
	4	10	8	20	12	27
FULL INTEGRATION	134	127	7	21	107	108
FULL & HERRMANN FORMULATION	157	130	84	35		
REDUCED INTEGRATION			117	57		
REDUCED & HERRMANN FORMULATION			120	61		
COMPOSITE/GASKET			149	150		
REBAR			146	23		

Figure 5.5: Selection of element class in the FEM Software

5.4. Contact

After the rolls placed correctly, their definition in the contact manner indicates, which elements or surfaces (rolls) deformable or rigid are. Also the method of the contact body control will be defined, which will execute the movements of the rolls during the deformation. All defined elements should be deformable and all must represent

one contact body, which will be exposed to deformation. Every station will represent one rigid contact-body independent from each other. In the last station there is also a flattener bottom roll representing another contact rigid body. It is proved that inserting a flattener bottom roll at the last station reduces corrugating on the profile base better than inserting a subsequent flattener roll station (Figure 5.6).

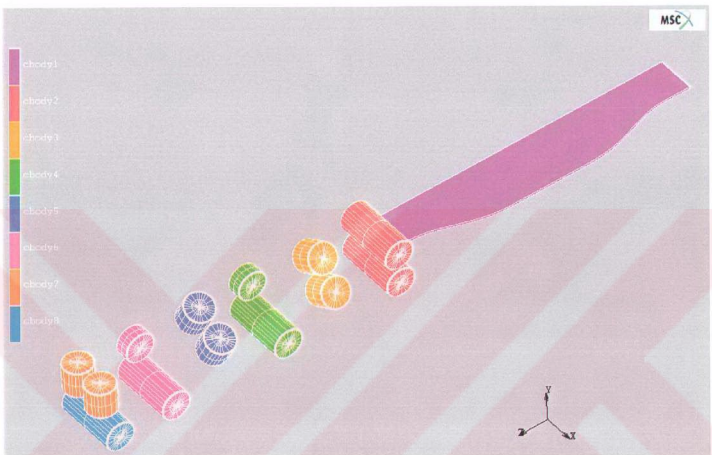


Figure 5.6: Constructed sheet metal as deformable contact body and rolls as rigid contact bodies. (COPRA FEA RF, data M)

There are three possible ways to control the rigid contact-bodies. The control can be carried out by referencing the velocity, position or load. It is proved that each way can be chosen to execute the movement of the flattener rolls. However, defining the translation move in addition with the rotation in many axes is only achieved by applying the load control method. In kinematical movement tests, it is also succeeded to rotate the rolls with position control method. However, the rotation was capable of a rotation only around one axis, which means the rotation gave just one additional degree of freedom to the whole roll kinematics. Since, the purpose was to reach six degree of freedoms (three translational and three rotational) in the flexible production; its accommodation to the software application is achieved with applying the load control method. Therefore, the flattener rolls are decided to have position

control method (only translational) and the rotational rolls have load control (translational and rotational).

The position control of the flattener rolls is achieved by defining the forward move in the Z-direction (longitudinal direction). The movement on Z-direction is defined by a table that is used for all stations in the simulation, because every station will proceed at same speed and will advance same time interval on the longitudinal axis even during the rotation process.

The load control definition is achieved by defining two additional nodes called; "Control Node" and "Auxiliary Node". These nodes will be the references for defining the concurrent rotational and translational movements of the rolls. After defining these nodes for each station, the necessary movement definitions will be given in the boundary conditions with varying tables. Before defining the tables these points should be inserted the right position. Since the rotational points in each station defined scientifically, the right position of the control and the auxiliary node will be the rotational point location.

In the FEM software the location of the center of rotation is presented by defining the control node at the designated rotational point location. Thence, the control node always acts as the center of rotation itself and will provide the rolls to rotate around its orbit. The control node and the auxiliary node may have the same coordinates. But one should know that the centre of rotation point will be the "Control Node" not the auxiliary node. Forces and prescribed displacements can be applied to this control node, which can be a free node not connected to the mesh or a node of an existing mesh.

For 2-D, this node has two translational degrees of freedom and for 3-D, it has three degrees of freedom. If rotations and moments are to be applied to the load-controlled rigid body, they are applied to the auxiliary node which can also be associated with the rigid body. Auxiliary node has one rotational degree of freedom for 2-D and three for 3-D. If no auxiliary node is given, the rotation of the rigid body is suppressed. The rolls will rotate by referencing a rotational axis. That axis must be the y-axis itself, because any divergence from y-axis will cause a displacement in y-direction which

causes deviation and eventually a collision between rolls and the profile (Figure 5.7, Figure 5.8, Figure 5.9). These rotational degrees of freedom are referred to as Y-displacement in the boundary conditions menu. Rotations that are applied to the auxiliary node are with respect to described "control point".

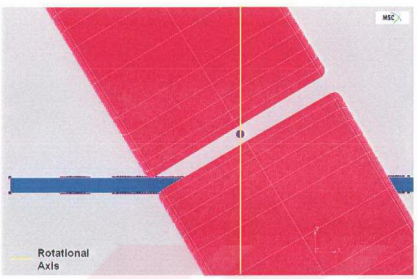


Figure 5.7: Rotational axis on defined rotational point and at 30° station (COPRA FEA RF, data M)

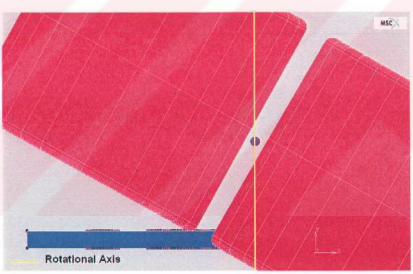


Figure 5.8: Rotational axis on defined rotational point and at 60° station (COPRA FEA RF, data M)

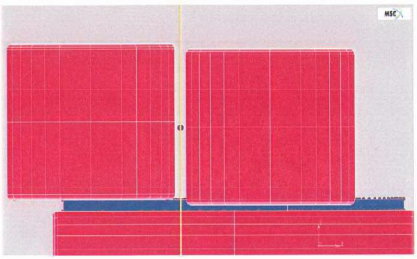


Figure 5.9: Rotational axis on defined rotational point and at 90° station (COPRA FEA RF, data M)

It is worth to remind that "the control nodes" that shown here are the determined rotational points, which are extracted by referencing from the touching point to the middle of the profile leg.

Eventually, 6 nodes have been additionally defined to achieve the load control of contact bodies. In boundary conditions definition, these nodes will be selected exclusively; therefore these nodes should be labeled with numbers and must be noticed to get the ID of them easily in later stages.

After the introducing the contact bodies, contact tables should be defined to organize the calculation time and present the contacts to the simulation. That provides the simulation to count only the deformation in the rigid bodies that are defined in the contact table and accelerates the calculation time. According to these contact tables or contact events "Load Cases" will be defined in next step. Every load case assigns the duration of the contact in the contact tables and will take over the result to the next load case. Because of that, time intervals should be specified and the total time of the production process must be decided correctly. These time intervals are also determine the destiny of a correct result and they must overlay with the real production time. It has been assumed that the sheet metal moves 1mm per second in longitudinal direction (Z-direction).

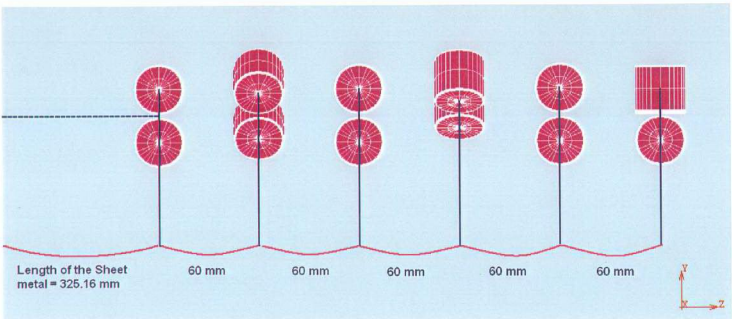


Figure 5.10: Distances between roll stations (COPRA FEA RF, data M)

Thus, the total production time will be circa 650 seconds. It means every station will advance 650 mm until the end of the process. As a new station enters and touches the sheet metal, the contact table hands over its task to a new defined contact table. The production starts with the contact of the first flattener roll. Since the feed rate is 1mm/s, after 30 seconds the second station will be in touch and it necessitates a new contact table that defines the contact of two stations. During the specification of the contact span, the effect area of the rolls should be taken into consideration. That effect area is the radius of the roll and some distance of the gap between two stations. After advancing to the approximate middle of the gap of the first station, the duration for a new station to advance the next contact table will be identical until the last station. As the last station touches the sheet metal in the last table, the position of the first station must be controlled whether it has left the sheet metal and has no more contact **[18]**. According to that info the contact table of the last station is built. Moreover, with the addition of the effect area and the time that will take the last station to leave the sheet metal completely, the duration of the last load case will be 380 seconds, constituting overall 650 seconds of production time.

Table 5.1: Definition of times table for each station. As stations start to touch the deforming sheet metal, the defined time table is activated, until the next station enters. The last station is supposed to proceed along the sheet metal. (T = Touching)

Tables / Stations	1st	2nd	3rd	4th	5th	6th
Contact Table 1	T – 30s	-	-	-	-	-
Contact Table 2	T – 60s	T – 60s	-	-	-	-
Contact Table 3	T – 60s	T – 60s	T – 60s	-	-	-
Contact Table 4	T – 60s	T – 60s	T – 60s	T – 60s	-	-
Contact Table 5	T – 60s	T – 60s	T – 60s	T – 60s	T – 60s	-
Contact Table 6	T-380s	T-380s	T-380s	T-380s	T-380s	T-380s

Production time = 30 + (60*4) + 380 = 650 seconds **(5-3)**

5.5. Implementation of Tables

After determining the critical values, theories, roll locations and rotational points, the necessary tables should be derived from these information. The distance between the stations affects the table arrangements. The material table is already described and it doesn't need to be shifted. However, the contour-way table and the table of rotational movement must be arranged. The definition of the contour-way was defined theoretically and created in the Autocad environment. The transfer of the contour-way from the Autocad has the same principal as the transfer of the pre-cut shape. Hence, the defined contour must be divided into points and on its borders two points must be defined exclusively. Than with the mentioned application "pointsout" the coordinates of the points are written into a text file. After opening this text file in the Excel the values should be edited.

In definition the coordinates don't have be adapted to the pre-cut shape because the defined contour-way table will be applied to the rotational point, which is already placed according to the pre-cut shape. Therefore, the important issue is the incremental progress of the points constituting the contour-way. The description

should be edited as starting from the (0,0) point. This will help to check the increments more comfortable. The values should be applied to the X and Y values. As we mentioned before, the tables are always supposed to be defined in X and Y coordinates in 2-D. Their 3-D tasks will be determined by assigning them to the appropriate node (like rotational point - the contact node or the auxiliary node). After editing the starting points so the increments, the code that is required to create a procedure file is given. The code "*table_add" must be written to the beginning of every line. Thus, a procedure file is created and read in the FEM Software, which gives the pattern graphic below (Figure 5.11 and Figure 5.12).

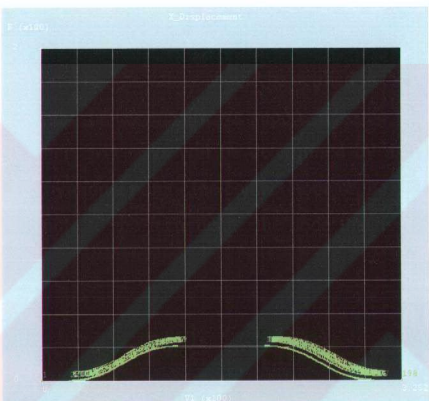


Figure 5.11: Obtained tool path graphic (COPRA FEA RF, data M)

In order to derive the necessary tables from this contour graphic, the simulation medium must presented to the graphic. The total duration was 650 and the distance between the stations was 60mm. Thus, for the first station this graphic must shifted 60mm and afterwards a coordinate point (650,0) must be defined.

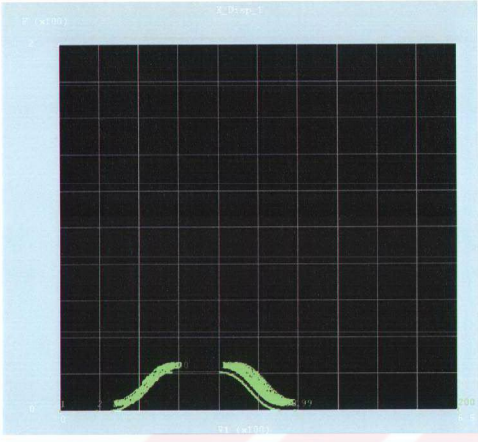
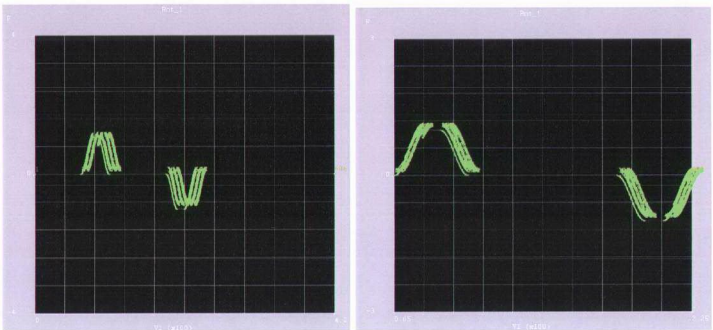


Figure 5.12: Obtained tool path graphic for a station to follow during the whole process in 650 seconds scale (COPRA FEA RF, data M)

The other stations can be defined by this way. The definition of the rotational movement was derived by the contour-way description. Its existence is proved to be associated with the contour-way. During the definition of the rotational movement table, the coordinate values of the contour-way will also be facilitated.

During its definition the maximum magnitude on the y-axis will show the maximum rotation angle. However, in the table definition the maximum value will be assumed as 1 because, the real values will be given in the boundary conditions section, where the rotation tables are applied to the nodes. Thus, the progress of the contour-way regions becomes important, as they determine how long a region in the rotational table will last.



A B

Figure 5.13: A-) Obtained rotation graphic in FEM Software B-) Obtained rotational graphic for a station to follow during the whole process in 650 seconds scale (COPRA FEA RF, data M)

5.6. Boundary Conditions

The boundary conditions definition can be separated into two different stages. At the first stage, the displacement locks are defined. The second part consists of the definition of the kinematical parameters and assessment of tables. The focal point on second stage should be the boundary definitions of the control and auxiliary nodes that has been described before. They must be both locked and be given a movement definition. That means, in both stages the control and auxiliary nodes will be selected.

The boundary conditions will set the rules of the simulation and must represent the real production environment. It is known that in roll forming the length of the sheet metal mustn't change at the end of deformation. That constriction leads the sheet metal edges to be restrained in the longitudinal direction (z-direction) .This boundary condition should also comprises the control and auxiliary nodes (Figure 5.14).

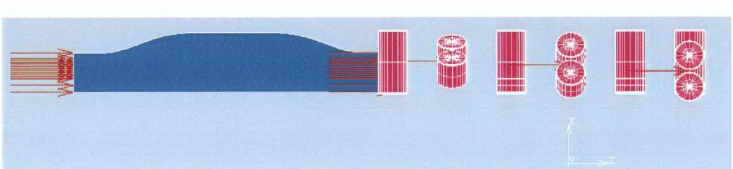


Figure 5.14: Z - Displacement lock (COPRA FEA RF, data M)

Since we have the half shape of the sheet metal the symmetry surface must also have boundary condition. This surface should be fixed in X-direction, considering the fact that it is not split into two pieces. Control and auxiliary nodes are also included (Figure 5.15).

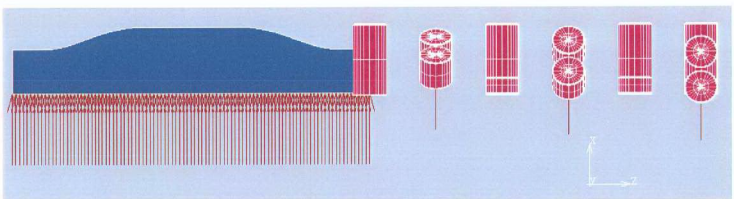


Figure 5.15: X – Displacement lock (COPRA FEA RF, data M)

The thickness of the sheet metal should also be defined with a boundary condition to make the thickness deformable during the simulation. The selection of nodes here is significant. The nodes must be selected from two underside edges of the sheet metal. Selection of three or five nodes at both edges will be enough to define the desired condition (Figure 5.16). This boundary condition allows the sheet metal to change its thickness during the deformation, which represents the real deformation conditions.

Additionally, with the selection of the control and auxiliary nodes in this boundary condition, these nodes become restricted in all three degree of freedoms that is required them to indicate their exact position.

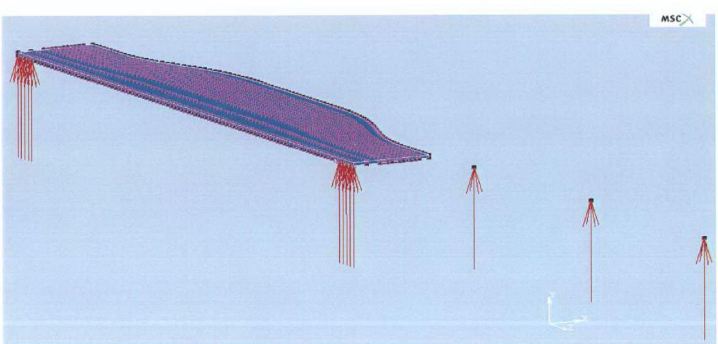


Figure 5.16: Y- Displacement lock (COPRA FEA RF, data M)

The second stage of the boundary conditions is the definition of the movements to the desired nodes. It is important to remind that, the displacement movements must be defined with control nodes and the rotational movements must be defined with auxiliary nodes. Since the straight movement of flattener rolls in z-direction already defined, only the rotating rolls' movements will be specified in boundary conditions.

At first, all rolls should have the displacement movement in z-direction. Therefore its table that has been used to define the flattener rolls can be used here again. Three control nodes of three stations are selected and in definition field their specified tables are assessed. After that the displacement movement in the x-direction must be defined with another boundary condition. Since the stations carry out the action in different time steps with varying tables, each station will require different boundary conditions. In each condition the control node of the station is selected and the proper table is defined.

Afterwards the rotation movements must also be defined separately for each station. But this time the auxiliary nodes must be selected. After selecting the auxiliary node, any defined displacement movement or table will be respected as a rotational move. Thus, one shouldn't select the rotation-y option in the describing field during the definition (Figure 5.17). Especially, the displacement y must be selected.

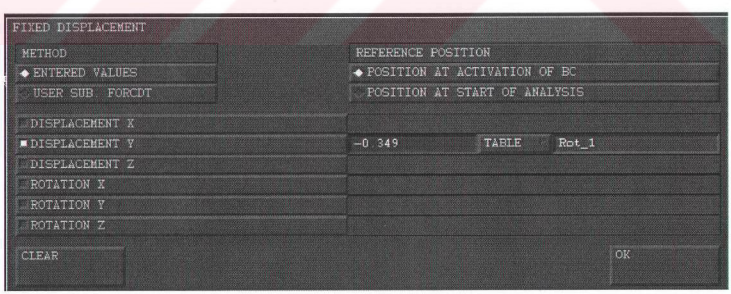


Figure 5.17: Definition of the rotation in the boundary conditions

As a remainder, we have defined the maximum angle value of the rotation table as 1. Here it is time to give the real angle to the blank. The angle values are from radian values. The value here represents the rotation angle of 20°degree. The minus sign

before the value points out the direction of the rotation. Since the rotation movement can be defined with tables, any rotation movement until 3 degree of freedoms can be specified.

Angle in degree = Angle in radian * 180/ Π **(5-4)**

Angle in radian = 20 ° x Π / 180° = 0.349 radian **(5-5)**

5.7. Loadcases

The subdivision of the simulation into seven time steps according to contact conditions causes seven different load cases. Actually, all load cases have the same adjustment. The differences are their duration and the contact bodies that they host. In solution control "non-positive definite system" must be used and as iterative "Full Newton-Raphson". The tangent stiffness-matrix is reformulated for each iteration (cycle) in "Full Newton-Raphson" method. In every load case all of the boundary conditions must be activated because the tables are defined from the very beginning until end of the event **[12]**.

5.8. Jobs

Loadcases should be selected according to their order of action. The analysis parameters of the 3-D mechanical simulation are determined in this stage. Once you have defined the load-case, activate the constant dilatation procedure for all elements to avoid numerical problems due to the incompressible plasticity and activate the large strain plasticity procedure based on the mean normal plasticity solution procedure.

Large displacement option has the effect that the analysis is nonlinear. It signals the program to calculate the geometric stiffness matrix and the initial stress stiffness matrix. This parameter should be used when performing a linearized buckling analysis with a nonlinear preloading. "The Lanczos method" is usually more efficient for modal solution method, in particular for large models and when several modes are to be extracted **[18]**. It also handles multiple eigenvalues better. For the buckle

solution method the default method "inverse power sweep method" gives better results **[19]**.

In "Updated Langrange Procedure" formulation, element quantities are evaluated with respect to a reference system that is updated by the current displacements (Figure 5.18). The program uses and prints Cauchy (true) stresses and the corresponding strain measure, the true strain. For small strains, this procedure is typically used for beam and shell structures where the rotations are large. It should be used in conjunction with the "Large displacement" option **[18]**.

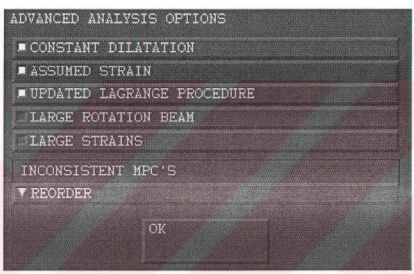


Figure 5.18: Selection of the advanced job parameters

The constant dilatation option is already explained and should also be selected in job definition. It is recommended for elastic-plastic analysis and creep analysis because of the potentially near incompressibility behavior. The bending behavior can be improved by using the assumed strain formulation for element type 7 (3-D brick). This procedure replaces the standard bi- or trilinear interpolation functions with an enriched group that is able to represent pure bending behavior. This formulation results in improved accuracy for isotropic behavior, but it should be noted that the computational costs increase .

6. SIMULATION RESULTS

6.1. Results and Discussions

Simulating the created model takes circa 3-4 hours with a Pentium 4 processor and 1 GB memory. The time for the simulation depends on the assigned increments. Increment is the processing time interval for the computer to follow. The simulation period was determined as 650 seconds and also 650 mm proceed in the longitudinal direction. However one increment was determined as 0.5 mm, which means the whole process consists of totally 1300 increments. The number of increments affects the processing time and determines the detail level in the calculation with finite element method. If time increments last longer, the equations and matrixes for FEM calculation get more complex. E.g. the stiffness matrix has more rows and columns, which make the calculation time longer. The current increment value is assigned depending on the experience that is gained from the investigations.

Cut-back feature is the indicator of the equation amount that could not be solved and is rolled to a closer value. The more cut-back number is indicated, the more deviation in the result will appear. Therefore, an alarm for this indicator is set. If number of the cut backs reaches to 10, the calculation stops automatically. This precaution secures simulation to become safer and reliable.

During the setting of "job" section, the desired result evaluations are determined before the simulation is commenced. So that, stress, total strain, elastic strain, equivalent von misses stress, equivalent elastic strain, total equivalent plastic strain, thickness of element, hardness, displacements in each coordinate and total displacement, damage and grain size scalar results are demanded from the calculation. More attention is given to geometric properties and material properties during the evaluations of results.

6.1.1. Geometric Properties

The dimensions of the final geometry were the most significant issue to evaluate in this thesis. The dimensions from the user definition must be achieved within least tolerances. It is expected that the leg height of the final profile would probably have deviations because of the rotational position. This will cause some disruption on the leg height however, the amount is not yet clear and will be observed according to the results. Figure 6.1 illustrates a view from cross-section of front end. Scales in regions are the markers of total displacement.

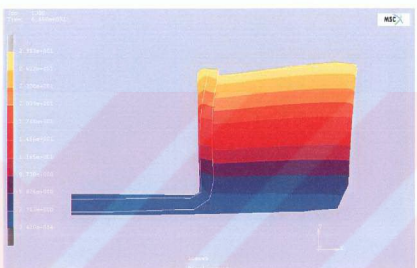


Figure 6.1: Cross-sectional view of deformed profile with total displacement analysis (COPRA FEA RF, data M)

The half of representation of the profile was preferred in order to reduce calculation time. The representation is the total displacement, which is useful to notice the end geometry of the finished profile. There is a slight amount of deviation at front end to the right. In each simulation that has been carried out, this deviation has been observed and it is not originated from any bad application. It is based on the residual stresses that occur during the widening. At back end, where rolls leave the channel, such deviation is also observed in relatively smaller magnitude. The residual stresses accumulated in widening and narrowing sections causing the front and back ends of the channel to deviate.

This deviation could have been called as "springback" effect, if the deviation amount along the channel was almost equal. Springback effect is a concept which is directly correlated to the channels with constant cross-sections. Therefore, another name for this problem can be called, since the deviation is regional along the channel.

The most obvious deviation in the cross-sectional direction is observed at the front end. The graphic in Figure 6.2 shows geometry of the inner side of the channel after deformation. The illustration is created by referencing the node positions after deformation.

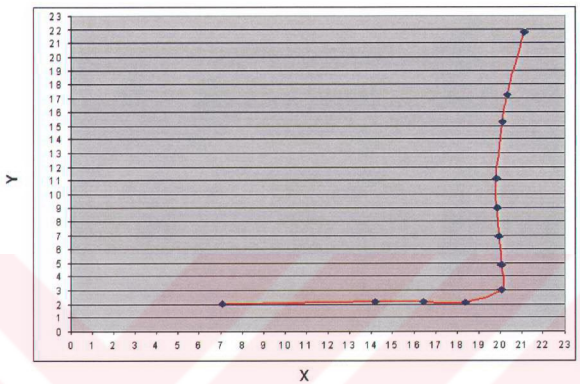


Figure 6.2: Magnitude analyse of deviation at the front end from the inner side

It is observed that the maximum deviation takes place at the top of the leg. It is measured that the maximum deviation is 1.12 mm. The design parameter that was given by the user was 20 mm, however the node at the top showed a value with 21.12 mm. So the deviation can be seen in Figure 6.3 better with a comparison.

This deviation in x-direction also causes a disruption on leg height with 0.2 mm shorter than expected. Since the wall thickness was 2mm, the height of the channel web seems to be normal.

A slight amount of deviation can also be observed at the back end, however it is relatively smaller than the disruption at the front end (Figure 6.4.). In both ends the deviation angle are equal, if the average deviation at the front end is taken. The local deviation is measured as 2° (Figure 6.5).

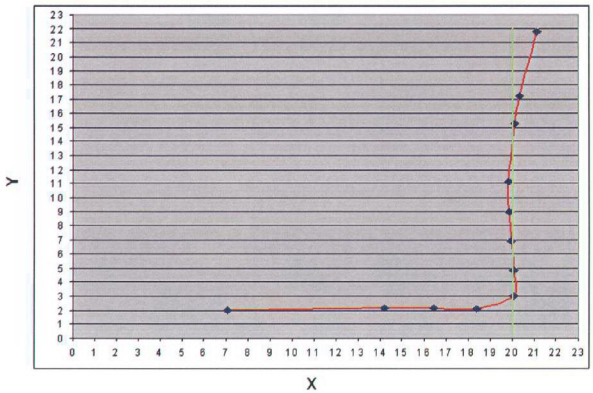


Figure 6.3: Observation of deviation at the front end

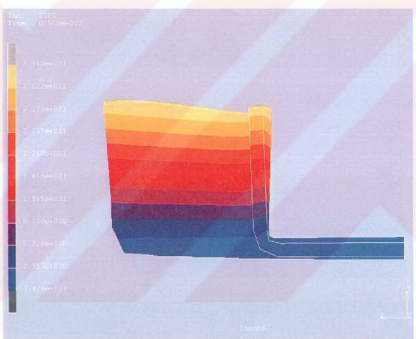


Figure 6.4: Channel back end with total displacement analysis (COPRA FEA RF, data M)

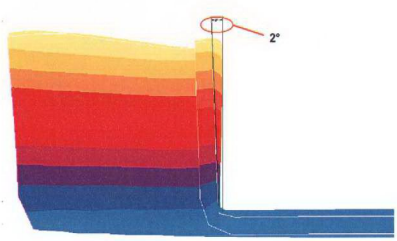


Figure 6.5: Illustration of deviation angle at the back end (COPRA FEA RF, data M)

This deviation does not continue along the channel. Thus, this problem is unlike "springback" effect. There is also certain deformation at the leg in the transition region rather than the bending zone Because of the geometry change in the transition section, residual stresses accumulate in the area. They increase the number of dislocations in the region and provide a steady geometry. Figure 6.6 shows a top view of the channel. The deviations can be observed along the U Channel. From this figure most of the user defined dimensions can be checked if the simulation results fit them.

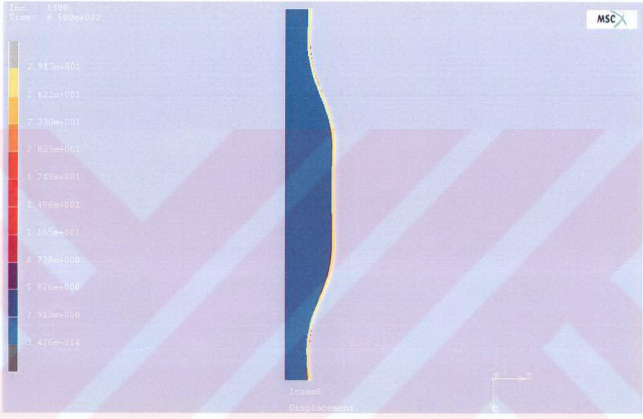


Figure 6.6: Top view to check the dimensional consistency with total displacement analysis (COPRA FEA RF, data M)

After measuring the dimensions in FEM program, it is observed that the dimension consistency is pretty high. The tolerance limitation is set as ± 0.5 mm for the dimensions in the longitudinal direction. This precision fits even the tolerance limitations for a straight cross-sectioned profile. So the dimension deviations are acceptable.

The difficulty lies on the consistency of the leg height along the channel. Figure 6.7 illustrates the leg height of the channel. From this aspect the slight disturbance on the leg height can be observed easier. This deviation amount is measured with maximum 2 mm difference. Figure 6.8 shows the peaks and bottoms of the leg height along the channel. Maximum leg height was observed as 22.9 mm where the minimum was

20.99. The expected leg height was 22 mm, which determines the tolerance allowance as -1 mm / +1 mm.

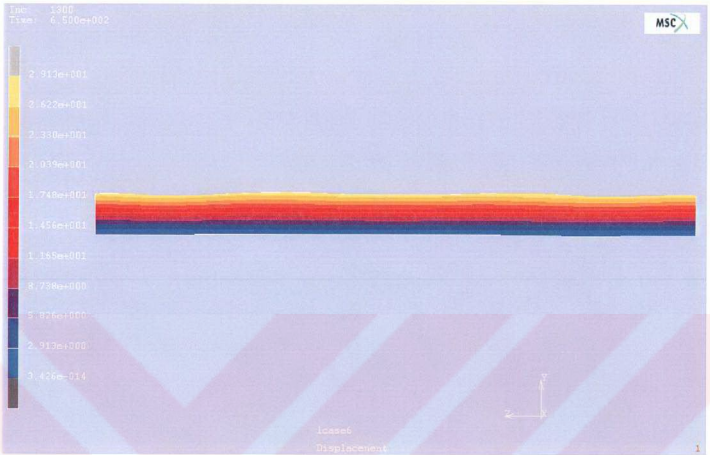


Figure 6.7: Right view to check the leg height consistency with total displacement analysis (COPRA FEA RF, data M)

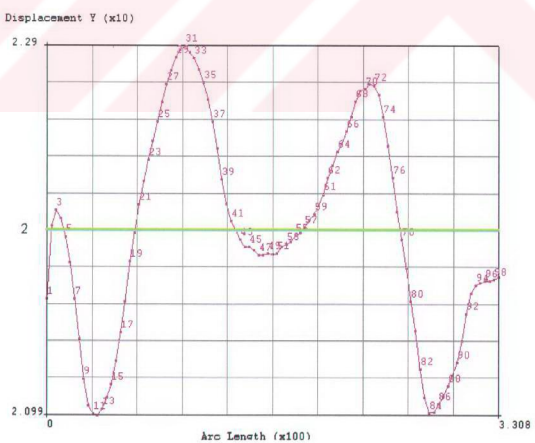


Figure 6.8: Leg height progression along the channel (purple line is the leg height progression data from FEM program, green line is the aimed height; the tolerance is ± 1 mm)

There are several reasons for the deviation of leg height. First of all, this disruption on the leg should be caused by the position of the center of rotation point. It is worth to remind that with the current simulation program it was impossible to define two different control points (center of rotation points) for one station depending on the shape.

In the current shape there were two different arcs and their central points were lying on the different positions even in the different sides of the current profile. During the simulation process the center of rotation point for a rotational station is supposed to move for each arc on the shape. The average of the two central points was selected at the middle of the profile, which optimizes the deviation and reduces it as possible as it should be. Nevertheless, this assumption causes slight amount of optimized deviation.

On the other hand, the precut shape and the contour-way are defined by relying on the dilatation value, the method to calculate the dilatation value also becomes important. It is explained that there are several methods to calculate the dilatation and from each method a different value can be obtained. However, the obtained value must also be supported and confirmed by the value that FEM program calculates. The used method in this application and its reliability in the FEM program was already tested and proved to suit each other. However for the flexible forming, the leg is also a region, where deformation takes place other than the bending zone. This could prove to the used dilatation method to unfit the flexible form. Perhaps another method should be developed. However, the leg disturbance would not be so much, if the problem was caused because of that reason.

The last possibility for the leg disruption can be longitudinal elongation or shrinkage of the channel due to the occurred stresses. As mentioned before, there is also a deformation at the leg other than the bending zone. This can cause local dilatations (elongations or shrinkages), while the total length and also the edge length of channel is kept. This dilatation affects the leg height because the length of the channel was constricted in the boundary conditions phase. Therefore, dilatation on the leg, which is caused by deformation, can not change the channel length and turns into an elongation or a shrinkage effect on the leg height.

The disruptions on the leg are observed to be located in the transition regions. "In the concave transition region, shrinkage is observed on height, while in the convex transition region elongation was observed on height". The convex and concave concepts are relative and they can be identified with an axis. In this example, the definitions were made by referencing the symmetry plane as an axis to identify the convex and concave regions.

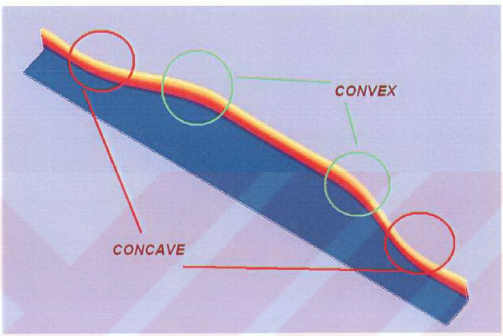


Figure 6.9: Convex and concave regions on along the leg (COPRA FEA RF, data M)

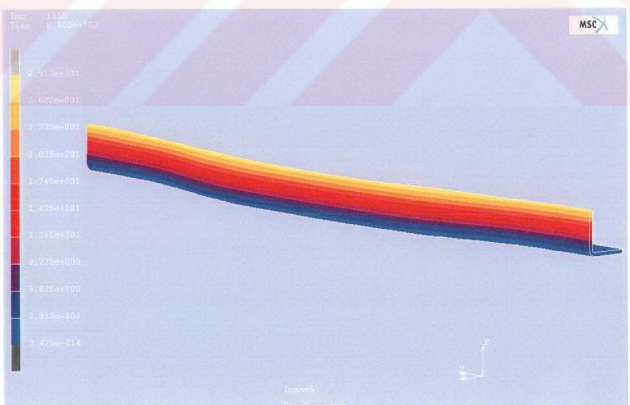


Figure 6.10: Acquired leg height with ± 1mm tolerance with total displacement analysis (COPRA FEA RF, data M)

6.1.2 Material & Mechanical Properties

The normal stress analysis result shows us how the stress accumulates in the widening and narrowing regions along the profile by creating compressive and tensional forces. These stress accumulations are observed easily and showed in the Figure 6.11. It is also observed that the accumulation rate increases as the flexibility factor increases. The arrows in the figure point the compressive stresses. The stress analyse according to the von-misses stress criteria is shown in Figure 6.12.

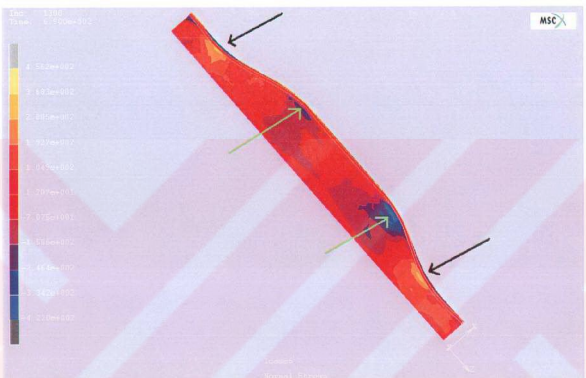


Figure 6.11: Normal stress analysis. Compressive stresses are shown with their directions (COPRA FEA RF, data M)

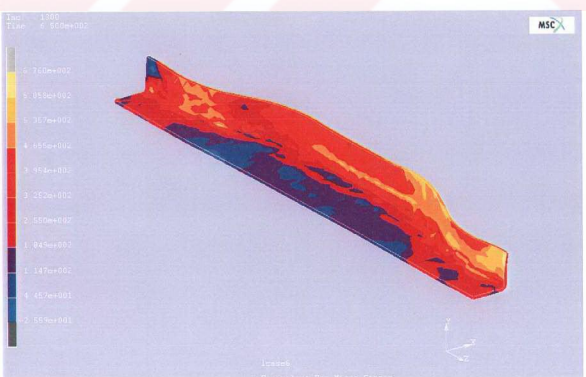


Figure 6.12: Isometric view of Von Misses stress analysis with illustration of tension and compression forces (COPRA FEA RF, data M)

The combination of elastic and plastic strain can be easily observed in Figure 6.13. The bending zone reveals itself distinctly. The width of the bending zone is appeared to be constant and equal along the profile, which also proves that this assumption during precut contour evaluation was correct.

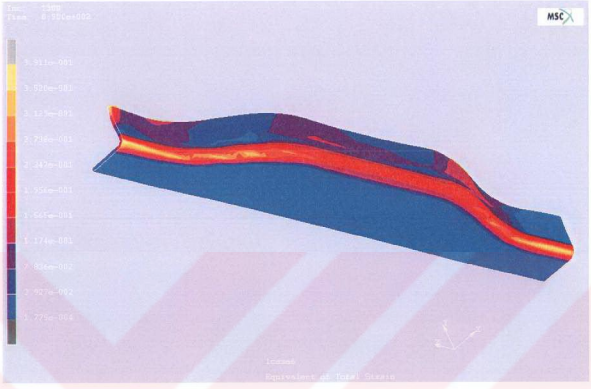


Figure 6.13: Result of equivalent total strain (COPRA FEA RF, data M)

Total equivalent plastic strain is observed intensively in the bending zone as expected and in the widening and narrowing sections on leg. This proves that he accumulated stress values in these regions are able to exceed the yield force of material and achieve a plastic strain by exceeding the resilience energy. However, the plastic strain value does not exceed the ultimate tensile strength, which prevents the fracture or any non-uniform deformation that shall cause micro cracks on the profile leg surface.

Additionally, the plastic strain is also observed on the leg intensively, which shows the certain dilatation on the leg. This dilatation was associated with the leg height disruption and it proves that this possibility was correct. Other than the dilatation at the bending zone there is also a dilatation along the leg, which is also a reason for a possible disturbance on geometry. This value should not be underestimated because its effects could have caused more drastic deviations than the one that is observed in this study.

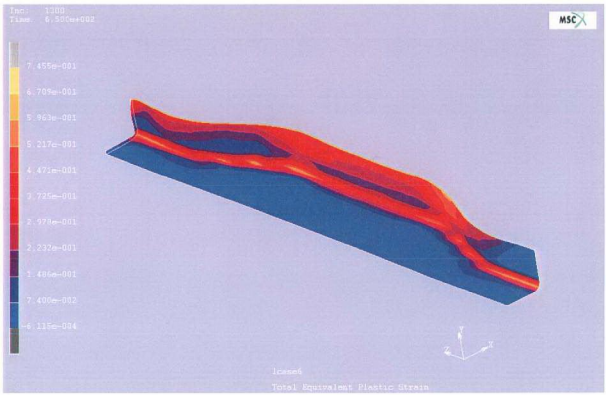


Figure 6.14: Total equivalent plastic strain (COPRA FEA RF, data M)

The hardness values have reached highest levels almost in every section of leg, bending zone and even some regions of channel web. These hardness values are originated from the accumulated stress values that provide the number of dislocations to increase and lock with each other, resulting the hardness and the strength of the channel reach higher values. Also the current strain values cause deformation hardening since there is no heat treatment in the process.

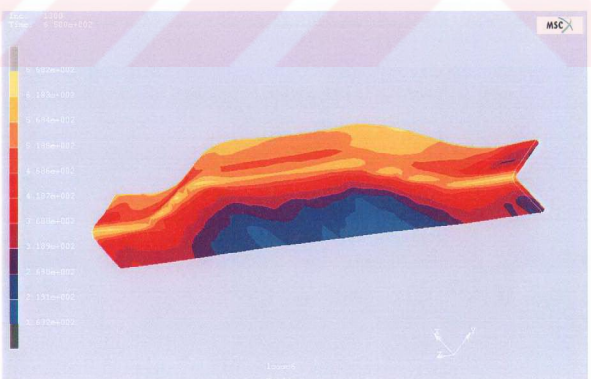


Figure 6.15: Hardness analysis (COPRA FEA RF, data M)

7. SUMMARY

7.1. Conclusions

The main objective of this thesis was to explore the feasibility of the flexible roll forming in computer environment, which contains 3-D kinematics of the rolls and gives the correct results by using up to six degree of freedom flexibility. The objectives that were set at the beginning of project are achieved with good precision. The developed methods were explained with their rate of importance. After the methods carried out, one case study was performed. The case study was commenced with an arbitrary user definition that has arbitrary dimension values for a cross-section varying profile.

The end shape of the profile was referenced as the initial point. Thereafter the appropriate precut unfolding shape was calculated with the necessary explanations. Then the necessary tool path was also calculated. The most convenient rotation process was defined by referencing the specified tool path to keep the perpendicularity. Then the rotational center point for the rolls is specified for each station. It is observed that the rotational point must not be stable during the process because of the different sides of the arc centers that exist in the defined profile. However with the restriction that came from the FEM Software the rotational point could not be moved, therefore an optimized position is specified for least deviation.

The importance of the roll size with respect to the profile widening range was emphasized. After these pre-processing steps, the necessary data were carried to the FEM program with the most practical way, since the preparation of the simulation is a long and tedious work. The FEM program must have been explored in order to accommodate it to non-linear simulation of the flexible roll forming. After investigations, the availability of the roll movement flexibility up to 6 degree of freedoms was succeeded.

After all the methods and calculations are confirmed the finite element analysis was executed. It is observed that the dimensional shape consistency fits the user definition within the tolerance limit. However, the leg height varied in some cases and after iterations the leg height deviation was reduced to ± 1mm, which was still out the tolerance limitations for a roll formed profile.

The reason of deviation on the leg height was associated with the position of the rotational center point. The excessive strain values in the bending zone and on the leg could also have been the reason, however after observing the strain values from the results, it was proved that the used method fit the results. Therefore, the association of the deviation on the leg height was proved to be originated from the location of rotational center point because an optimized position was assigned in order to achieve the simulation by reducing the foreseen deviation and balance it on the both arc regions that exist in the widening and narrowing section in the profile. Thence, in this assumption the correct rotational points in the arc centers could not have been defined to the finite element program. Software and caused small amount of deviation on leg height.

7.2. Future Work and Further Recommendations

First of all, as the location of the rotational center point of the rolls could not have been defined separately in the FEM program, the further investigations are supposed to continue to find the way of defining the rotational central points separately in the FEM program. In this profile there were two different arc regions, so two different rotational centers. However, a flexible profile shall have many different curved regions so many different rotational centers, which would be quite difficult to optimize. Therefore, the necessity of this feature must be emphasized in the first order.

As the kinematical movement of the rolls was achieved to be simulated up to 6 degrees of freedom, many different profile types can be developed and inspected. Obviously achieving all 6 degree of freedom in one profile section would be hard or would cause excessive amount of stress accumulation, however this feature would constitute a step to develop this concept in the future. Figure 7.1 shows a hat type profile that is designed to be manufactured with flexible roll forming.

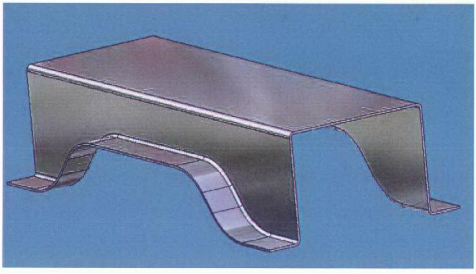


Figure 7.1: Application of knowledge for different channel types

From the aspect of software development, there are also some issues that should accelerate the processing time of simulation and simplifying the user definitions. The meshing concept should be evaluated again in order to reduce the element numbers in the deformable body. Furthermore, the mesh size expansion should be inserted in a certain order to impulse the stress values much better that are originated from the bending zone (Figure 7.2).

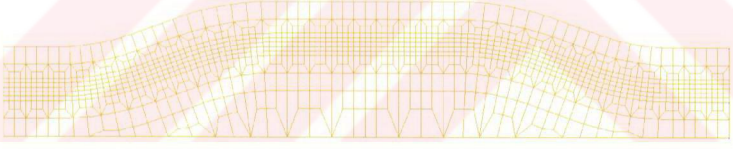


Figure 7.2: An alternative meshing design that has reduced number of elements and gradually increasing mesh size

The user definition for a profile shape also should be classified and formulized with certain shape functions in the software like the shape function definition in fourth chapter of this thesis in Table 4.1. However, the offset feature must also be added to the formula, so that the precut unfolding shape and the tool path definitions should be extracted directly from the user end profile definition.

Moreover, another dilatation case was observed on the leg during the evaluation of results. The dilatation of bending zone was taken into account during this study. However, the observed additional dilatation must not be underestimated and must be

taken into account in further studies. Although an exaggerated flexibility factor was assumed as the user definition and a ± 1 tolerance limit was reached, this effect could influence the result more according to the channel type and leg geometry.

Finally from the aspect of manufacturing, the simulated flexible profile should be produced with flexible roll couple with a supporting flattener roll. The flexible rolls can be mounted to robotic control mechanism that has also 6 degrees of freedom flexibility. In the conventional roll forming the moving part was always the sheet metal, however in this application the rolls should move along the stable sheet metal. This eliminates the flattener rolls when they are needed only with driving purposes. Nonetheless, one roll couple should represent all bending stations by changing the bending angle in each station. As one bending step is achieved in forwards direction, an upper bending step could be achieved in backwards direction during the returning to the initial point. This brings savage for production time and also reduces the number of rolls to two. As the case maybe, a roll magazine should be inserted to the mechanism. Building such roll form machine will requires more degrees of freedom perhaps up to 6 degrees of freedom. Since the simulation method is developed, tangible studies can be carried out for building such mechanism.

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