LICENTIATE THESIS

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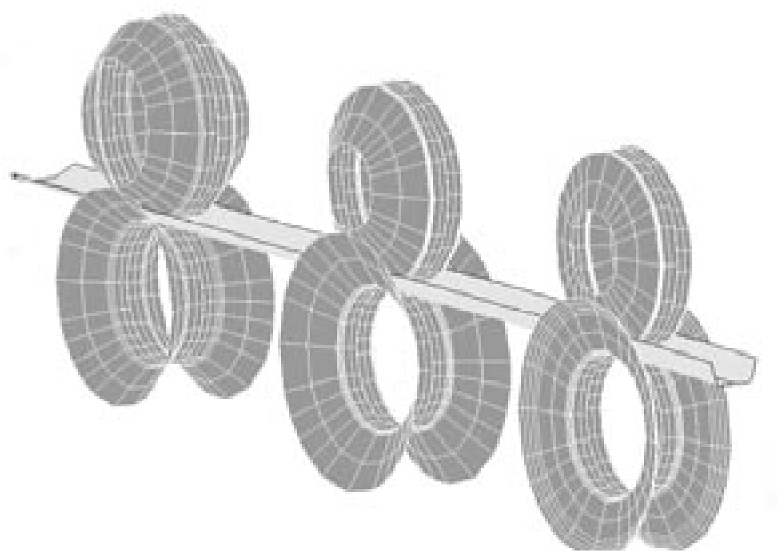
Modelling and Simulation of the Roll Forming Process



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Preface

This work has been carried out at Dalarna University. The financial support was provided by the Swedish Foundation for Knowledge and Competence Development (KK-stiftelsen), Jernkontoret, ORTIC AB and Dalarna University.

I would like to thank the following people:

My supervisor, professor Lars-Erik Lindgren for his experienced guidance and continual support.

Dr Lars Ingvarsson, for sharing his great experience in roll forming with me.

All colleagues at Dalarna University and ORTIC AB, for their friendship and for making the workplace a great place to be at.

Finally, I would like to thank my family for always being there.

Borlänge, June 2005

Michael Lindgren

Abstract

One of the first decisions to make when a new roll forming line is designed is the number of forming steps needed to produce a profile. This is dependent on the material properties, the cross-section geometry and the tolerance requirements. The tool designer wants to minimize the number of forming steps to keep reduce the investment cost for the customer. There are several computer aided engineering (CAE) systems on the market that can assist in the tool design process. These include simple formulas to predict the deformation during the forming. In recent years it has also been possible to use FE-analysis to investigate the deformations in the profile during the forming. The objectives with this thesis were to create a FE-model and improve the simple formulas and thereby give better design of roll forming machines.

A FE-model has been build to investigate the roll forming of a U-channel, paper A. The model has been used to investigate the longitudinal peak membrane strain and the deformation length when increased yield strength, paper B. The simulation shows that the peak strain decreases and the deformation length increases when the yield strength increases. In paper C a two-level factorial design is used together with FE-analysis to investigate which parameters that affect the peak strain and the deformation length. The parameters are used to create improved formulas for the peak strain and the deformation length.

Thesis

This thesis consists of a survey and the following three appended papers:

Paper A
M. Lindgren, Finite Element Model of Roll Forming of a U-channel, Presented at International Conferences on Technology of Plasticity, Verona, Italy October 2005

Paper B
M. Lindgren, Cold Roll Forming of a U-channel Made of High Strength Steel, Submitted to Journal of Materials Process Technology, June 2005

Paper C
M. Lindgren, An Improved Model for the Longitudinal Peak Strain in the Flange of a Roll Formed U-channel Developed by FE-analyses, Submitted to Finite Elements in Analysis and Design, June 2005

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Notation

a	=	Flange length
A	=	Integration constant
b	=	Web width
B	=	Integration constant
e	=	Longitudinal engineering strain in the edge of the flange
e_p	=	Longitudinal peak strain in the edge of the flange
e_t	=	Transverse longitudinal strain in the flange
h	=	The distance from the neutral layer to the inner side of the bend
k_1	=	Constant used in transverse bending
L	=	Deformation length
p	=	Perpendicular moment arm
R_1	=	Female tool radius
r	=	Distance from bend
r_0	=	Radius to the neutral layer
s	=	Parallel moment arm
t	=	The thickness of the material
W_b	=	Plastic work due to transverse bending
W_s	=	Plastic work due to longitudinal bending
W_t	=	The total plastic work for one bending
Y	=	Yield strength
z	=	Coordinate in longitudinal direction
x	=	Coordinate in transverse direction
Θ	=	Bend angle for the active bend
$\Theta_{1,2}$	=	Bend angle for the female tool
$\Delta\Theta$	=	Bend angle increment
Θ'	=	The derivate of the bend angle
α	=	Angle between the web and the infinite small element
β	=	Bend angle for the inactive bend
ε_{Ls}	=	Longitudinal stretching of the flange
ε_{Lb}	=	Longitudinal bending of the flange
ε_t	=	Strain due to transverse bending in the bending zone
γ	=	Shear strain in the flange

1. Introduction

1.1. The cold roll forming process

Cold roll forming (CRF) is a metal forming process which is spread throughout the world and today one can find roll forming products in numerous applications, for example buildings, vehicles, airplanes, furniture and domestic appliances, **Figure 1**. It is a highly productive process and the use of the process increases every year. The benefit of the process in comparison to other metal forming processes is that auxiliary operations such as punch, welding, clenching etc. can be included and thus it is possible to produce profiles which are directly ready to use.

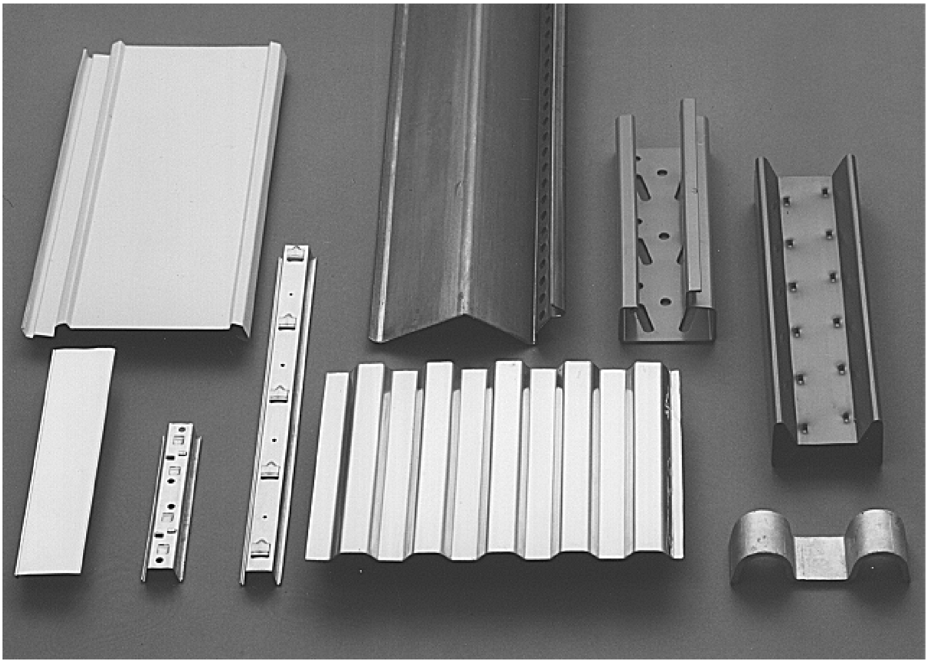

Figure 1. *CRF products can be find in many applications as vehicles, buildings, domestic appliances etc.*

In CRF the bending occurs in several steps from an undeformed strip to a finished profile, **Figure 2**. The forming is geometrical complex due to the forming does not only occur in the forming tools, but also between each forming stand. Due to the latter, this will cause the material in the flange to travel a longer distance than the material in the bending zone, **Figure 3**. This causes a longitudinal strain in the flange, which should not be plastic in order to avoid large, longitudinal residual stresses in the finished profile.

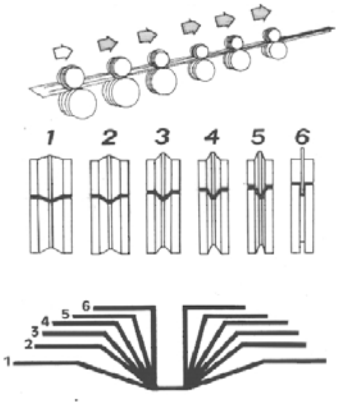

__Figure 2.__ The strip is formed in several forming steps, from an undeformed strip to a finished profile,[1].

All materials that can be bent can also be roll formed, for example aluminium, steel, stainless steel, copper etc. The material can be pre-painted or pre-coated. The speed that the profile can be produced in is between 15 m/min to 185 m/min, [2] depending on the tolerance of the cross-section, the material and how fast the machine can be fed with raw material or how fast the finished product can be removed from the run out table. The thickness of the material that can be roll formed is between 0.15 mm to 19 mm [3].

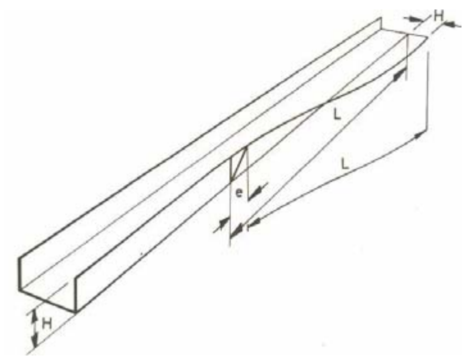

__Figure 3.__ The material in the flange will travel a longer distance than the material in the bending zone. That difference will cause a strain (e) in the flange. In the figure are (H) the flange length, (L) the deformation length and (e) the strain in the flange, [1].

The CRF process is very robust provide it is set up correctly. There are only small variations in the geometry of the produced profiles. However, the profile can have defects as bow, twist, flare, spring back and oil-canning, **Figure 4**, if the roll forming process is not well designed. Most of the defects depend on the number of forming steps being too small, which gives residual stresses in the profile causing unwanted deformations.

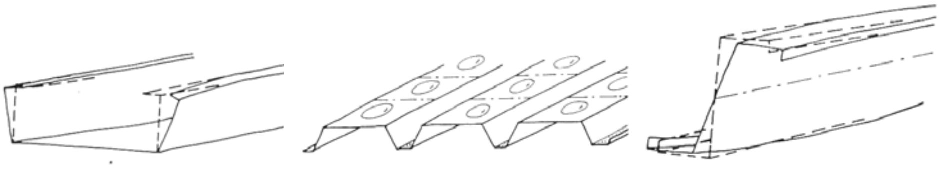

Figure 4. *Different defects that the finished profile can have, for example the number of forming steps are too few. From left, ''flare'', ''oil canning'' and ''twist'' [4].*

When a new roll forming machine is created the tool designer must decide how many steps that the forming of the profile requires. The number of steps is dependent on the cross-section, tolerances, the finish of the surface and the material properties. Today one can find several computer aided engineering (CAE) systems that can support the tool designer when creating tools. The CAE system uses simple formulas and "rules of thumb" for predicting the strain and stress in the profile.

For the past few years FE-analysis has been used to validate the design that the CAE system proposes. The disadvantage of FE-analysis in CRF is the large required CPU time. The profile can have a complicated cross-section and up to 40 forming steps, [5], can be needed. The simulation time can be as long as five to ten days. This is not practical for industrial use. In the future the FE-analysis will undoubtedly be used as a compliment to the CAE system when new CRF machines are created.

The tools for a CRF machine are expensive and therefore trail and errors when designing a machine are costly. An alternative is to use FE-analyses to investigate the strain and the stress in a formed profile. The result from the simulations can be used to improve the simple formulas and the ''rules of thumb'' that are used in the CAE systems. Improving these formulas will thus give a more correct information to the tool designer and thereby reduce costs.

1.2. Research question and approach

The research question for this thesis can be formulated as:

How should the CRF process be modelled and how can these models support the design of a roll forming line?

The research has focused on creating models that can predict the longitudinal strain in the flange and the deformation length during the forming of a U-channel. The models can then be implemented in a CAE system and improve the design of a roll forming line.

The approach used in this work has been to:

- Review the current state of the sciences in roll forming.
- Create a FE-model to simulate the CRF process.
- Investigate the yield strength influence of the strain and the deformation length using FE-analyses.
- Using factorial design to establish which parameters that influence the peak strain and deformation length and create models that can predict the longitudinal peak membrane strain and the deformation length.

2. Literature survey

In this chapter will a literature survey be presented. The chapter is dived into three parts, experimental work, theoretical work and FE - analyses of the CRF.

2.1. Experimental work

2.1.1 Strain histories in roll forming

The strain history, when forming a U-channel, in roll forming has been measured in several experiments, [6 - 8]. The experiments show, **Figure 5**, that the longitudinal flange strain starts between the forming stations and increases rapidly to a maximum value just before the centre of the forming station. The web strain has the same behaviour but the strain is more compressive. These strain decrease rapidly when approaching the roll centre. Some strains cause residual stresses giving defects on the finished profile. Chiang [6] also measured the longitudinal membrane strain across the strip when forming a U-channel and a V-channel. The measurement results that Chiang obtained showed that the strain was largest at the flange edge.

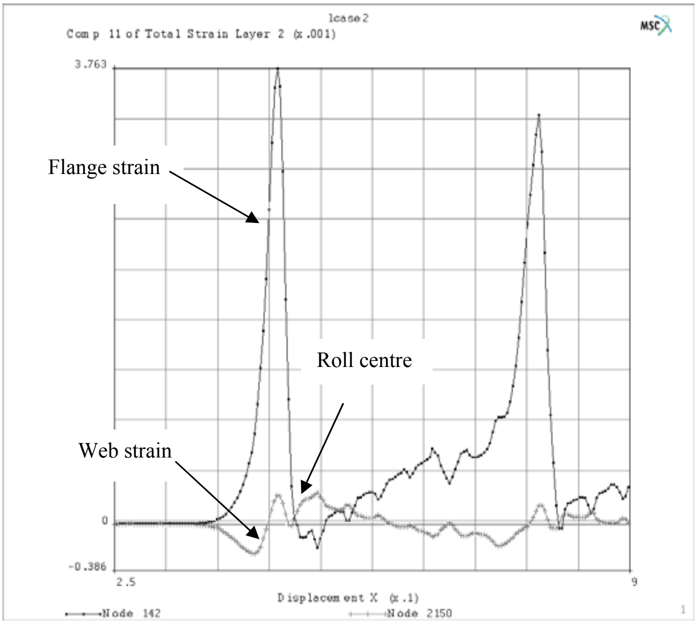

Figure 5. *In the figure is the strain histories for the longitudinal web strain and the longitudinal membrane flange strain presented for two forming stations.*

2.1.2 Longitudinal membrane strain

Bhattacharyya and Smith [7] investigated the longitudinal strain when a single roll station and multiple roll stations were used. They also investigated the strain variation with different bend angle and bend angle increments, **Figure 6**.

The conclusions were:

- For the case with a single roll station ($0°$ - $\Theta_1°$) the strain increased almost linear with the bend angle, $\Theta_1°$.
- When multiple roll stations were used ($0°$ - $\Theta_1°$ - $0°$), where the first and last forming steps were flat rolls, the longitudinal strain was reduced with 10% - 15% than in the case with a single station.
- With multiple roll stations ($0°$ - $\Theta_1°$ - $\Theta_2°$) the strain level was on the same level as for the case ($0°$- $\Theta_1°$- $0°$).
- The level of peak strain is dependent on the bend angle increment $\Delta\Theta° = (\Theta_2° - \Theta_1°)$ not the roll angle used at the roll station.

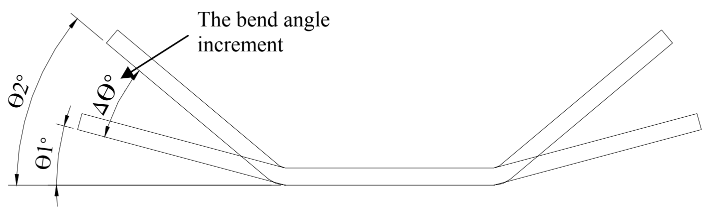

Figure 6. *The definition of the parameters for the bend angle and the bend angle increment.*

Chiang [6] investigated how the flange length (*a*), the web width (*b*) and bend angle (Θ) effected the web strain and the longitudinal membrane strain in the flange of a U-channel. A single roll station was used to study the bend angle and the result that Chiang obtained was similar to Bhattacharyya and Smith's. The longitudinal strain increased almost linear with the bend angle but the variation for the web strain was small. The experiment with varying flange length showed that the longitudinal strain decreases when the flange length increases. When the web width increased the longitudinal strain slightly decreased, **Table 1**.

Table 1. *The peak strain in the flange edge for various flange length and web width.*

Web (*b*)	Flange (*a*)	Average peak strain (10^{-3})
20	10	3.75
	15	3.10
	20	2.70
30	10	3.70
	15	2.85
	20	2.60

Zhu [9] investigated the flange length (*a*), material thickness (*t*), the bend angle (Θ) and bend angle increment ($\Delta\Theta$) influences on the longitudinal strain distribution in an experiment. The obtained results were:

- The longitudinal strain increase in the beginning for flange length shorter than 15 mm, for flange length over 15 mm the strain starts to decrease.
- When the material thickness increases the longitudinal strain increases.
- Increasing bend angle increment increases the longitudinal strain
- Increasing bend angle at constant bend angle increment decreases the longitudinal strain. For example is the longitudinal strain higher for 0° - 20° than for the case 20° - 40°. This was not obtained by Bhattacharyya and Smith [7].

2.1.3 Deformation length

Bhattacharyya *et al* [10] formed a U-channel and measured the deformation length, **Figure 7**, for mild steel and aluminium. They also compared the result with a model, Equation (1), which they had derived. The derivation of the deformation length will be reviewed in the section on theoretical work.

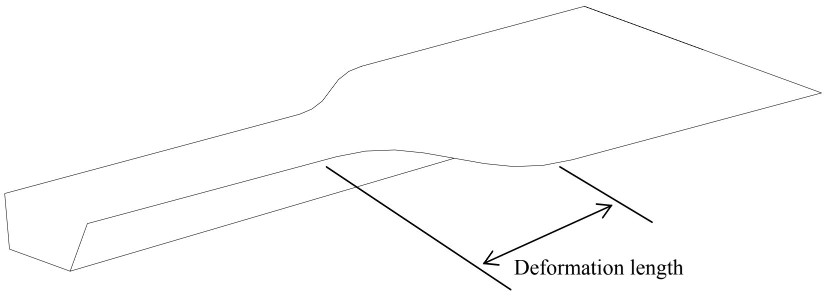

Figure 7. *Deformation length.*

$$L = \sqrt{\frac{8a^3\Delta\theta}{3t}} \qquad (1)$$

The conclusion was:

- It is a good agreement between the experiment and Equation (1). The error was in most cases around 6 %.
- Due to the good agreement they concluded that the deformation length (*L*) is dependent on the three variables, flange length (*a*), bend angle increment ($\Delta\Theta$) and material thickness (*t*), and independent of the material properties.

2.2. Theoretical work

2.2.1 Deformation types

In a bending operation is the major part of the deformation in a transverse direction. In roll forming which is also a bending operation but the bending occurs gradually one can find other deformation types besides deformation in the transverse direction. Paton *et al*. [11] propose four fundamental deformation types, longitudinal stretching, longitudinal bending, transverse bending and shear.

The following assumptions were made to derive the deformation types, **Figure 8** and **Figure 9**:

- The thickness of the strip is small compared to other geometrical dimensions.
- Bending only takes place in the fold line of the active bend.
- Deformation at the inboard side is neglected.
- The outboard region remains constant in the cross-section and rotates around the active bend.
- Transverse sections of the strip remain plane and the profile is bent as a beam. The latter means that cross-sections remain orthogonal to the centreline along the profile.

With help of the infinitesimal element of length *dz*, **Figure 8** and **Figure 9**, the following strain models were derived:

Longitudinal stretching

$$\varepsilon_{Ls} = \frac{1}{2} r^2 \left(\frac{d\theta}{dz} \right)^2 \qquad (2)$$

where the (r) is the distance from the bend.

Longitudinal bending

$$\varepsilon_{Lb} = h \left(s \left(\frac{d^2\theta}{dz^2} \right) - p \left(\frac{d\theta}{dz} \right)^2 \right) \qquad (3)$$

where (h) is the distance from the neutral layer to the inner side of the bend, (s) is parallel moment arm and (p) is the perpendicular moment arm.

Shear

$$\gamma = p \left(\frac{d\theta}{dz} \right) \qquad (4)$$

Transverse bending

$$\varepsilon_t = \frac{h}{r_0} \qquad (5)$$

where (r_0) is the radius to the neutral layer.

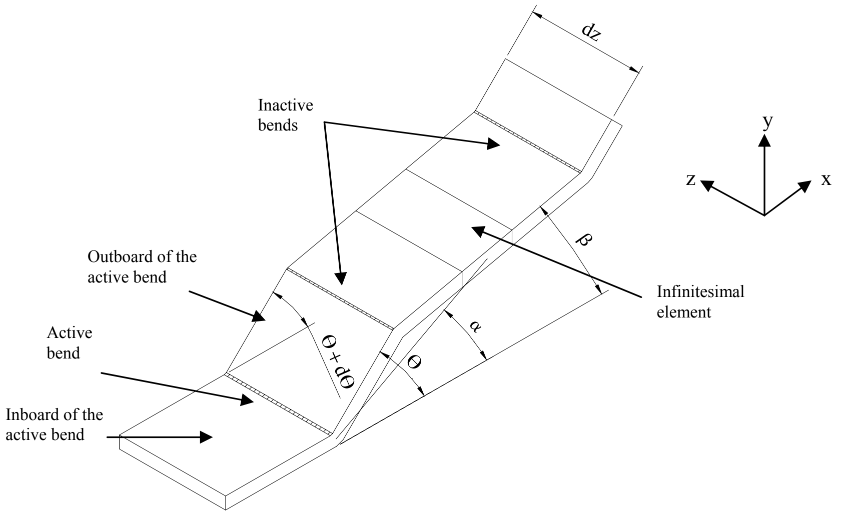

Figure 8. *An element strip between two roll forming passes.*

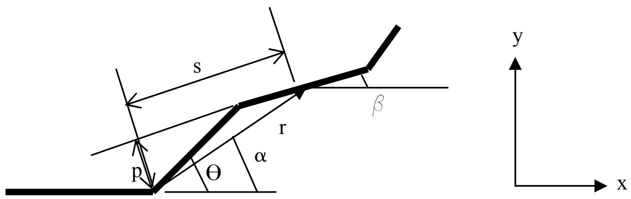

Figure 9. *View in z direction***.**

The conclusion by Paton *et al.* was that the shear strain is larger than the longitudinal strain in sections with inactive bends and must thereby be considered as a factor in roll forming. The shear strain is small for a simple section like a U-channel without inactive bends.

2.2.2 Deformation length

Bhattacharyya *et al.* [10] derived an expression for the deformation length (L), **Figure 7**, by minimising of total plastic work (W_t) for the bending in transverse and longitudinal direction. Their assumptions were:

- The material is rigid perfectly plastic.
- The bend only takes place along the fold line.
- Out of plane bending of the flange and the longitudinal bending of the web are neglected.
- The flange adopts a shape that minimises the plastic work.

Plastic work due to transverse bending

$$W_b = \frac{1}{4} Y t^2 \theta \qquad (6)$$

where (Y) is the yield strength.

Plastic work due to longitudinal bending per unit volume

$$W_S = \frac{1}{2} Yx^2 \left(\frac{d\theta}{dz} \right)^2 \qquad (7)$$

where (x) is coordinate in transverse direction.

Plastic work per unit length

$$W_S = \int_0^a \frac{1}{2} Yx^2 \left(\frac{d\theta}{dz} \right)^2 (tdx) =$$

$$= \frac{1}{6} Ya^3 t \left(\frac{d\theta}{dz} \right)^2 \qquad (8)$$

The total work done for one bend is

$$W_t = \int_0^L \left[\frac{1}{4} Yt^2 \theta + \frac{1}{6} Ya^3 t \left(\frac{d\theta}{dz} \right)^2 \right] dz \qquad (9)$$

The function $\Theta(z)$ that minimises the Equation (9) satisfies the Euler Equation (10)

$$\frac{dF}{d\theta} - \frac{d}{dz} \left(\frac{\partial F}{\partial \theta'} \right) \equiv \frac{d^2\theta}{dz^2} - \frac{3t}{4a^3} = 0 \qquad (10)$$

where $F = F(z, \theta, \theta') = \frac{t\theta}{4} + \frac{a^3}{6} \left(\frac{d\theta}{dz} \right)^2$

the general solution is

$$\theta(z) = \frac{3t}{8a^3} z^2 + Az + B \qquad (11)$$

The end conditions give the integration constants (A) and (B), $\Theta(0) = 0$, $\Theta(L) = \Delta\Theta$, $\Theta'(0) = 0$ and $\Theta'(L) = 0$.

The end conditions and Equation (11) gives the deformation length

$$L = \sqrt{\frac{8a^3 \Delta\theta}{3t}} \qquad (12)$$

where ($\Delta\Theta$) is the bend angle increment, (t) is the thickness of the material and (a) is flange length.

2.2.3 Longitudinal membrane strain

Chiang [6] developed two models, (A) and (B) for the longitudinal membrane strain, model (A) was based on the paper by Bhattacharyya *et al* [10], Equation (13), and a model (B) that Chiang derived by geometrical considerations, Equation (16).

Equation (2), Equation (12) and Equation (11) give the model (A)

$$e = \frac{9}{32}\left(\frac{t^2}{a^6}\right) r^2 z^2 \Bigg|_{0 \le z \le L}^{0 \le r \le a} \qquad (13)$$

The peak strain and transverse strain be obtained from Equation (13) in model (A). The peak strain for the flange edge, (*r = a, z = L*), is written:

$$e_p = \frac{3}{4}\left(\frac{t}{a}\right)\Delta\theta \qquad (14)$$

The transverse longitudinal strain at any position z is written:

$$e_t = k_1 r^2 \qquad (15)$$

where $k_1 = \frac{9}{32}\left(\frac{t^2}{a^6}\right) z^2$

Chiang compared the model (A) with an experiment and concluded that the model overestimated the strain three times too large when approaching the roll station.

The model (B) based on geometry for the engineering strain in the flange edge is written:

$$e = \sqrt{1 + \frac{3t}{4a\Delta\theta}\left(1 - \cos\Delta\theta\right)} - 1 \qquad (16)$$

The model predicts that the strain is uniform in the deformation zone and gives no information about the transverse strain. The model was compared with an experiment and it gave a closer approximation of the value of the peak strain than the model (A).

2.2.4 Geometrical restriction from the female tool

Zhu [9] studied how the geometry of the tool influences the bend angle in the flange of a U-channel. The forming was divided in to three stages, **Figure 10**, the first stage is where the bend angle does not change, the stage two is where the bend angle changes but the strip is not in contact with the tool and the third stage is when the strip is contact with the tool.

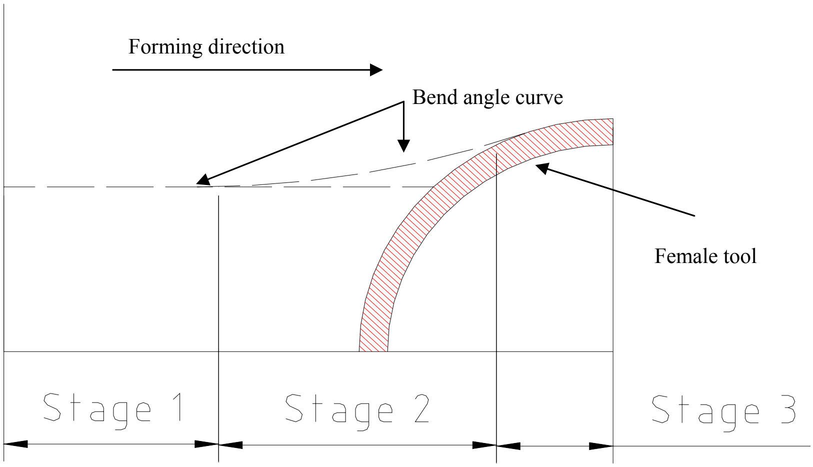

Figure 10. *The bend angle is divided in to three stages, stage one where the angle does not change, stage two where the angle changes but the strip is not in contact with the tool and stage three where the strip is contact with the tool.*

Zhu studied both horizontal and vertical rolls. The study of horizontal tool is discussed here. Zhu derived models for three cases:

a) The roll fully overlaps the outer edge of the flange.
b) The outer edge of the flange overlaps the roll at any position.
c) The outer edge of the flange overlaps the roll at initially.

Below is only case a) presented as cases b) and c) are not being used in practice.

The obtained model for the case a) is

$$z = L - \sqrt{\frac{a^2 \cos^2 \theta}{\cos^2 \theta_2} + 2aR_1 \frac{\sin(\theta_2 - \theta)}{\cos \theta_2} - a^2} \qquad (17)$$

Zhu assumed that the derivative for Equation (17) could be used to predict forming severity at the point where the strip contacts the female tool for the first time. The derivative is

$$\frac{d\theta}{dz} = \frac{L - z}{\frac{a^2 \sin 2\theta}{2\cos^2 \theta_2} + aR_1 \frac{\cos(\theta - \theta_2)}{\cos \theta_2}} \qquad (18)$$

The theoretical work was compared with the experiment and the conclusions were:

- A concept, the bend angle curve, was proposed and it good agreement between the predicted bend angle distribution and the experimental results was found.
- The longitudinal membrane strain reaches a maximum when the strip is in contact with the female tool for the first time.
- Increasing flange length will decrease the longitudinal membrane strain.

- Increased tool radius will decrease the longitudinal membrane strain.
- The longitudinal peak membrane strain increases with increased bend angle increment.
- Constant bend angle increment and increasing bend angle decreases the longitudinal peak membrane strain. But when the bend angle is close to 90° it has the opposite effect.

2.3. FE-analysis of roll forming

N. Rebelo *et al.* [12] compared the effectiveness of implicit and explicit finite element analysis in metal forming. The simulated U-channel was modelled with 4-node shells, 20 through the width and 40 through the length. The strip was pulled through three roll station and the rigid rolls rotated freely. The material was modelled as an elastic-plastic material with yield strength of 229 MPa and with Young's moduls of 206.7 GPa. The implicit finite element analysis was almost three times faster (47 CPU hours) than the explicit analysis (125 CPU hours). The conclusion was the implicit formulation has a relative advantage, due to the problem is very "one dimensional" and therefore having a small wave front.

Brunet *et al.* [13] developed a "master" 2D cross-section model with a "slave" 3D analysis. The 2D analysis was a generalised plane-strain analysis and for the 3D analysis was thick shell element used. The tools were modelled as rigid surface and instead of rotating tools they were modelled as continuously moving rigid surfaces from one forming station to the next station. The friction between the sheet and the tools was modelled as Coulomb friction. Both the 3D and the 2D analyses included Hill's anisotropic model of initial anisotropy with isotropic hardening. The computed longitudinal deflection was compared with measured in order to validate the model. They concluded that the difference between the model and the experiment was reasonable.

Heislitz *et al.* [14] used the explicit code PAM-STAMP to simulate roll forming. The strip was pulled through the rolls with constant speed. The rolls were not rotating and the friction between the strip and the rolls was ignored. Two different elements were tried, 8-node brick elements and four node shell elements, in the final simulations the used 8-node brick element. The tools were modelled with rigid 4-node shell elements. The mass density was increased with a factor 100 without inertia effects affecting the result. The material model used was Swift's isotropic strain hardening and Hooke's law. The simulations were compared with an experiment and the maximum deviation was about 10 %. The conclusions from the simulations were:

- The adaptive mesh refinement can help to speed up the simulation.
- "At the current status of development, the simulation of roll forming by using PAM-STAMP is not very efficient due to the required CPU time". The simulation time for a U-channel was 250 CPU hours.
- FEM code PAM-STAMP can accurately be used to simulate roll forming. It is possible to obtain both the strain distribution and the final geometry after spring back.

Sukmoo *et al.* [15] used the finite element program (COPRA FEA-RF) to simulate the roll forming of a U-channel and compared the deformation length with an experiment available in literature. The FE-program COPRA FEA-RF is a rigid-plastic finite element analysis that uses a combined 2D and a 3D algorithm. The conclusion from the studies was that the work hardening exponent has the most significant effect on the forming length. Increasing work hardening exponent gives increasing forming length. Sukmoo *et al*. also concluded that it was a good agreement between the simulation results and the experiment.

Alsam *et al.* [16] utilised the FE-code EPFEP3, which is a 3D implicit elastic-plastic FE program, to developed a remeshing technique to simulate roll forming. A dual mesh was used, one mesh for storing the deformation history and another for FE computational. The conclusion for the simulation with remeshing was the computational time was much less when compared to a conventional FE-model. The result from the simulation was also acceptable compared computations with out remeshing.

3. Summary of appended papers

3.1. Paper A

FINITE ELEMENT MODEL OF ROLL FORMING OF A U-CHANNEL PROFILE

A FE-model is created and the result from the simulations is compared with knowledge about the process from the literature. The simulation starts from an undeformed strip and ends when a U-channel has been formed. The model includes friction and the tools are rigid rotating surfaces, which is an improvement compared to models used in the literature. The strip is modelled with thick shell elements which accounts for transverse shear stress. An elastic-plastic material model is used, the hardening is isotropic and the von Mises yield surface and the associated flow rule is used.

The conclusion from the simulations was, that a model of the CRF process has been successfully developed and the simulation time is acceptable for research but still too long for industrial use. The result from the simulation agrees well with existing knowledge about the process and the model can be used to further investigate important parameters. Thereby, can the model be used to improve existing design rules.

3.2. Paper B

COLD ROLL FORMING OF A U-CHANNEL MADE OF HIGH STRENGTH STEEL

The change of the longitudinal peak membrane strain at the edge of the flange and the deformation length investigated when the yield strength increases are investigated in this paper. This is done by FE-analyses using the model developed in paper A. The result from the simulations show that the longitudinal peak membrane strain decreases and the deformation length increases when the yield strength is increased.

The conclusion is that it is beneficial to use high strength steel in roll forming as the profile will require fewer forming steps than when mild steel is used. The result from the simulations can also be used when deciding how many forming steps that are needed to form a U-channel without residual stresses in the flange. The simulation result in this study can explain why Ingvarsson [17] obtained a straight V-section when ultra high strength steel was roll formed. This is in contrast to some existing design formulas that predict that the yield strength of the material does not affect the flange strain in roll forming.

3.3. Paper C

AN IMPROVED MODEL FOR THE LONGITUDINAL PEAK STRAIN IN THE FLANGE OF A ROLL FORMED U-CHANNEL DEVELOPED BY FE-ANALYSES

A factorial design and FE-analyses are combined to investigate which parameters that affect the longitudinal peak membrane strain and the deformation length. The result is used to created simple models relation them to process parameters. The models are then compared to the result from paper A and paper B and they agree well.

The conclusion is that the created simple models can easily be implemented in a CAE system and improve the design of the roll forming lines for a U-channel. The approach can also be used to develop design rules for forming of other profiles.

4. Discussion and future work

Roll forming is a process that is used worldwide and the use of the process increases every year. However, the understanding of the roll forming process is limited and so is the science about the process. The reason for this is that the complex geometry of the process has made it difficult to develop simple models for how the strip will be formed. Only a few analytical models for the strip deformation are found in the literature. The models are limited to more simple sections and large assumptions are made for the assumed pattern and the material behaviour.

Another approach to investigate the deformation in the strip is to use FE-analyses. Very little has been published about FE-analyses of roll forming. This may be due to the fact that the simulations are still very time consuming. The current work shows that it is possible to simulate the process in reasonable time for use in research. Still the simulations are too demanding for everyday use in the industry. However, the use of FE-analyses will undoubtedly become more common with the advancement of computing power.

The research question was;

How should the CRF process be modelled and how can these models support the design of a roll forming line?

It has been found that the FE-method is an appropriate approach to investigate roll forming. A FE-model has been created and used to investigate the deformation in the strip during the forming of a U-channel. These analyses have been used to create improved design formulas to predict the longitudinal peak membrane strain and the deformation length. The models can be implemented in a CAE program to improve the tool design process.

The developed FE-model is believed to be correct, based on comparison with existing knowledge about the CRF process, and more accurate that existing models. However, the future work will include experimental investigations in order to validate FE-models in detail. This will enable further development of the model.

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PAPER A

FINITE ELEMENT MODEL OF ROLL FORMING OF A U-CHANNEL PROFILE

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Summary

Cold roll-forming (CRF) is a highly productive process and therefore an interesting metal forming process. CRF products can be found in many applications like buildings, furniture and vehicles. However, it is a geometric complex process and therefore the knowledge that has been obtained through simple models is limited. The use of FE models to simulate sheet metal forming processes in general is common but not in case of CRF. Finite element models can be used to enhance the understanding of the process and as design tools. They can also be used to create simpler design rules.

The objectives of this study are to create a model that can be used to predict the longitudinal membrane strain in the flange and to analyse the contact between the tools and the strip. This strain is important as it determines the number of forming steps needed to form the profile.

The created finite element model accounts for friction and elasto-plastic deformations of the strip. The rotating tools are assumed to be rigid. The strip is modelled with thick shell elements and the simulations start from an undeformed strip to a finished U-channel.

Keywords: Cold roll forming, Finite element analysis, Computer simulation

1 Introduction

In cold roll forming (CRF) the sheet is continuously and progressively formed in several forming stands from sheet metal to a finished cross section, **Figure 1**. The number of forming steps needed to obtain a wanted cross-section is the first choice when designing a CRF machine. They depend on the wanted cross-section, thickness and the material. Other important parameters are spring back, deformation length and longitudinal membrane strain in the flange. The longitudinal membrane strain develops as the profile is successively formed. The material in the edge of flange will travel a longer distance ΔL than the material in the bending zone between the forming stands, **Figure 2**. This strain should not be plastic in order to avoid wave edge or another defect on the finished profile. If plastics strains are present, then more forming stands are needed.

Today there are several computer programs available on the market that can support the design of CRF machines. The programs are based on "thumbs of rules" and simplified formulas. However, only limited conclusions can be drawn based on these programs due to the complex geometry of the formed strip and the simplifications in their design rules. The finite element method can be used to increase the knowledge of the roll forming process.

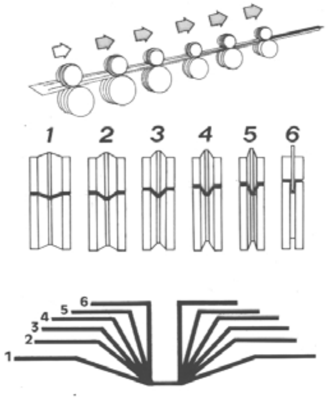

Figure 1. The strip is successively formed in several steps, from an undeformed strip to a profile, from [1].

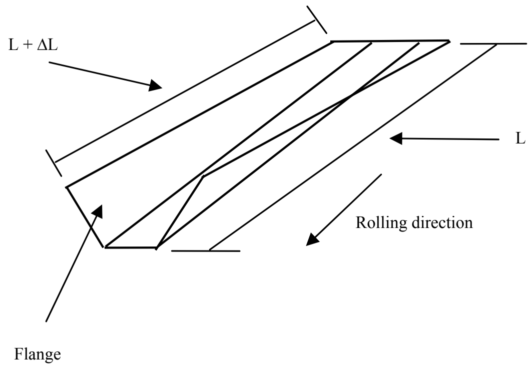

Figure 2. *The material in the edge of the flange will travel a longer way ΔL than the material in the bending zone.*

2 Previous work

Rebelo *et al.* [2] studied implicit and explicit finite element formulation used in metal forming process simulations. The advantage of explicit formulation is that the analysis cost increases in direct proportion to the size of the mesh. Whereas in the implicit formulation it increases with the square of the wave front times the degrees of freedom. They concluded that in roll forming the wave front is small due to the problem being very one dimensional. Therefore the simulation was faster with implicit formulation when CRF was simulated.

McClure and Li [3] simulated roll forming with the ABAQUS software and compared the result with experiments from Bhattacharryya and Smith [4]. The model ignored friction between the tools and a horizontal force was applied in the leading edge to pull the material through the roll stations. The obtained membrane strain was similar to the experiments by the latter.

Heislitz *et al.* [5] used the code PAM-STAMP to simulate the roll forming process. The strip was pulled through the rolls with a constant speed, without friction and without rotating tools. The explicit FEM code was used. They tried both eight node brick element and shell element and they also concluded that re-meshing reduced the simulation time when they used shell elements. They concluded that ‘‘at the current status of development, the simulation of roll forming by using PAM-STAMP is not very efficient due to the required CPU’’.

Brunet *et al.* [6] tried a specially developed FEM code, PROFIL. It used a ‘master’ 2D cross-section analysis with a ‘slave’ 3D shell analysis between two or four successive roll stands. The tools were modelled as rigid surfaces and they were not rotating. The forming of one thin channel, one thick channel and a circular tube were simulated. The calculated peak strain in the flange overestimated the experimental values with 10-30%.

Alsamhan *et al.* [7,8] have developed a re-meshing technique to simulate CRF. The result from the simulation showed that re-meshing can reduce the computer simulation time.

3 Finite element model

In this study a CRF process has been modelled with the FE package MARC/MENTAT [9].

3.1 The geometry

The model consists of six forming stands and two stands where no forming occurs. The latter are used as a belt feeder to the six forming stands. The forming starts from an undeformed strip and ends with a finished symmetrical U – channel, **Figure 3**. The distance between each of the forming stands is 330 mm.

To simulate the CRF process the geometry was generated with the ORTIC CAE system [10]. The tools are then modelled as rigid surfaces in the FE program.

The strip is 1.502 mm thick, the width is 31.8 mm and the length is 1000 mm. To obtain a steady state condition three rolls shall be engaged in the same time, therefore the chosen length of the model. Due to the symmetry, only one half of the geometry is modelled.

The strip is modelled with 2750 thick shell elements. The element's size is 4*1 mm in the bending zone and in other regions the element's size is 4*4 mm.

The strip is modelled with a bilinear thick shell element type number 75 [9]. This is a four node element that calculates membrane strains and the curvatures at the middle surface. The element can also account for transverse shear strains. The element can be used in curved shell analysis and due to the simple formulation the element is not so expensive [9]. Therefore is the shell element 75 attractive for the CRF simulations. Three layers of integration points are used in the thickness direction.

The initial angular speed of the tools is 10 rad/s which gives the strip a speed of 0.6 m/s. The speed is increased by 0.5% in every forming stand in order to counteract buckling between the stands.

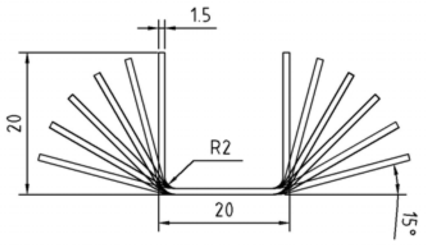

Figure 3. Flower pattern for the used geometry, six forming stands are used. The forming steps are from 0 - 90 degrees in steps of 15 degrees.

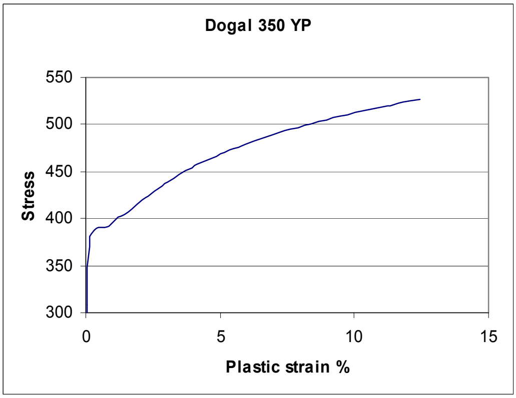

Figure 4. *Stress - strain curve for Dogal 350 YP.*

3.2 Material model

An elastic-plastic material model where the material hardening is isotropic and the von Mises yield surface and the associated flow rule is used. The tensile test data for the used material is shown in **Figure 4**. The material is cold forming steel, Dogal 350 YP. Stress versus plastic strain for the material is implementing as a table in the FE program.

3.3 Contact

In roll forming the tools are lubricated to minimise the wear on the tools and the strip. The lubrication type is boundary lubrication. This is assumed to correspond to a friction coefficient of 0.1. The friction model is Coulomb friction.

The clearance between the tools is 1.5 mm and the strip is 1.502 mm thick. That gives a contact pressure of 280 MPa.

3.4 Reduction of CPU time

Two solvers were tested, a direct sparse solver and a multifrontal sparse solver with bandwidth optimisation metis. The direct sparse solver is the better one. The computer simulation time was reduced by 30% with this solver.

The rolling contact between the tools is small in roll forming which leads to a number of iterations to find contact. Separation between the tools and the strip also occurs regularly. These contact situations make the required CPU time sensitive to the choice of the contact tolerance. It also depends on the tool radius and the element size. After trial and error a value of about 4% of the thickness was found to be appropriate.

4 Result and discussions

The simulation has been performed on a 2 GHz computer with 512 Mb RAM. Thirty-four CPU hours were needed to finish the simulation above.

The longitudinal membrane strains in the edge of the strip increase between the stands then drop just before the contact between the upper and lower tools, **Figure 5**. This result is similar to earlier papers that have been written about FE simulations of CRF [3], [5].

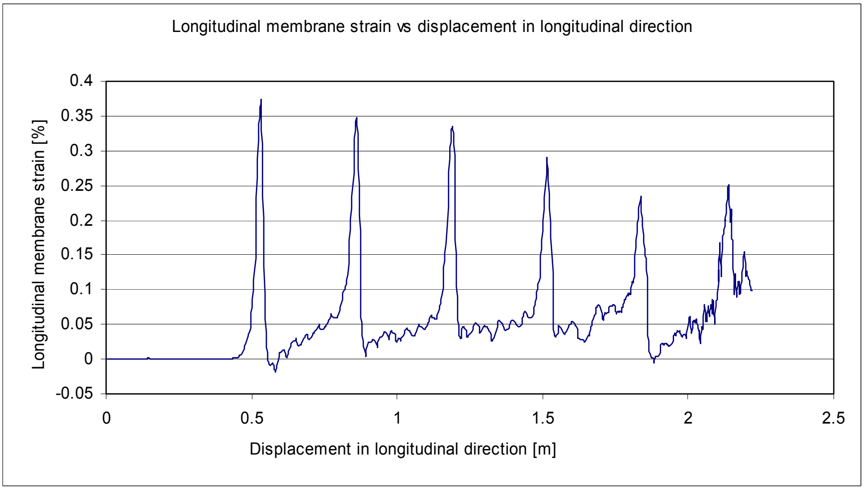

Figure 5. *The longitudinal membrane elastic - plastic strain in the edge of the strip in six forming stands. Constant forming steps are used (15 - 30 - 45 - 60 - 75 - 90).*

When the strip is in contact with the lower tool for the first time the strain will drop from a maximum value and compress until the contact zone between the upper and lower tools is reached. This is in agreement with what Bhattacharyya and Smith observed [4].

It has been known that the tool radius influences the membrane strains in the flange. A smaller radius gives a more severe forming as the material will not roll smoothly into the tool. Zhu [11] obtained a model for the lower tool geometry and proposed a bend angle curve for the lower tool. The derivative of the bend angle curve at the point where the strip is in contact with the lower tool for the first time, shows how severe the forming is.
The tool radius is included in his model and it predicts more severe forming when the lower tool radius decreases. Zhu also concluded that the peak strains will decrease when constant forming steps are used. This agrees with the result from the simulation in this study, **Figure 5**.

5 Conclusion

A model of the CRF process, which includes friction and rotating tools, has been successfully implemented. The simulation time is acceptable for research but still too long for industrial use.

The results from the simulations agree well with existing knowledge about the process. The model can be used to further investigate important parameters as flange length, thickness of the material, Young's modules, yield strength and contact conditions. Thereby, the model can be used to improve existing design rules.

6 Acknowledgements

The author thanks ORTIC AB, Knowledge foundation, Jernkontoret and Dalarna University for their technical and financial support.

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PAPER B

COLD ROLL FORMING OF A U-CHANNEL MADE OF HIGH STRENGTH STEEL

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Abstract
Cold roll forming (CRF) is a bending process where the bending occurs gradually in several forming steps from an undeformed strip to a finished profile. The process is very interesting for the sheet metal industry due to the high speed in which the profile can be produced. High strength steel has, in recent years, become more common in CRF. These materials have advantages but also disadvantages that affect the design of the CRF process.

The objectives of this study are to investigate the change in the longitudinal peak membrane strain at the flange edge and the deformation length when the yield strength increases. These are important since they can be used to determine the number of forming steps and the distance between them when designing the CRF machine. The result from the simulations shows that the longitudinal peak membrane strain decreases and the deformation length increases when the yield strength is increased.

Keywords: Cold roll forming, High strength steel, Finite element analysis

1 Introduction
In cold roll forming (CRF) a profile is formed in several forming steps from an undeformed strip to a finished profile, **Figure 1**. The forming process is geometrically complicated due to the fact that the forming does not only occur in the tools but also between each forming stand. When creating the tools the tool designer must decide how many forming steps the profile demands. The number of steps is dependent on the shape of the cross section, tolerance, thickness and the material properties.

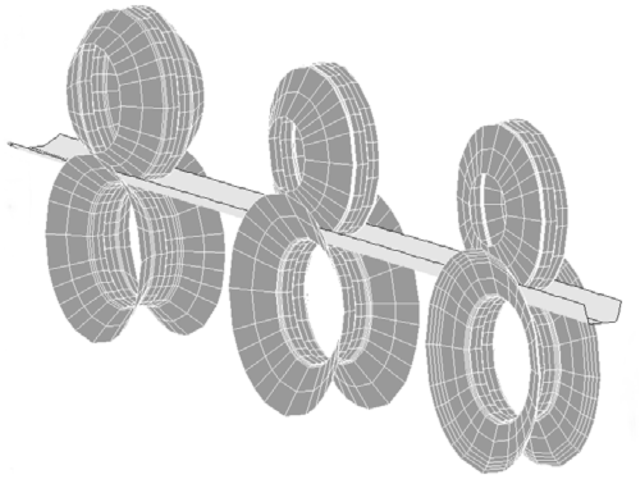

Figure 1. *The profile is formed in several forming stands from an undeformed strip to a finished profile.*

It is important to minimise the number of steps as this reduces the cost of the CRF machine. Then the CRF process can be a competitive alternative also for smaller production volumes. Therefore the knowledge of how high strength steel affects the number of forming steps is important.

Existing relations between the longitudinal peak membrane strain, deformation length and the yield strength of the material have been investigated and compared with finite element analysis in this study.

2 Notations

L	=	Deformation length
a	=	Flange length
t	=	Thickness of the strip
θ	=	Bend angle
r	=	Distance from the bending zone
z	=	Distance from where the bending starts
ε	=	The longitudinal membrane engineering strain at the flange

3 Background

The strip is formed in several steps and that will cause longitudinal strain in the flange. The strain develops as the material in a flange of a profile will travel a longer distance than the material in the bending zone. The longitudinal strain will have a peak value just before the contact zone between the upper and lower tools. Panton *et al.* [1] concluded that the longitudinal peak strain occurs when the strip is in contact with the tools for the first time. The peak strain should not be plastic as plastic strain will give a residual stress that causes defects on the profile as wave edges, longitudinal curvature, etc.

Bhattacharyya *et al.* [2] created a model of the deformation length by minimising the total plastic work for a U-channel. The obtained model predicts that the deformation length is independent of yield strength. It is written as

$$L = \sqrt{\frac{8a^3\theta}{3t}} \qquad (1)$$

Chiang [3] derived a model for the longitudinal engineering strain in the flange based on minimising of the plastic work due to stretching and bending of the profile. It is written as

$$\varepsilon = \frac{9}{32}\left(\frac{t^2}{a^6}\right) r^2 z^2 \left\} \begin{matrix} 0<r<a \\ \\ 0<z<L \end{matrix} \right. \qquad (2)$$

The model overestimated the strain when the strip approached the tool. Therefore Chiang derived an improved expression by a geometrical consideration for the peak strain, leading to

$$\varepsilon = \sqrt{1 + 2\left(\frac{a}{L}\right)^2 (1 - \cos\theta)} - 1 \qquad (3)$$

This model showed that the longitudinal strain is uniform in the deformation zone. All models predict that the behaviour is independent of the material properties.

Ingvarsson [4] compared mild steel with ultra high strength steel in an experiment where a V – section was cold roll formed with the same number of forming stands. The ultra high strength steel gave a straight profile, but not the mild steel. The conclusion was that fewer forming stands could be used when ultra high strength steel is being roll formed.

4 Approach

FE simulations are used in the current study to evaluate the yield strength influence on peak strain and deformation length. Since the analytical formulas for longitudinal peak membrane strain do not account for the yield strength

Several papers have been written about the FEM simulation on cold roll forming for example [5], [6], [7].

5 The finite element model

Fourteen different simulations have been carried out with varying yield strength and bend angle, **Table 1**. The FE package MARC/MENTAT was used to perform the simulations.

Table 1. *Series of experiments where the forming steps are 0° - 10° - 10° and 0° - 20° – 20°, when seven different yield strengths are used.*

	0°-10°-10°	0°-20°-20°
200 MPa	x	x
400 MPa	x	x
600 MPa	x	x
800 MPa	x	x
1000 MPa	x	x
1200 MPa	x	x
1400 MPa	x	x

The simulation starts from an undeformed strip and stops when the material reaches the second forming step. The total-, plastic- and elastic longitudinal peak membrane strain at the edge of the flange, are evaluated.

5.1. The geometry

The model consists of four forming stands where the two first stands are used as a belt feeder to the other. Due to the symmetry only half of the strip is modelled.

The strip is modelled with 1600 thick shell elements. The mesh size is 4*1 mm in the bending zone and in other regions the mesh size is 4*4 mm.

The length of the strip is 800 mm so that the forming steps 0° - 10° - 10° and 0° - 20° - 20° are engaged at the same time when the simulation has come to an end. The cross section geometry of the strip, see **Figure 2**.

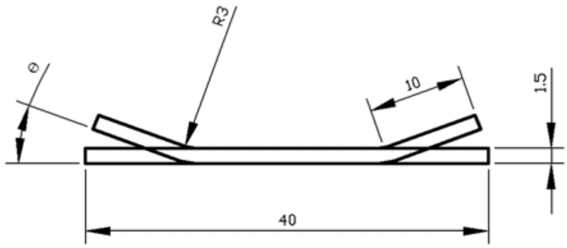

Figure 2. The geometry of an undeformed strip and a strip that has been formed.

The strip is modelled with a bilinear thick shell element type number 75 [8]. This is a four node element that calculates the membrane strain in the middle surface. Three layers of integration points are used in the thickness direction.

The tools are modelled as rigid surfaces and they rotate, giving the strip an initial speed of 0.6 m/s. The speed is then increased by 0.5 % in each forming stand to counteract buckling.

5.2. Contact

The clearance between the tools is 1.5 mm and the strip thickness is 1.504 mm which gives a contact pressure of 560 MPa. The friction is modelled as Coulomb friction and the friction coefficient is 0.1.

5.3. Material model

The material is modelled as an elasto-plastic material. The material hardening is isotropic and the von Mises yield surface and the associated flow rule are used. The tensile test data for cold forming steel is implemented in the FE program as a table. The yield strength is then scaled so the material starts to yield in seven different points from 200 MPa – 1400 MPa, **Figure 3**. The model account for large deformations and strains. An additive decomposition of total strain rate into elastic and plastic stain rates is assumed.

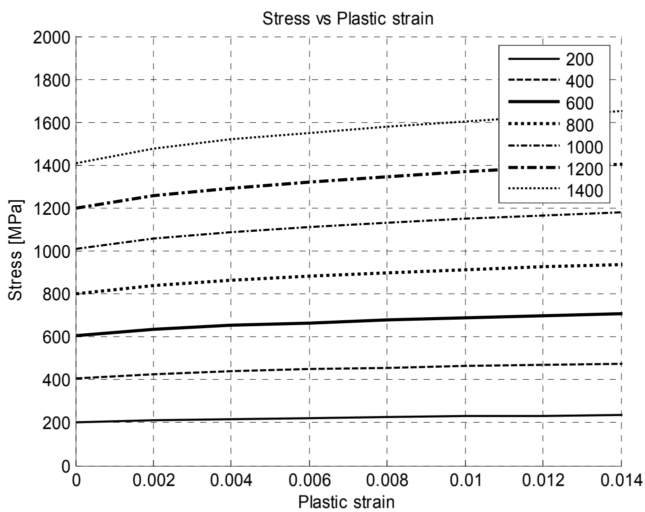

***Figure 3**. The tensile test data for seven different materials. They have been implemented in the FEM program as a table.*

6 Result and discussion

The simulations show for a bend angle of 10° that the total (plastic and elastic) strain decreases when the yield strength increases, **Figure 4**. The total strain decreases more in the beginning when plastic strain is present.

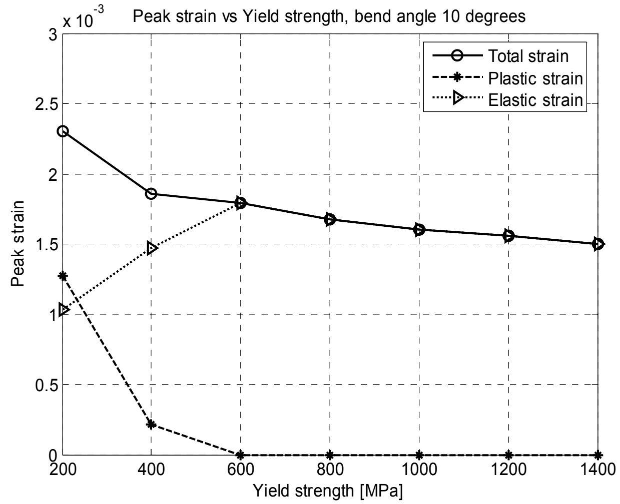

***Figure 4**. When the yield strength increases the longitudinal peak membrane strain will decrease. When the plastic strain goes to zero the total strain will flatten out and the strain is purely elastic.*

In **Figure 5** the bend angle is 20° and behaviour is similar as in **Figure 4**. The difference between the cases is that the strain becomes purely elastic at higher material yield strength. The strain is also greater for a bending angle of 20° which agree with Chiang [3].

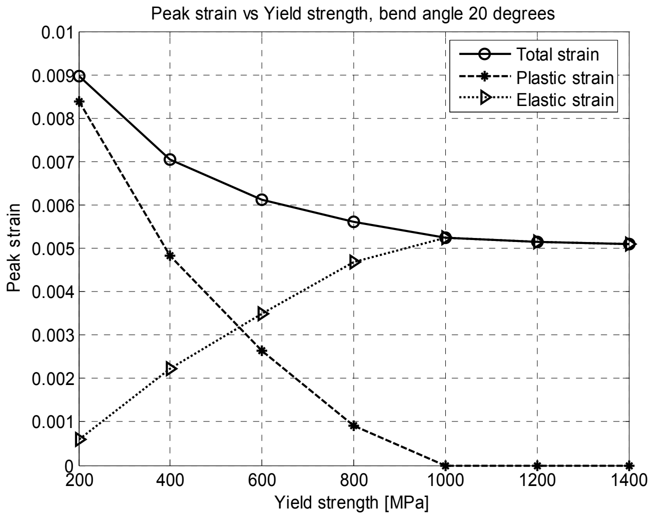

***Figure 5**. The behaviour for the longitudinal peak membrane strain is similar as for the case with a forming step of 10°. But now is the curve for the elastic and plastic longitudinal peak membrane strain displaced to a higher level of yield strength.*

The deformation length, Equation (1), is the distance between where the transverse bending starts and the forming stands. In this study a strain based deformation length is used. It is defined as the distance from the forming stand to the point in the flange edge where the strain is greater than 2e-5. The strain based deformation length for the cases 10° and 20° will increase when the yield strength increases, **Figure 6**. The length is greater for the bend angle 20° than 10° which agrees with Bhattacharyya *et al.* [2].

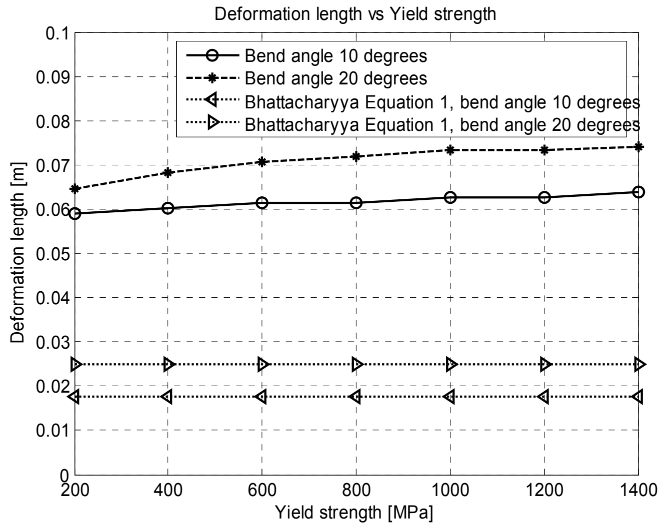

Figure 6*. The Deformation length for bend angel 10° and 20° will increase when the yield strength increases. The length is greater for bend angle 20°.*

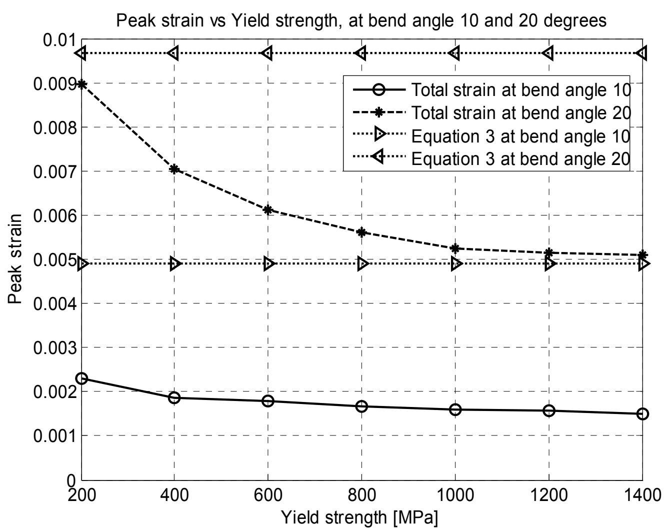

Figure 7*. The simulations are compared with the model Chiang derived, Equation (1), and one can see that they not agree well.*

In **Figures 6 and 7** the simulation results for the peak strain and the deformation length are compared with the models, Equations (1 and 3), that Bhattacharyya *et al.* and Chiang derived. One can see that they do not agree due to the large simplifications in the assumed pattern and material behaviour in their models [2], [3]. The assumptions for the deformation length were:

- The material is rigid perfectly plastic.
- Bending takes place only along the fold-line.
- The longitudinal bending of the web and the out-of-plane bending of the flange can be neglected.
- The flange adopts the shape that minimise the plastic work.

The model for the peak strain, Equation (3), has the additional assumption that the flange edge remains straight during the deformation.

7 Conclusions

The longitudinal peak membrane strain decreases, the deformation length increases for materials with higher yield strength. This information has not been possible to obtain from simple models as in Equations (1-3). This makes it possible to use fewer forming steps for high strength steels. However, high strength steel has a larger spring back that has to be accounted for.

The result from the simulations can be used to decide how many forming steps that are needs to form a U-channel, with minimum of plastic strain in the flange. For example in **Figure 5** one can see if the yield strength is 1000 MPa the bend angle step can be 20° instead of 7° - 15° which are more common when designing tools for a U-channel.

The simulation results in this study can explain why Ingvarsson [4] obtained a straight V-section when ultra high strength steel was used.

8 Acknowledgement

The author thanks ORTIC AB, Swedish Knowledge Foundation, Jernkontoret and Dalarna University for their technical and financial support.

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PAPER C

AN IMPROVED MODEL FOR THE LONGITUDINAL PEAK STRAIN IN THE FLANGE OF A ROLL FORMED U-CHANNEL DEVELOPED BY FE-ANALYSES

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Abstract

Today one can find cold roll forming (CRF) products in many applications, for example vehicles, furniture and in the building industry. Though CRF is a well known sheet metal process it is still not entirely understood due to the geometrically complex forming. There are several computer aided engineering (CAE) programs on the market that can assist the tool maker when designing a new CRF machine. However, they are often based on simple formulas when predicting the stress and the strain in the strip.

The main objective of this study is to improve formulas for the longitudinal peak membrane strain and the deformation length when a U-channel is formed. These are important since they can be used to determine the number of forming steps and the distance between them. A two-level factorial design is done using the finite element analysis to investigate which parameters that affect the peak strain and the deformation length. The parameters are then used to build models for the peak strain and the deformation length.

Keywords: Cold roll forming, Factorial design, Finite element analysis

1 Notations

a	=	Flange length
t	=	Thickness of the strip
S	=	Yield strength
Θ	=	Bend angle
Θ_2	=	Bend angle of the female tool
$\Delta\Theta$	=	Bend angle increment
R	=	Fictive tool radius
r	=	Tool radius
K_i	=	Constants
A,B	=	Integration constants
z	=	Cartesian coordinate in longitudinal direction
L	=	Deformation length
L_S	=	Strain based deformation length
y	=	Distance from the bending zone to the flange edge
e	=	Engineering strain

2 Introduction

In cold roll forming (CRF) is the sheet continuously formed in several forming steps from the sheet metal to a finished cross section. Due to the geometrically complex forming the research about CRF is limited. The knowledge of how the tools shall be designed is mainly based on the experience of the toolmaker. Today there are several computer aided engineering (CAE) programs available on the market that can support the toolmaker when designing the tools for the CRF machine. The computer programs are usually based on simplified formulas.

Some research has been done to simulate the CRF process by using the finite element analysis [1 - 3]. There are also CAE programs that can offer a module based on the finite element method (FEM) that can simulate the CRF process based on the geometry generated by the CAE program. The disadvantage of FEM in CRF simulations is that the profile can have a complicated cross-section and some times are up to forty roll stands needed to complete the finished section, thus the simulation time becomes long. However, FEM analysis will be a competitive alternative in the future and is today an excellent tool to use in research to increase the knowledge about the CRF process. The objective of this work is to use FE-model to improve existing formulas for the longitudinal peak strain in the flange of a formed U-shape cross-section. These are important concerning the number of forming steps and the distance between them.

3 Background

Longitudinal strain develops in the flange of a roll formed cross-section due to the material travelling a longer distance Δz in the flange than in the bending zone as shown in **Figure 1**. The strain depends on how many forming steps that are used, material properties, wanted cross-section and thickness of the material.

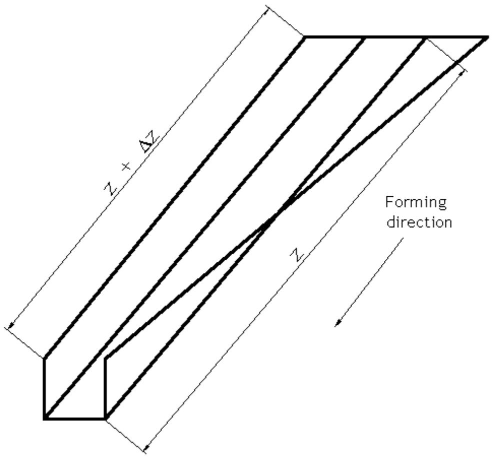

Figure 1. *The material will travel a longer distanceΔz in the flange than in the bending zone.*

Bhattacharyya *et al.* [4] studied a channel section and derived a model for the bend angle distributed between two roll stations by minimising the total plastic work due to bending and stretching. It is written as

$$\theta(z) = \frac{3t}{8a^3} z^2 + Az + B \qquad (1)$$

where (z) is Cartesian coordinate in longitudinal direction, (t) is the thickness and (a) is the flange length.

From this and the known boundary conditions Bhattacharyya *et al*. could obtain a model for the deformation length

$$L = \sqrt{\frac{8a^3 \Delta\theta}{3t}} \qquad (2)$$

where ($\Delta\Theta$) is the increment in the bend angle.

The model predicts that the material properties do not affect the length. In the same study they derived a model for the engineering longitudinal strain in the flange of a profile. It is given by

$$e = \frac{1}{2} y^2 \left(\frac{d\theta}{dz} \right)^2 \qquad (3)$$

where (y) is the distance form the bending zone to the flange edge.

Chaing [5] created another relation for the longitudinal strain in the edge of the flange with help of Equation (1-3). This expression is

$$e = \frac{9}{32} \left(\frac{t^2}{a^6} \right) y^2 z^2 \Bigg|_{0<z<L}^{0<y<a} \qquad (4)$$

Chaing compared the model with an experiment and he concluded that the model predicts a peak strain about three times larger than the measured.

Zhu [6] studied the female tool geometry and obtained an implicit bend angle curve model for the female tool, which is

$$z = L - \sqrt{\frac{a^2 \cos^2 \theta(z)}{\cos^2 \theta_2} + 2ar \frac{\sin(\theta_2 - \theta(z))}{\cos \theta_2} - a^2} \qquad (5)$$

where (Θ_2) is the bend angle of the female tool.

Zhu concluded that the longitudinal peak strain occurs when the strip is in contact with the female tool for the first time. Zhu also concluded that the derivative of the bend angle curve at that specific contact moment can be used to determine the severity of the forming. The derivative is

$$\frac{d\theta}{dz} = \frac{L - z}{\dfrac{a^2 \sin 2\theta(z)}{2\cos^2 \theta_2} + ar \dfrac{\cos(\theta(z) - \theta_2)}{\cos \theta_2}} \qquad (6)$$

The model predicts that the forming severity decreases when the tool radius increases and thereby decreasing the longitudinal peak strain. Zhu also observed that the peak membrane strain decreases when a fixed forming increment is used in each roll station, for example 0° – 90° in steps of 15°.

Panton *et al.* [7] proposed a bend angle curve model by combining Equation (1) and Equation (5). They also concluded that the longitudinal peak membrane strain occurs when the strip is in contact with the female tool for the first time. They found that their combined model had a good correlation between theory and experiment for ($\Theta(z)$).

Zhu *et al.* [8] investigated the effects of geometry with help of the bend angle curve that Panton *et al.* [7] proposed.

The model predicted:

- The peak longitudinal strain increases with the material thickness.
- The peak longitudinal strain and the deformation length increase with the bend angle increment.
- When fixed forming increment is used, the peak longitudinal strain falls but then rapidly increases when the angle finally approaches 90°.
- Increasing the female radius decreases the peak longitudinal strain due to longer contact length with the tool.
- When the flange length increases the peak longitudinal strain increases initially, but at a certain flange length it starts decreasing.

The simple formulas for the deformation length and the longitudinal strain, Equations (2) and (4), do not include the effect of material properties and the tool geometry. However, the studies that Zhu *et al*. [8] , Ingvarsson [9] and Lindgren [10] have done show they do affect longitudinal strain and the deformation length.

Ingvarsson [9] roll formed a V-section of mild- and ultra high strength steel with the equal number of forming steps. The ultra high strength steel gave a straight profile whereas the mild steel did not. The conclusion was that fewer forming steps are needed when high strength steel is used.

Lindgren [10] investigated the yield strength influence on the longitudinal peak strain and the strain based deformation length. The conclusion was that increased yield strength gives increased deformation length and decreased longitudinal peak strain.

4 Approach and scope

In this project a CRF process has been modelled with the FE package MARC/MENTAT. The objectives with this study are:

- With help of two level factorial design using FE-analysis investigate which parameters that influence the longitudinal peak membrane strain and the strain based deformation length.
- Create a simple model that can predict the peak strain and the deformation length.

The developed simplified model is compared with earlier FE – analyse of the CRF process [3], [10] and with the formulas in Equation (2) and (4).

5 Finite element model

5.1. The geometry

The finite element model consists of two forming stands and two stands where no forming occurs, **Figure 2**. The latter are used as belt feeder to the other two, where the forming takes place. Two different strips are simulated, **Table 1**.

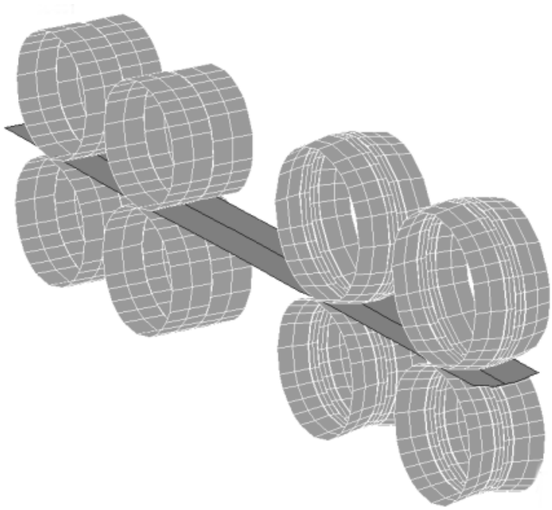

Figure 2. *The finite element model consists of two forming stands and two stands where no forming occurs. The latter are used as belt feeder to the other two.*

Table 1. *The strip models.*

	Strip 1	Strip 2
Length	800 mm	800 mm
Thickness	0.75mm, 2 mm	0.75 mm, 2 mm
Width	20 mm	35 mm
Number of element	1600	2400

The strip is modelled with a four node thick shell element type number 75 in MARC [12].The element size is 4*1 mm in the bending zone and in other regions the element size is 4*4 mm. Three layer of integration point are used in the thickness direction.

The tools are modelled as rigid surfaces and due to the symmetry, only half of the geometry is modelled. The initial angular speed of the tools is 10 rad/s, which gives the strip a speed of 0.6 m/s. The speed is stepped-up by 0.5% in the 1st and 2nd forming stand. This is done in order to counteract buckling between the stands.

5.2. Material model

An elastic-plastic material model where the von Mises yield surface and the associated flow rule is used. The hardening is isotropic. The used data for the material is shown in **Figure 3**. Flow stress versus plastic strain for the material is implemented as a table in the FE program.

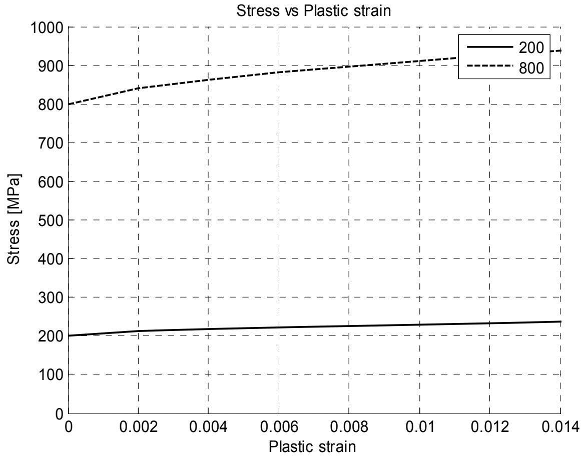

Figure 3. *Stress – strain curve for the material hardening.*

5.3. Contact

Coulomb friction is assumed in the model and the friction coefficient is 0.1. The clearance between the upper and lower tools is 2.00 respectively 0.75.

6 Factorial design

A two-level factorial design [13] has been used to investigate factors what factor are most influential on the longitudinal peak membrane strain and the deformation length. The investigated factors are flange length (*a*), strip thickness (*t*), tool radius (*r*), yield strength (*S*) and bend angle increment ($\Delta\Theta$). The factors have two levels, the low-level and the high-level, **Table 2**.

Table 2. *The factors and there levels.*

Factors	Levels	
	Low	High
Flange length (*a*)	10 mm	25 mm
Thickness (*t*)	0.75 mm	2.00 mm
Bend angel increment ($\Delta\Theta$)	10°	20°
Tool radius (*r*)	60 mm	120 mm
Yield strength (*S*)	200 MPa	800 MPa

The test series are set up in a standard order in a table of contrast coefficients [13], not shown here. The five parameters need 2^5, that is 32 simulations. The longitudinal peak membrane strain and the strain based deformation length are the results for each simulation. It is assumed that parameters that have a small influence on the results is like “noise” and will follow a normal distribution. The factors that have a large influence on the results will therefore deviate strongly from a normal distribution. These parameters can be easily identified by plotting the results in normal probability plot as in **Figure 4** and **Figure 5**. This plot is such that results along the indicated straight line do follow a normal distribution. They have a small influence on the results. One can see that five cases in **Figure 4** and six cases in **Figure 5** deviate from normal distribution. Thus they should be included in models for the peak strain and the deformation length. The parameters that affect these changes have been identified based on the table of contrast coefficients. These parameters are written as identification text in the figures near these points.

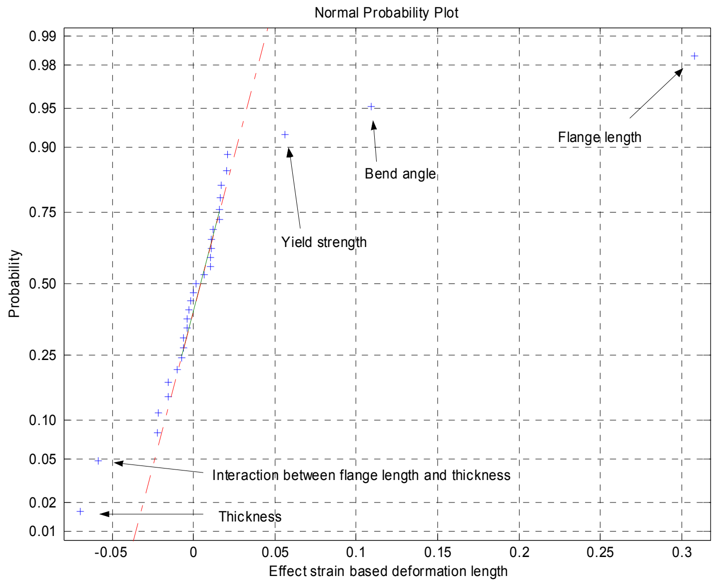

Figure 4. *Normal probability plot for the deformation length.*

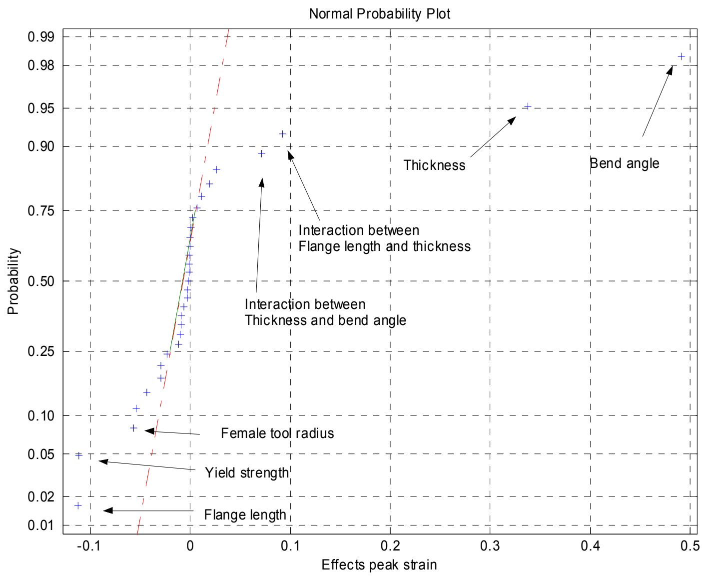

Figure 5. *Normal probability plot for the longitudinal peak membrane strain.*

6.1. Proposed models for the longitudinal peak strain and the deformation length

A study of **Figure 4** indicates that the strain based deformation length model should include four variables, bend angle, flange length, the thickness and yield strength. The bend angle, the flange length and the yield strength effects do have positive effects in **Figure 4** as they are in the positive part of abscissa. Increasing the thickness reduces the deformation length and therefore its effect is negative in the figure. Positive effects are placed in the numerator and negative effects in the denominator of the proposed model in Equation 6.

$$L_s = K_1 \frac{a^{K_2} \Delta\theta^{K_3} S^{K_4}}{t^{K_5}} \qquad (6)$$

A study of **Figure 5** indicates that five variables should be included, the thickness, bend angle, flange length, yield strength and the tool radius, Equation (7). One can also see interactions between the parameters in **Figure 4** and **Figure 5** and considerations for interactions will be included in the models. Interactions are those simulations where different parameters in the table of contrasts coefficients are varied simultaneously. The final outcome of the relevant parameters is

$$\varepsilon_{peak} = K_1 \frac{t^{K_2} \Delta\theta^{K_3}}{a^{K_4} S^{K_5} r^{K_6}} \qquad (7)$$

6.2. The female tool radius

Zhu [6] concluded that when constant forming increments are used, for example 0° – 90° in steps of 15°, the longitudinal peak membrane strain will decrease in every forming step. Zhu proposed a model for the female geometry, Equation (6), that includes the tool radius, but the model has the disadvantage that one must know where the strip is in contact with the tool the first time. The suggestion given in this paper is to use an effective radius. When the edge of the flange is in contact with both the upper and lower tool, the direction of the normal vector to the point where the edge is contact with the tools can be used as an effective radius, **Figure 6**.

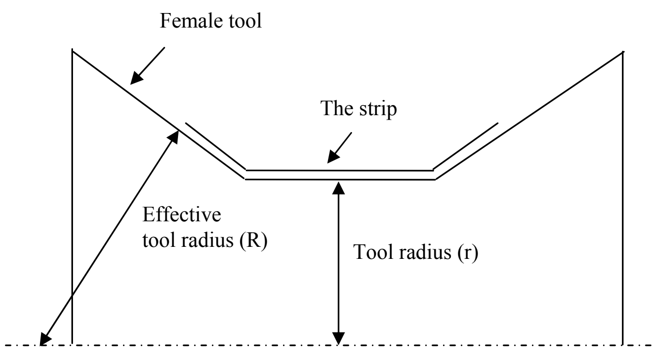

Figure 6. *The female tool and the effective tool radius.*

The model for the effective tool radius (R) is:

$$R = a \tan\theta_2 + \frac{r}{\cos\theta_2} \qquad (8)$$

The advantage of the effective radius is that the radius will increase when the bend angle increases. The model can also be implemented in a CAE system. The disadvantage of the effective radius is that the model will predict an infinite radius when the flange reaches 90° in the forming process. In [8] they also observed that problem with the last forming step and concluded that it has to do with the severe boundary conditions between the tool and the strip.

The tool radius (r) in Equation (7) replaces with the effective tool radius (R) Equation (8), the peak strain model, will now account for constant forming increment. It is written as:

$$\varepsilon_{peak} = K_1 \frac{t^{K_2} \Delta\theta^{K_3}}{a^{K_4} S^{K_5} R^{K_6}} \qquad (9)$$

6.3. Determine the model parameters

The coefficients and exponents (K_i) in the proposed models for strain based deformation length and the peak strain, Equation (6) and Equation (9), are determined so the model fits the results from the simulations done in the factorial design.

7 Result and discussion

The obtained models for the strain based deformation length and the longitudinal peak membrane strain are:

$$L_s = 12 \frac{a^{0.8} \Delta\theta^{0.41} S^{0.07}}{t^{0.25}} \qquad (10)$$

$$\varepsilon_{peak} = 0.67 \frac{t^{0.85} \Delta\theta^{1.9}}{a^{0.28} S^{0.28} R^{0.15}} \qquad (11)$$

where the variables are given in the units, millimetre, radians and Newton.

The model that Bhattacharyya *et al.* [4] obtained for the deformation length, Equation (2), predicts that the deformation length increases with increasing flange length, bend angle and decreasing thickness. Equation (10) predicts the same but it also predicts increasing deformation length when the yield strength increases. The yield strength's influence on the deformation length also agrees with the FE-simulations by Lindgren [10]. In **Figure 7** are Equation (2) and Equation (10) compared with these results. The agreement between the Equation (10) and the simulation result that Lindgren [10] obtained is good. The Equation (2) and the results from the simulations do not agree well due to the large simplifications in Equation (2). It simplified both the material as well as the deformation behaviour. The assumptions for prediction of the deformation length were:

- The flange adopts the shape that minimises the plastic work.
- The material is rigid perfectly plastic.
- Bending takes place only along the fold line.
- The longitudinal bending of the web and out-of-plane bending in the flange can be neglected.

Two additional differences between the models for the deformation length, L, are:

- Equation (2) is based on the bend angle of the flange for a strip where elastic strains are neglected, whereas the current computational model includes these.
- The strain based deformation length, Equation (10), is defined differently from the definition used by Bhattacharyya *et al.* [4]. It was found convenient to identify it in the finite element model as the length from the point where the longitudinal strain in the edge of the flange is greater than $2 \cdot 10^{-5}$ to the point where the upper and lower tools are in contact with the strip.

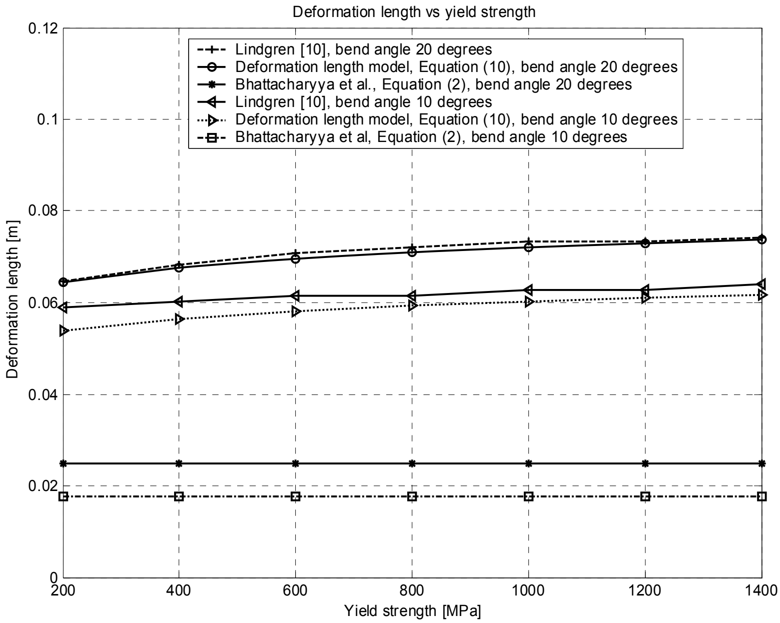

Figure 7. *The models Equation (2) and Equation (10) are compared with the work done by Lindgren [10]. One can see that Equation (10) agrees well with Lindgren [10] but not Equation (2).*

In **Figure 8** is Equation (11) for the peak strain compared with the simulation result which Lindgren [10] obtained. One can see that the model predicts the decrease in peak strain when yield strength increases well. Equation (4) gives a peak strain of 0.019 for the bend angle of 10° and a peak strain of 0.039 for bend angle 20° independent of the yield strength. This is peak strain is larger than in Lindgren [10] and in Equation (11), Chaing [5] also concluded that Equation (4) overestimated the peak strain.

Zhu [6] concluded that by increasing the female tool radius the peak strain will decrease, Equation (6). The factorial design in this study gives the same result. Zhu *et al*. [8] investigated the effect of the geometrical variables and the conclusions were that the peak strain increases when thickness increases, the bend angle increases and the female tool radius decreases. This agrees with the peak strain model Equation (11). They also concluded that the peak strain will decrease when a constant forming increment was used. The model Equation (11) also account for that. In **Figure 9** is the peak strain model compared with the simulations results that Lindgren [3] obtained. In this case is a constant forming increment of 15° used from 0° – 90°. One can see that the model predicts the decreasing peak strain well except for the bend angle 90° where the peak strain model, Equation (11) is not valid as the effective tool radius, Equation (8), will be infinite.

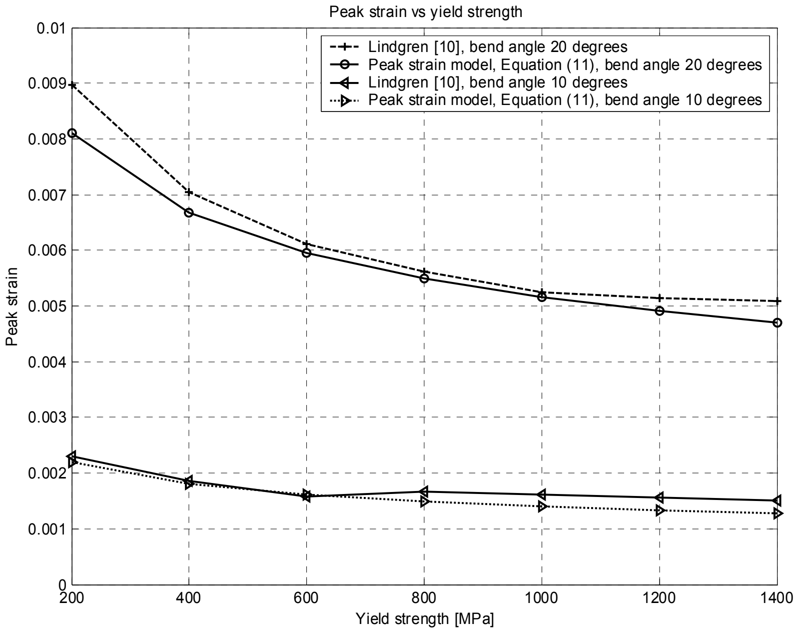

Figure 8. *The model Equation (11) is compared with the simulation result that Lindgren [10] obtained. One can see that they agree very well.*

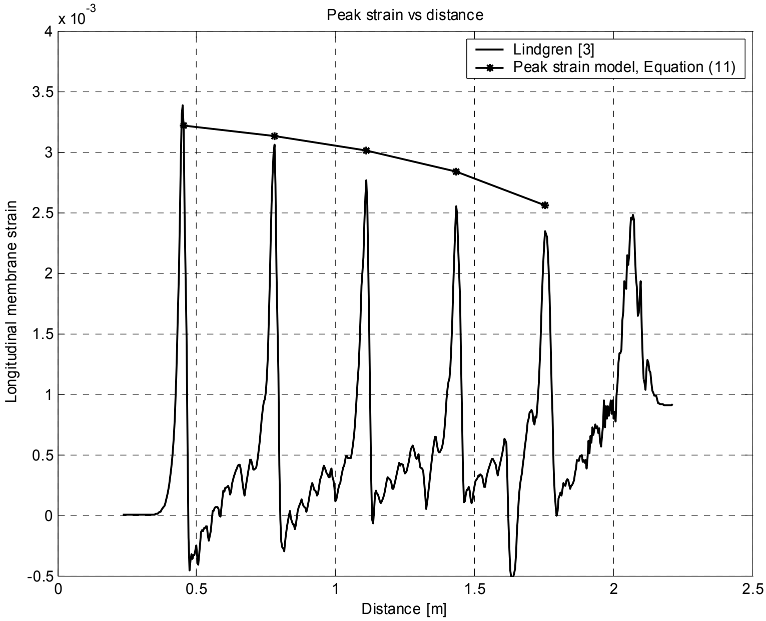

Figure 9. *The model Equation (11) is compared with the simulation result Lindgren [3]. The model predicts decreasing peak strain well when constant forming increment is used. In this case is the constant forming increment 15°. For the 90° forming step is the Equation (11) not valid.*

8 Conclusion

FE-analysis and factorial design have been used with success to create simple formulas for the strain based deformation length and the longitudinal peak membrane strain. It should be noted that the model is developed for the forming of a rectangular U-shape.

The model for the longitudinal peak membrane strain, Equation (9) is improved compared with the analytical model, Equation (4). The model can now predict decreasing peak strain when constant forming increment are used, **Figure 9**, and also decreasing peak strain when the yield strength increases, **Figure 8**.

The model for the strain based deformation length includes parameters similar as for Equation (2) but the model also accounts for increasing length when the yield strength increases, **Figure 7**.

The simple models that have been developed can easily be implemented in a CAE system to estimate the longitudinal peak membrane strain and the strain based deformation length and thereby giving better design.

9 Acknowledgements

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