

# SIMULATION OF THE DEEP DRAWING PROCESS: A HIERARCHICAL METHOD

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## ABSTRACT

The finite element method becomes widely accepted to be a simulation tool for the deep drawing process. A necessary condition to generate accurate simulation results is a correct use of the numerical algorithms that are used in the finite element method.

This paper concentrates on a hierarchical approach to perform an accurate simulation of a specific deep drawing product, i.e. the S-Rail. The necessary numerical algorithms for this simulation are investigated with the strip model. The results of this investigation are applied in the simulation of the complete S-Rail. Finally the simulation results are compared with experiments, leading to the conclusion that in a relatively short time an accurate simulation can be performed which shows a good agreement with the experimental results.

## 1. INTRODUCTION

The deep drawing process is a commonly used deformation process in several branches of industry such as the automotive industry, the packaging industry and the household appliances industry. Formerly these deep drawing products were manufactured using a heuristic approach with a trial and error process, sometimes helped by simple analytical models. Nowadays the use of numerical methods in the development of deep drawing products is increasingly emphasized.

Although the numerical methods such as the finite element method becomes widely accepted to be a simulation tool, a necessary condition to generate accurate simulation results is to know and understand the advantages and shortcomings of the numerical algorithms that are used in the applied numerical model. Concentrating on the finite element method, examples of these numerical algorithms concern element description, description of material behavior, solvers, constitutive equations and convergence criteria.

This paper focuses on the investigation of numerical algorithms with respect to element types, element integration schemes and material models with the help of a hierarchical method, leading to an accurate simulation of a specific deep drawing product, i.e. the S-Rail.

## 2. THEORY

The entrance to know and understand the advantages and shortcomings of the used numerical algorithms can be the underlying theory of these algorithms. In this section the theory of the specific numerical algorithms will be treated briefly.

### *Integration scheme*

The finite element method is based on the weak form of mechanical equilibrium, see equation (1). The body forces are omitted in this formulation.

$$\int_{\Omega} \frac{1}{2} (\delta \underline{v} \cdot \bar{\nabla} + \bar{\nabla} \cdot \delta \underline{v}) : \underline{\sigma} d\Omega = \int_{\Gamma_t} \delta \underline{v} \cdot \underline{t} d\Gamma \quad (1)$$

In this formulation,  $\underline{\sigma}$  is the stress,  $\delta \underline{v}$  the virtual velocity and  $\underline{t}$  the surface traction. The weak form for rigid plastic material behavior can be written in incremental form as:

$$\left( \int_{\Omega} \underline{B}^T : \underline{D} : \underline{B} d\Omega \right) \cdot \Delta \underline{u} = \int_{\Gamma_t} \underline{N} \cdot \underline{t} d\Gamma \quad (2)$$

in which  $\underline{D}$  is the plasticity tensor. In case of elastic plastic material behavior, equation (1) has to be written in rate form since its constitutive relation is formulated in rate form. This gives rise to geometric non linear terms in the rate form of equation (1).

The domain of equation (2) is restricted to one element. Within these elements an arbitrary quantity is interpolated between discrete points, known as the element nodes, using interpolation functions  $N$ . The tensor  $B$  contains the derivatives of the interpolation functions. For numerical integration of equation (2) the integrals will be replaced by summations. As an example the first integral can be expressed in a summation where the functions  $f(\Omega_{i,j,k})$  are evaluated at each sampling point and multiplied by the corresponding weighting factor  $w_{i,j,k}$ , see equation (3).

$$\int_{\Omega} f(\Omega) d\Omega = \sum_{i,j,k} f(\Omega_{i,j,k}) w_{i,j,k} \quad (3)$$

The location of the sampling points for natural co-ordinate systems are determined with the Gauss-Legendre quadrature to achieve the greatest accuracy. With this integration scheme a polynomial of degree  $(2n-1)$  can be integrated exactly using  $n$  integration points [1].

In the used finite element code, triangular plane stress plate elements are used to model sheet deformations. The elements have three integration points in the plane of the element and 2 up to 7 integration points over the height. The locations and the accompanying weight factors of these integration points are summed in [2]. Table 1 displays the location of the integration points over the height.

2	$\pm 0.57735$	6	$\pm 0.23862$
3	0.00000		$\pm 0.66121$
	$\pm 0.77460$		$\pm 0.93247$
4	$\pm 0.33998$	7	0.00000
	$\pm 0.86116$		$\pm 0.40585$
5	0.00000		$\pm 0.74153$
	$\pm 0.53847$		$\pm 0.94911$
	$\pm 0.90618$		

**Table 1. Location of Gauss integration points over the height**

#### Element type

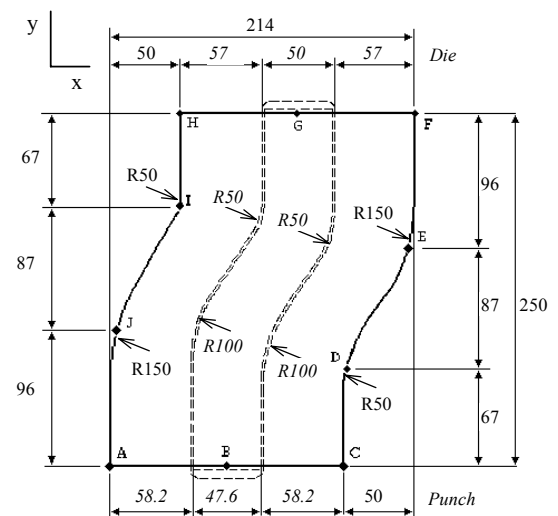
Sheet metal forming processes are often described by plate elements. The stress in normal direction is assumed to be zero due to the small sheet thickness. The geometry of the sheet will be described by only using the variables on the mid-plane. Three different plate deformation theories with its specific elements are distinguished, i.e. membrane theory, Kirchhoff theory and Mindlin theory. The membrane theory assumes that the bending and shear stiffness can be neglected compared to the membrane stiffness. The Kirchhoff theory takes both the bending stiffness and the membrane stiffness into account and the Mindlin theory takes the shear stiffness into account as well.

#### Material model

The material model consists of a constitutive equation, describing the relation between stresses and strains, and a yield criterion which defines a combination of multi-axial stresses at which the material starts to deform plastic. Commonly used constitutive equations are the elastic-plastic formulation and the rigid plastic formulation. Although the rigid plastic formulation is numerically more stable, it is not able to describe elastic phenomena such as spring back behavior. Commonly used yield criteria in sheet metal forming are the Von Mises yield criterion which describes isotropic material behavior, and the Hill yield criterion which describes planar anisotropic material behavior. The Hill yield criterion is preferred when its parameters can be determined out of the available material data.

### 3. S-RAIL SIMULATION

The S-Rail is used as a benchmark problem at the Numisheet '96 conference [3] to compare the simulations and experiments for shape distortion, wrinkling and spring back. The dimensions of the blank and tools (dotted lines and dimensions printed in *italics*) are given in Figure 1. The product height of the S-Rail is 37 mm. In this paper the simulations are performed with the finite element code DiekA, whereas the experimental results are an average of the experimental benchmark participants. The material behavior is assumed to be elastic plastic since the rigid plastic approach is not able to predict spring back. Since spring back behavior and wrinkling of the S-Rail must be investigated, Kirchhoff elements are used to perform the strip simulations instead of membrane elements. The use of Mindlin elements is expected not to be necessary since the shear stress distribution over the plate thickness is negligible due to the small plate thickness / tool radius ratio.



**Figure 1. Initial blank and tool dimensions**

Simulations of a complete deep drawing product are very time consuming. Furthermore the demanded result is commonly gained in the  $n^{\text{th}}$  simulation of the specific product, where the previous  $n-1$  simulations served as a trial and error process. A decrease of the calculation time (CPU-time) during the trial and error process can be achieved by a

procedure in which only a small strip of the complete product is simulated. This so called strip model can be a fast and powerful tool for preliminary studies of a complete deep drawing simulation.

### 3.1 Strip model

The plane strain strip model, see Figure 2, is used to determine the number of elements and the number of integration points per element which are necessary to gain accurate results of the deep drawing and spring back of the S-Rail.

#### Number of elements

The demand of accurate simulation results necessitates the meshed blank to follow the tool surface accurately. This can only be achieved when the element dimensions are sufficiently small. To investigate the minimum length of an element needed to describe the S-Rail radii of 5 mm accurately, four simulations are performed with element lengths of respectively 1 mm, 2.5 mm, 5 mm and 10 mm, see Figure 3.

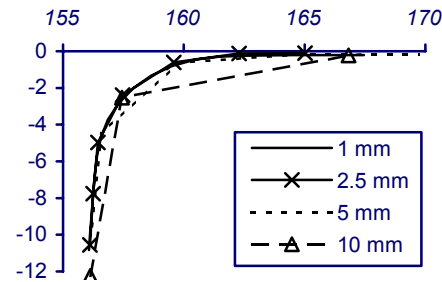
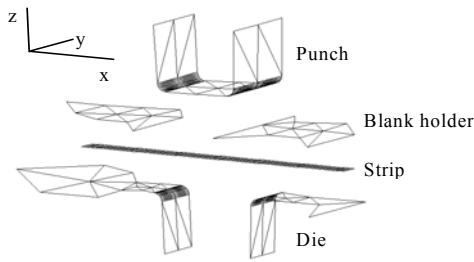


Figure 2. Set up for Strip Model

Figure 3. Die radius described with different element lengths

It can be concluded that an element length of 2.5 mm is able to describe the tool geometry of the S-Rail accurately. The total CPU-time of the four simulations together was 435 seconds.

#### Number of integration points

The Kirchhoff elements have three in-plane integration points and 2 up to 7 integration points over the height per in-plane integration point. An increase of the number of integration points over the height will increase the accuracy of calculated stress and strain states over the height. However an increase in integration points yields an increase in calculation time and memory use. The strip model will be used to determine the minimum number of integration points to gain accurate results.

Figure 4a shows the theoretical shape of the tangential stresses in blank thickness direction at the die radius after drawing and after spring back. Figure 4b till 4g show the simulated tangential stress distribution for 2 up to 7 integration points over the height.

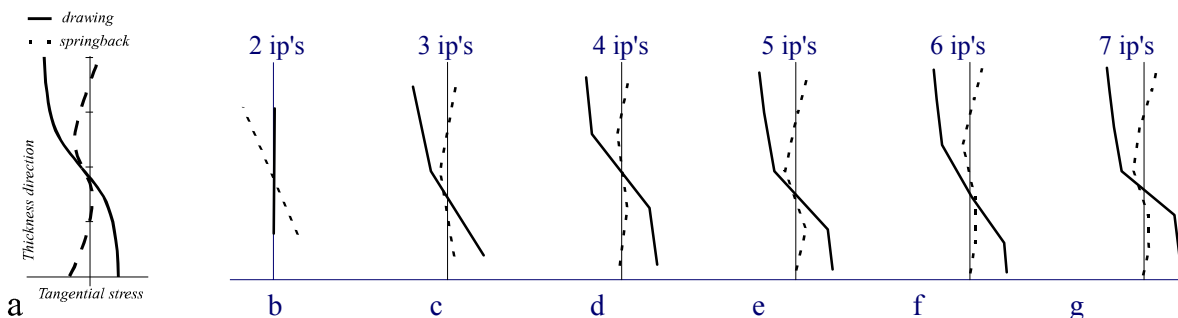


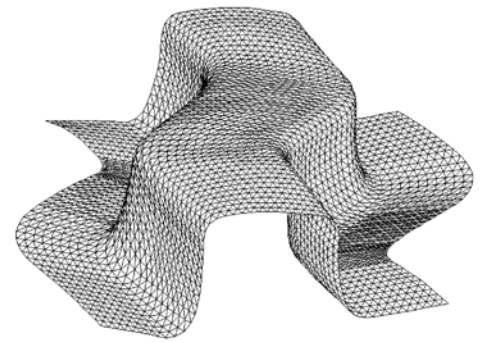
Figure 4. Tangential stress distribution for different number of integration points

The simulations with 2 or 3 integration points do not well describe the expected stress distribution. The simulations with 4 up to 7 integration points show a similar stress distribution, whereas the simulation with 7 integration points should be the closest to the exact stress distribution. The simulation with 4 integration points is preferred when also the computational costs are taken into account. The total CPU-time of the six simulations together was 2446 seconds.

### 3.2 Complete S-Rail

The strip model is used to determine the necessary number of integration points and the maximum element length to perform an accurate S-Rail simulation. As a result the blank for the complete S-Rail simulation is meshed with 6000 Kirchhoff elements with an element length of 2.5 mm and 4 integration points over the height, using an elastic plastic Hill anisotropic material model.

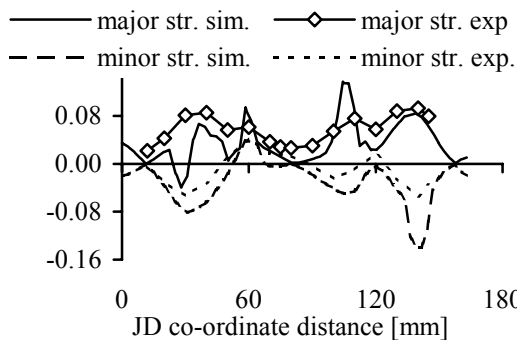
The deep drawing of the S-Rail is simulated in approximately 130 steps, while spring back takes another 10 steps. The CPU-time of the complete S-Rail simulation was 41058 seconds. Figure 5 shows the deformed S-Rail after spring back, where the spring back displacements are heavily exaggerated.



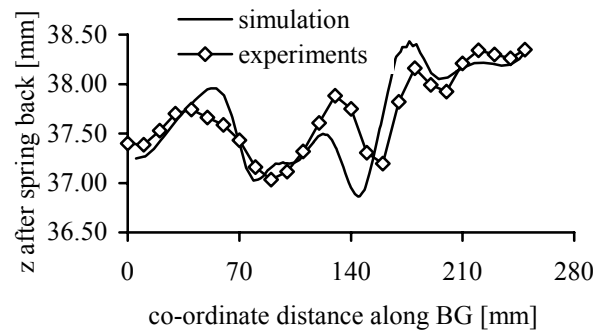
**Figure 5. S-Rail after spring back**

The major and minor strains along line JD, see Figure 1, are presented in Figure 6a. The strains are evaluated at the die side of the product. The peaks in the graphs for the major and minor strains represent the bending around the die and punch corners. They compare very well concerning the position and fairly well concerning the values. At a coordinate distance of 30 mm, which is near the die corner, the simulation shows a negative peak for the major strain. This peak is a result of the strain extrapolation from the integration points to the outer side. At this position a large gradient in strain distribution over the thickness can be seen.

The z-co-ordinates along line BG, see Figure 1, are printed in Figure 6b to show the shape distortion and wrinkling in the bottom of the S-Rail for both the simulations and the experiments. Again the simulation show a good agreement with the experimental results, concerning both the curve shape and z-co-ordinate values. For a more detailed discussion of the simulation results the reader is referred to [4].



**Figure 6a. Strain along line JD after spring back**



**b. Z-co-ordinate along line BG after spring back**

#### 4. CONCLUSION

1). The simulation results and the experimental results of the S-Rail compare well for both the investigated strain distribution in and the shape distortion of the S-Rail.

2). The strip model is a powerful tool to get a fast insight in deep drawing simulations when it is used as a part of the hierarchical method. The total CPU-time for the simulations to define the element size was 435 seconds. The total CPU-time to determine the minimum number of integration points was 2446 seconds. These calculation times needed to gain this necessary information are small compared to the CPU-time of the complete S-Rail simulation which amounts 41058 seconds. When this hierarchical approach is not used, gain in time can only be achieved when the S-Rail is accurately simulated at once.

3.) The beforehand drawn conclusions, based on knowledge that membrane elements could not be used and Mindlin elements are not necessary to use, are verified with two simulations. The simulation with membrane element gained results which were far from reality. The results gained with Mindlin elements do hardly differ from the results gained with Kirchhoff elements.

#### 5. REFERENCES

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