Roll Forming Simulation using Higher Order NURBS-based Finite Elements

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1 Introduction

Roll forming is a continuous bending operation of a long strip of metal sheet. The sheet is gradually formed through pairs of rotating rolls (called stands) until the desired cross-sectional configuration is obtained (see Fig. 1). Although roll forming is a classical method to produce constant cross-sectional profiles, it remains a complex process. Finite element analysis (FEA) can assist the designer to improve this process.
During the roll forming process the metal sheet undergoes various states of plastic deformation that need to be properly represented by the finite element model. Depending on the sheet thickness and the radii of the profile, an accurate analysis of the stress field through the thickness is inevitable, which requires suitable volume type finite elements. Some examples of typical roll formed profiles are shown in Fig. 2.

Isogeometric analysis (IGA) is a new finite element analysis method that uses mathematical geometry descriptions from computer aided design (CAD) tools, such as non-uniform rational B-splines (NURBS). Therefore, the standard piecewise continuous Lagrange polynomials are replaced with higher order spline basis functions, leading to higher continuity across finite element boundaries.
In recent years NURBS-based finite elements have been added to the commercial simulation software package LS-DYNA. This paper examines the usability of higher order NURBS-based solid elements in the context of roll forming applications.

The paper will be organized as follows:
In section 2 the main motivation and the basic ideas of isogeometric analysis will be presented followed by a very brief introduction into NURBS solids. Section 3 describes the roll forming simulation. Two examples of roll forming simulation using IGA are presented in section 4 and compared with the classical finite element model. The paper closes with a summary and an outlook about the next development in roll forming simulation and higher order NURBS-based solid elements.

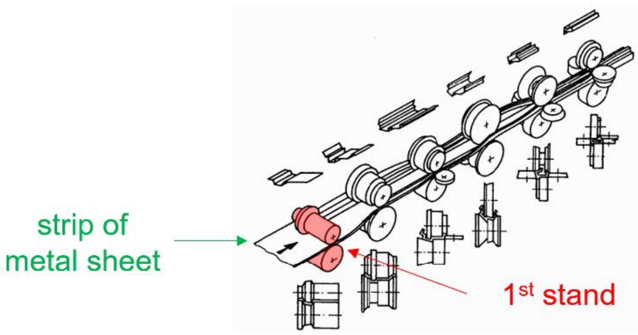

Fig.1: Principle of the roll forming process, courtesy of UBECO GmbH

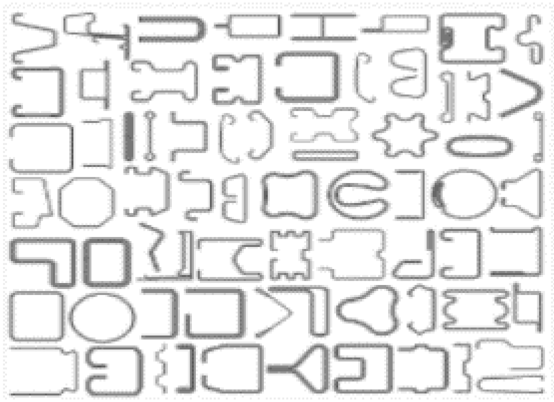

Fig.2: Some examples of roll formed profiles, courtesy of UBECO GmbH

2 Isogeometric Analysis – Some basics

This section will recall the initial motivation for the development of Isogeometric Analysis. A general definition of this term as well as some basic ideas of this method will be presented. Furthermore, a short introduction about NURBS will be given.

2.1 Motivation

Setting up a model for finite element analysis (FEA) requires many steps. One of those steps is the conversion of the geometry description from computer aided design (CAD) into a suitable mesh for FEA. This is necessary as the CAD community uses geometry descriptions like e.g. NURBS whereas standard finite element analysis is generally based on low order Lagrange Polynomials for the approximation of the geometry. Therefore, a re-parameterization of the initial CAD geometry is necessary, which can be quite labor cost intensive. Furthermore, this meshing procedure may lead to discretization errors as the initial geometry may often not be exactly represented with Lagrange Polynomials. Isogeometric analysis aims to overcome both of these drawbacks by using directly the geometry description from CAD for the analysis. In Fig. 3 a schematic comparison of the meshing procedure between standard finite elements and isogeometric analysis is displayed. It can be seen that the re-parameterization with Lagrange Polynomials leads to a discretization error that reduces with mesh-refinement, but will never fully vanish for this circular section. The research on isogeometric analysis started with the focus on the question if finite element analysis could be done with NURBS, which is the most widely used geometry description used in commercial CAD packages. First promising results were presented in 2005 [1] which initiated a lot of research activity in this field thereafter. A nice introduction into the topic of isogeometric analysis can be found in the textbook by Cottrell et al. [2].

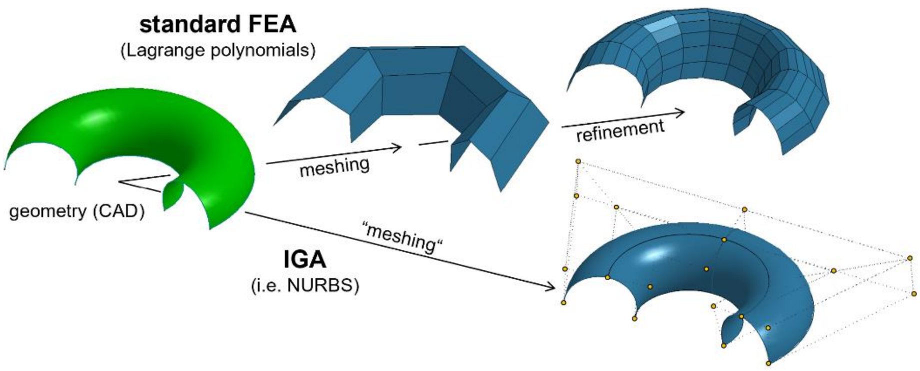

Fig.3: Comparison of meshing for standard finite elements and IGA

2.2 NURBS

To understand some significant differences of using NURBS instead of Lagrange polynomials for finite element analysis some basic properties of NURBS will be sketched in the following. For a deeper study of NURBS, the interested reader is referred to the monograph by Piegl and Tiller [3].

2.2.1 B-splines

Given the name Non-Uniform Rational B-Splines it is obvious that NURBS are built from B-Splines. B-Spline basis functions are constructed in a recursively manner, starting with a constant basis function and then increasing the order in every recursive step until the desired degree is reached (see Fig. 5).

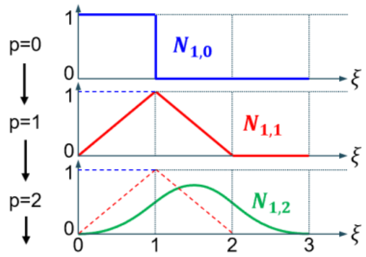

Fig.4: B-spline basis functions of order 0, 1 and 2 for uniform knot vector [2]

The recursion formula is given by

$$for\ p=0: \quad N_{i,0}(\xi)=\begin{cases}1 & \text{if } \xi_i \le \xi < \xi_{i+1}\\ 0 & \text{otherwise}\end{cases}$$
$$for\ p>0: \quad N_{i,p}(\xi)=\frac{\xi-\xi_i}{\xi_{i+p}-\xi_i}N_{i,p-1}(\xi)+\frac{\xi_{i+p+1}-\xi}{\xi_{i+p+1}-\xi_{i+1}}N_{i+1,p-1}(\xi) \quad (1)$$

where ξ_i is the i^{th} knot of the so-called "*knot-vector*" $\Xi=\{\xi_1,\xi_2,\dots,\xi_{n+p+1}\}$, which is a non-decreasing set of coordinates in the parametric space, p is the degree and n is the number of basis functions. Regardless of the degree, B-spline basis functions are always positive, they constitute the important partition of unity property and exhibit a C^{p-1}-continuity along the internal element boundaries if not multiple knot values are present in the knot-vector.

B-spline curves are created using so-called control points $\boldsymbol{P}_i$, which are used as coefficients of the B-spline basis functions. It must be noted that the control points are normally not a part of the actual geometry which stems from the non-interpolatory nature of the B-spline basis functions. A B-spline curve $\boldsymbol{C}(\xi)$ is defined through a linear combination of the B-spline basis functions with the corresponding control points.

$$\boldsymbol{C}(\xi)=\sum_{i=1}^{n}N_{i,p}(\xi)\boldsymbol{P}_i \quad (2)$$

B-spline curves may be refined (h-, p- and k-refinement) without changing the initial curve geometry.

2.2.2 NURBS Solid

Starting with the univariate B-spline basis functions discussed in the preceding section, NURBS basis functions are constructed using a tensor product on the univariate basis functions together with additional weights $w_{i,j,k}$ at the control points, leading to rational basis functions (see Equ. (3)). The final NURBS solid is then defined through a linear combination of these basis functions with the associated control points (see Fig. 5).

$$R_{i,j,k}^{p,q,r}(\xi,\eta,\zeta)=\frac{N_{i,p}(\xi)M_{j,q}(\eta)L_{k,r}(\zeta)w_{i,j,k}}{W(\xi)}\ with\ W(\xi)=\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{o}N_{i,p}(\xi)M_{j,q}(\eta)L_{k,r}(\zeta)w_{i,j,k} \quad (3)$$

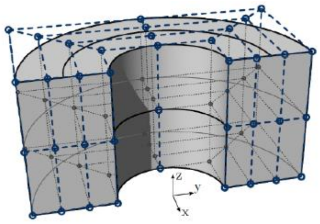

Fig.5: NURBS solid with the control points (blue dots) in physical space [4]

3 The roll forming simulation

The goal of a roll forming simulation for industry is to predict the behaviour of the profile for a given set of rolls with a high interest for the defects. Defects which may occur include torsion, waves and buckling along the edges, unbalanced springback etc. To understand the set-up of a roll forming simulation, the design steps and its vocabulary are simply explained in the following.

3.1 From the CAD to the FEA

The first step consists of defining the final profile cross section. Then the typical flower pattern is designed. That is, starting with the final section, the cross section of the profile at each stand is defined by unbending the arcs. Then, rolls for each stand are crafted using the flower pattern. These three steps are easily done in a CAD software. The roll form design software called PROFIL developed by UBECO GmbH was used. One of its advantages is that it automatically generates the full FEA inputs for LS-DYNA without knowing its language (see Fig. 6).

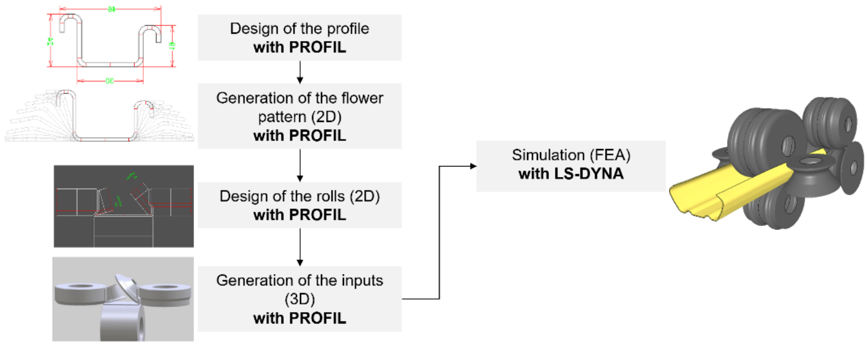

Fig.6: Overview how to create the simulation inputs from the final profile cross section

3.2 Modeling

3.2.1 Boundary conditions: Physical versus numerical process

In the actual process, the metal sheet is uncoiling, and its length is seemingly unlimited. In the simulation, representing the entire metal sheet would take too much time. Instead, only a part of the sheet is represented and to approximate the continuity, some guiding can be defined for the first row of nodes at the profile lead and the tail ends of the represented portion (see Fig. 7). In addition, simulating without them can cause non-physical deformations of the strip because the profile can hit a roll before entering the stand. To define the guiding, a shape equation $S(Z)$ is introduced which depends on the coordinate in longitudinal direction Z, the (horizontal) distance between two stands L (see Fig. 8) and the geometry of the profile.
Based on the shape functions $S(Z)$, the 3D shape of the deformed strip between the i-rolls at $Z = Z_1$ and the $i + 1$-rolls at $Z = Z_2$ is expressed by the following equation [5][6]:

$$
\begin{aligned}
Z &= Z(x, y) \\
X &= X_1(x) + [X_2(x) - X_1(x)]S(Z) \\
Y &= Y_1(x) + [Y_2(x) - Y_1(x)]S(Z) \\
Z &= Z_1 \sim Z_2
\end{aligned}
\tag{4}
$$

Because these equations are only geometric descriptions of the deformed curved surface of the strip, they cannot be sufficient to perfectly ensure the continuity of the simulated sheet. Consequently, for safety the strip should be long enough, usually longer than the inter-stand distance so that the guiding does not obstruct the results.

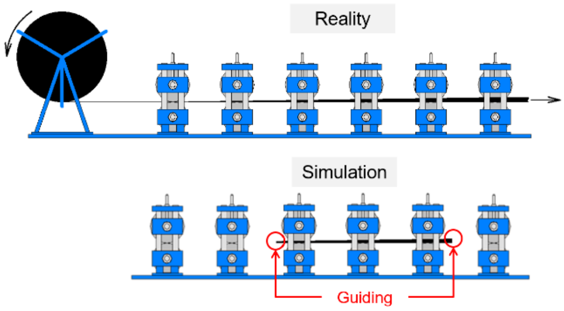

Fig.7: Physical versus numerical process

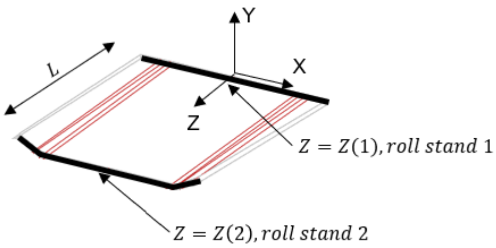

Fig.8: Example of a deformed sheet between roll stand 1 and 2

In a roll forming simulation, the referential is the strip. That is, the strip does not move but the rolls do. Furthermore, the tool rotation is not simulated and to avoid generating artificial deformation due to the friction, the coefficient of friction in the contact is set very low. In this manner only a portion of the roll can be represented and thus save some computational time.

For efficiency, the whole process is divided into p simulations where p is the number of stands. If an issue at stand $i \leq p$ appears, then the design at the stand i is corrected and started over. It avoids starting from the beginning. The results that are mainly mapped from the i-simulation to the $i+1$-simulation are the current stress and strain states and the equivalent plastic strain due to the forming process. This is done via a so-called DYNAIN-file using the keyword **`*INTERFACE_SPRINGBACK`**. Since usually between 6 and 32 stands are needed, arranged in a series, depending on the complexity of the desired profile, the keyword **`*CASE`** is used to start the full roll forming simulation by simply submitting a single input file.

3.2.2 Element type

For the conventional FEA, the strip is modelled with linear hexahedra element (**`ELFORM=1`** in **`*SECTION_SOLID`**) and four elements are defined through the thickness. It may be sufficient to correctly capture the stress state for no severe bending zone.
For IGA, the nodes of the conventional FE become the control points of the NURBS-solids. That is, between conventional FEA and IGA, the number of DOF is identical. As explained in the second section, the shape functions are different. The order of the shape function for NURBS-solids is adjusted in different directions: 2nd order in plane and 4th order through the thickness with one and only one element through the thickness (see Fig. 9).

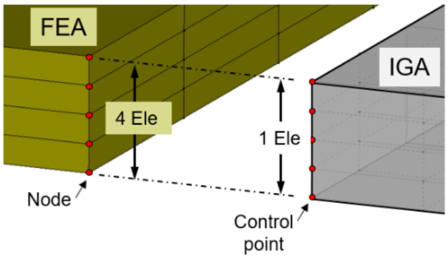

Fig.9: Finite element meshing and NURBS-solid for the strip

All remaining settings are unchanged: boundary conditions, contact, rolls, material laws and control options are identical. The only drawback is that some specific parallelization options defined in ***CONTROL_MPP_PFILE** keyword which turn out to be efficient for such process are not yet supported in IGA. Thus, CPU performances are not yet optimal and comparing CPU time between conventional FE and NURBS-solid is not relevant at this point. Currently, a IGA roll forming simulation runs around 3-4 times slower than FE.

3.2.3 Material law

For this study, it is decided for simplicity to use the isotropic elasto-plastic material law ***MAT_PIECEWISE_LINEAR_PLASTICITY** to model the strip of metal sheet. Neither damage nor rupture are modelled.
The rolls are supposed rigid and thus are modelled through a ***MAT_RIGID**.

3.2.4 Contact and interpolation elements

A ***CONTACT_AUTOMATIC_SURFACE_TO_SURFACE** is defined between the strip of metal sheet and each stand. This choice compared to a single contact saves computational time by activating (or deactivating) the contact at the right time for each stand. To measure the contact force of a roll, a ***CONTACT_FORCE_TRANSDUCER_PENALTY** is created.
Since CAD represents only the outer surfaces of the rolls and a ***CONTACT_AUTOMATIC_...** always considers the shell thickness, an offset distance from the plane of the nodal points to the reference surface of the shell is specified (see **NLOC** in ***SECTION_SHELL**) and taken in account into the contact (see **CNTCO** in ***CONTROL_CONTACT**).

LS-DYNA automatically creates so-called *Interpolation Elements* on top of the NURBS patches. These interpolation elements are standard linear solid elements whose newly created *interpolation nodes* are placed on the real solid geometry. In this study, the interpolation elements are used for contact treatment and post-processing.
It is important to notice, that the constructed interpolation nodes are dependent nodes with respect to the control points such that their motions are fully constrained to the underlying NURBS patch. When using the interpolation elements for contact, the contact forces are first evaluated at the interpolation nodes, but then transferred to the primary degrees of freedom (DOF) at the control points. For post-processing, the information at the integration points of the NURBS elements are mapped onto the interpolation mesh, such that the standard post-processing can be used.

4 Examples

In this part two examples of roll forming simulation using IGA are presented and compared with the classical finite element model.

4.1 1st example: U-profile

4.1.1 Presentation

The flower pattern and the 3D flower are shown in Fig. 10. Because the profile is symmetric, only one half of it is modeled. The thickness of the strip is 1.5 mm. The horizontal length of the profile is equal to the inter-distance which is 300 mm.

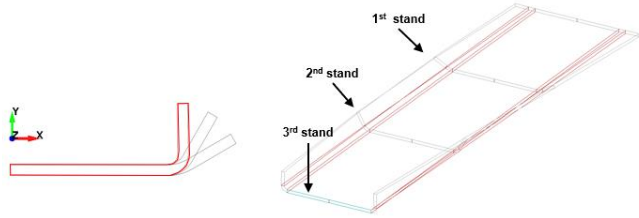

Fig.10: Flower pattern (left) and 3D flower (right) of the half U-profile

4.1.2 Results

Although the plastic deformations are quite similar between the two simulations, higher plastic strain on the surface of the sheet material is noticeable in the conventional FEA. The difference is about 5 % of plastic strain. This phenomenon is better represented in a section normal to the rolling direction. It seems that IGA gives a more plausible deformation continuity through the thickness compared to the conventional FEA (see Fig. 11). This continuity is also noticeable along the edge of the sheet for example. The Fig. 12 shows the effective plastic deformation in function of the Z-distance of the sheet. At the front of the strip (Z>275 mm), some instabilities in the plastic deformation are noticed. They are the results of the prescribed motion explained in the section 3.2.1. and thus, are ignored.

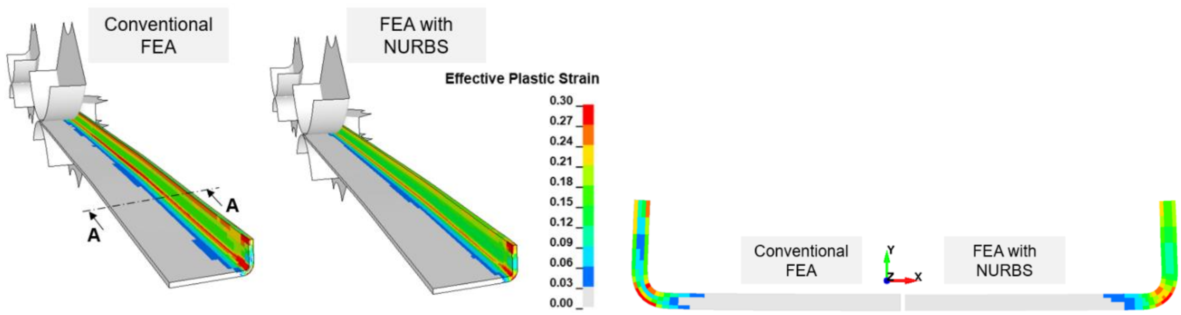

Fig.11: Comparison of effective plastic strain overview (left) and section (right) at the third and last stand

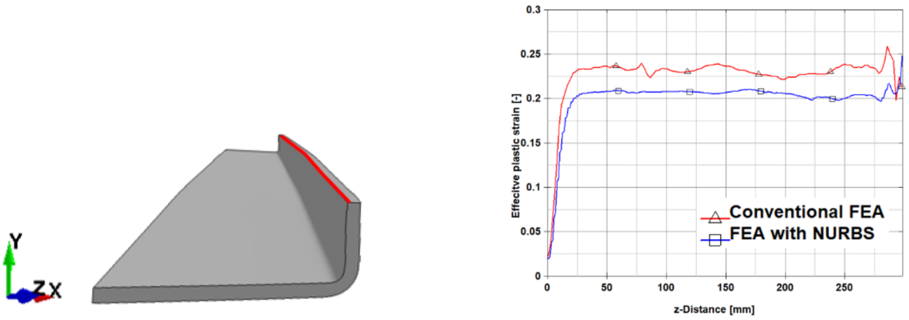

Fig.12: Comparison of effective plastic deformation in function of the Z-distance (right) along the edge (left) at the third and last stand

4.2 2nd example: Bumper-profile

4.2.1 Presentation

The flower pattern of the bumper is shown in Fig. 13. Since 13 stands are necessary to get the final section, the idea with such profile is to test the stability of the NURBS through many simulations involving a lot of non-linearity. The thickness of the strip is 1.5 mm. The horizontal length of the profile and the stand inter-distance are respectively equal to 350 mm and 300 mm.

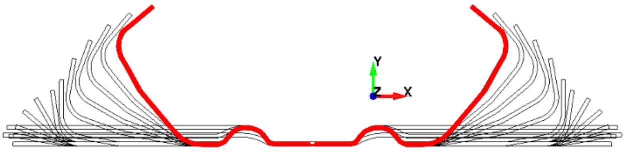

Fig.13: Flower pattern of the bumper-profile. The final profile section is represented in red

4.2.2 Results

The Fig. 14 represents the overview of the effective plastic strain at the end of some stands for IGA model. Like the previous example, the effective plastic stain distribution in a section normal to the rolling direction for the last stand between FE and IGA is similar (see Fig. 15) but again it seems that IGA provides more credible deformations.

The last picture (see Fig. 16) compares the thickness after the last stand between both models for a portion of the strip. NURBS capture quite well the thickness reduction. The difference is about 0.02 mm.

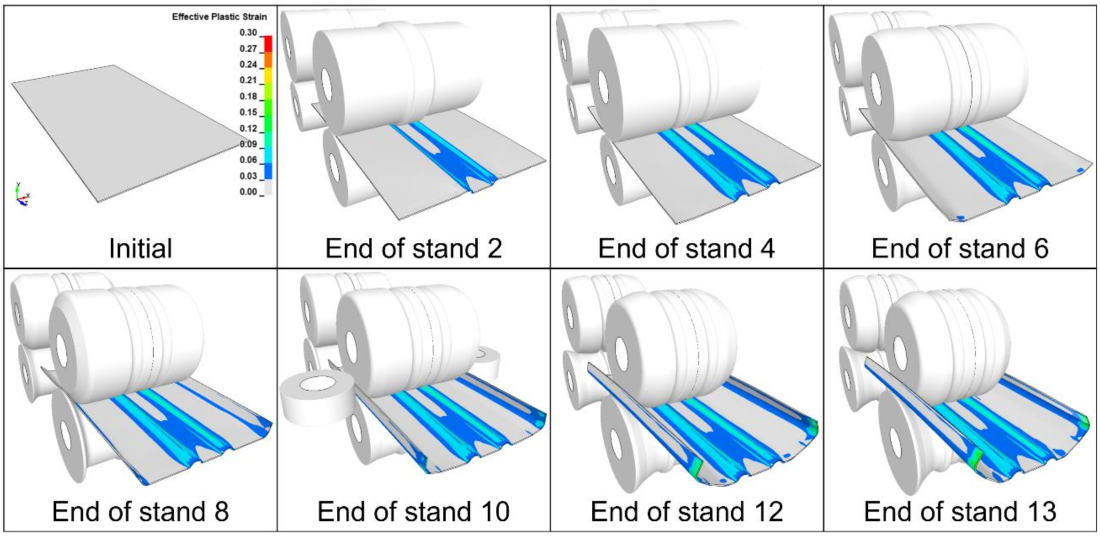

Fig.14: Overview of the effective plastic strain at the end of some stands for IGA model

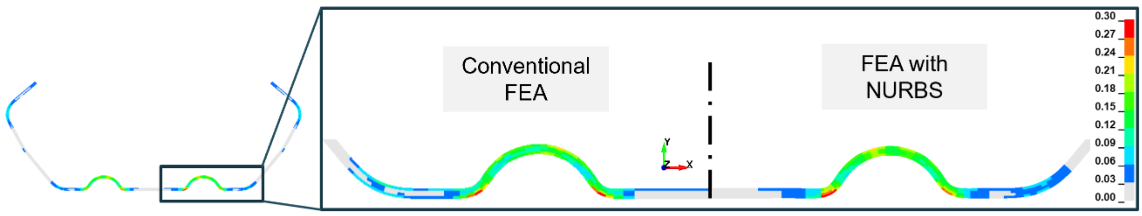

Fig.15: Comparison of the effective plastic strain section at the last stand

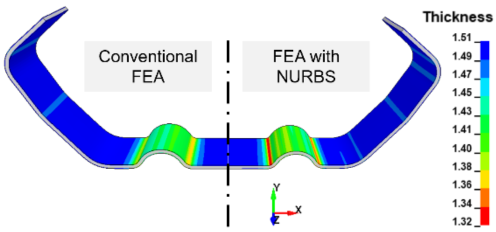

Fig.16: Comparison of thickness reduction after the last stand for a small portion of the strip

5 Summary

The general idea of Isogeometric Analysis (IGA) and the first possibilities of this method with NURBS solids in LS-DYNA have been compared with the classical finite element (FE) method for roll forming application.
It has been shown that the switch from FE to IGA is straightforward: Only the FE meshing should be converted for IGA. The comparison between FE and IGA shows similar results with more plausibility for IGA in particularly for plastic strain distribution through the thickness.
For roll forming, the next developments on the IGA will focus on better optimization of computing time, the implementation of trimmed solids, the modelling of the rolls with NURBS shells and the test on more complex modelling for the material like the anisotropy and the damage.
These first results with NURBS solids are promising not only for the roll forming application but also for massive forming. In the future, the quality and the time of the conversion from CAD to FEA will be improved and thus will reduce the error of discretization.

6 Literature

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