Periodic media transport and its application at voestalpine Krems

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Abstract: voestalpine Krems is a roll forming corporation constantly working on the improvement of product quality as well as the development of new production processes. Abaqus is used in both areas.

Ever since the introduction of periodic media transport in Abaqus 6.11 we were immediately drawn to it as it is very close in nature to our main production technology. Thus we intended to make use of it in order to decrease the time consumption while on the other hand being able to utilize the full capabilities of Abaqus.

Traditionally when modeling any kind of rolling process, a reasonable long strip of sheet metal is pulled through the mill or the production line, requiring a large number of "passive" elements not currently involved in the region of interest. The new feature "periodic media transport" enables the possibility to have only a small meshed region covering the interesting area.

Within this paper both approaches are shown and compared to each other. The first example problem shows a planetary rolling mill where we performed a feasibility study. The second example problem covers the whole roll forming process. The results are directly fed back to our engineering team to optimize the process. Critical further processing steps can be modeled afterwards by using predamaged parts.

Keywords: Cold Rolling, Design Optimization, Experimental Verification, Forming, Springback

1. Introduction

A periodic media analysis is a rather new modeling abstraction feature available in Abaqus/Explicit, which was first introduced in Abaqus 6.11 two years ago. The new feature was presented to us during a Dassault Systémes Simulia webinar and later on at the Austrian Regional Users Meeting 2011 in Salzburg.

This new technology is intended to model industrial processes where fairly simple structures are processed in a finite number of processing steps. The most prominent example problem listed in the manual is a simple conveyor belt, but metal rolling is also mentioned.

The idea behind that particular analysis technique is to stay well within the Lagrangian point of view all mechanical engineers are used to but focuses only on a stationary area of interest with material passing by, which is in principle a typically Eulerian problem.

As a result, a specific process can be analyzed for a predefined duration without the need of excessively large meshed parts. Instead of one large meshed part there are several topologically identical parts tied together.

Periodic media transport is not yet implemented in Abaqus/CAE. Therefore it has to be prepared at input file level by defining it at the model-level and activating it during the analysis step. According to the user manual, the required lines are like follows:

PERIODIC MEDIA, NAME=yourname***, INLET CONTROL NODE=***inletnode***, OUTLET CONTROL NODE=***outletnode***, ORIENTATION=***ori1***, TRIGGER NODE=***triggernode*
elset1, nodeset1, frontedgesurf1, backedgesurf1
elset2, nodeset1, frontedgesurf2, backedgesurf2
elset3, nodeset1, frontedgesurf3, backedgesurf3

***STEP**
***DYNAMIC, EXPLICIT**
***MEDIA TRANSPORT**
yourname, **ACTIVE**

Actually it is possible to specify the node number directly for all three control nodes, but a node set containing exactly one node each control node may be more convenient. The required sets and surfaces may also be defined at assembly level, while by using the parts and instances technique sets and surfaces defined on part-level may be the preferred method.

The definition of the periodic media is quite tolerant, for example the outlet control node can be specified by the keywords “OUTLETCONT”, “OUTLETCO”, or “OUTLET CONTROL NODE”. The periodic media in the first example, the roll forming analysis is defined as follows:

PERIODIC MEDIA, NAME=Ring***, INLETCON=***IN***, OUTLETCO=***OUT***, ORIENTAT=***PMTori***, TRIGGERN=***TRIGGER*
LS-21.band, LS-21.band, LS-21.Front, LS-21.Back
LS-20.band, LS-20.band, LS-20.Front, LS-20.Back
LS-19.band, LS-19.band, LS-19.Front, LS-19.Back
…
LS-3.band, LS-3.band, LS-3.Front, LS-3.Back
LS-2.band, LS-2.band, LS-2.Front, LS-2.Back
LS-1.band, LS-1.band, LS-1.Front, LS-1.Back

In this definition, node sets are used to specify the control nodes and the required sets and surfaces were defined at part level.

1.1 Roll forming

Here at voestalpine Krems we usually have both, a continuous process of metal forming by bending a metal strip at each stage a little bit more towards its final shape. That technology is called roll forming and it is very efficient in case of the production of almost any kind of basically extruded cross section. While the cross section is traditionally fixed, parts of different length can be produced without big difficulties. Figure 1 illustrates the forming principle on a typical roll forming cross section. The figure includes a schematic drawing of the cross section as well as a perspective view of profiled strip starting at the flat strip passing each forming stage towards the final tube. On the right hand side of Figure 1 the whole sequence of single forming steps is shown, which is commonly referred to as roll forming flower.

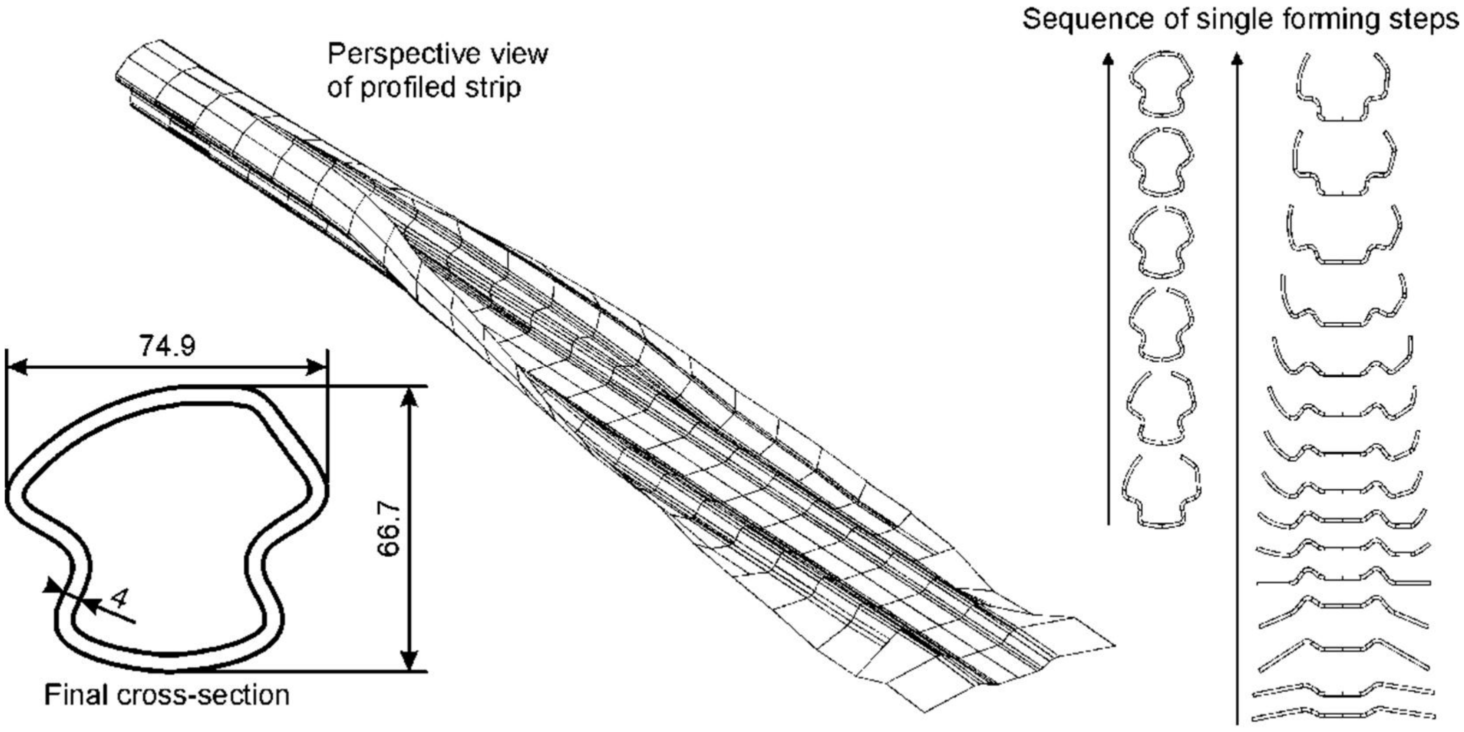

Figure 1. Profile forming principle.

As of now, there is no real theory available concerning roll forming. Most of the literature is based on the author's experience. One of the most encyclopedic is the 'Roll Forming Handbook' by George T. Halmos. As a result, even the best literature available covers only standard problems. If you are facing a very challenging cross section, which means both in terms of complexity of the cross section itself as well as compared to the capabilities of your roll forming line, you will almost never be able to find a good solution in the literature.

Usually, each generation of engineers within a company extends the roll forming knowledge a bit further and passes their knowledge on to the younger engineers.

In former days, the knowledge got extended by means of many trials with lots of scrap metal. Nowadays, this approach is still valid but because of the heavy competition in this market segment it is getting more and more too expensive. Thanks to increased computer power numerical experiments can be conducted to find an optimum sequence of single forming steps. Once an acceptable roll forming flower is found the necessary rolling tools are manufactured and the project is transferred into the production phase at the roll forming line.

2. Analysis setup

2.1 Roll forming process

Probably the biggest challenge on performing roll forming simulations is the problem size. Typically a production line consists of 15 to 60 possible forming steps with a distance between each other of a magnitude of about one meter. These numbers result in a workpiece just within the production line of a length of approximately 60 meters at a cross section usually fitting within a 0.3mx0.3m square. Using anything but shell elements would result in a not reasonable computation time.

Before abaqus' new analysis technique periodic media transport, which will be referred to as 'traditional' approach, a simulation of a roll forming process required a very long workpiece, usually approximately twice as long as the length of the production line. Advantageous of not using periodic media transport is the possibility of any boundary or load condition the engineer might see fit, even a symmetry boundary condition in case of symmetric profiles can be applied.

As soon as we use periodic media transport for that kind of simulation we can reduce the length of the metal strip drastically. It needs to be just a little bit longer that the length of the production line and splitting the strip into blocks of equal length as the distance between two consecutive forming steps proved to work out well. Because of the nature of that kind of analysis, boundary conditions can be applied only at two predefined nodes, being internally coupled to the front and back surfaces of the first respectively last block of the queue. Therefore, even on symmetric problems the full cross section has to be simulated. That cancels out any benefit in problem size for symmetric cross sections do to the reduced metal strip length compared to not using periodic media.

Both approaches will be compared to each other by forming a simple w-shaped profile as shown in Figure 2. The required material data was provided by the steel vendor.

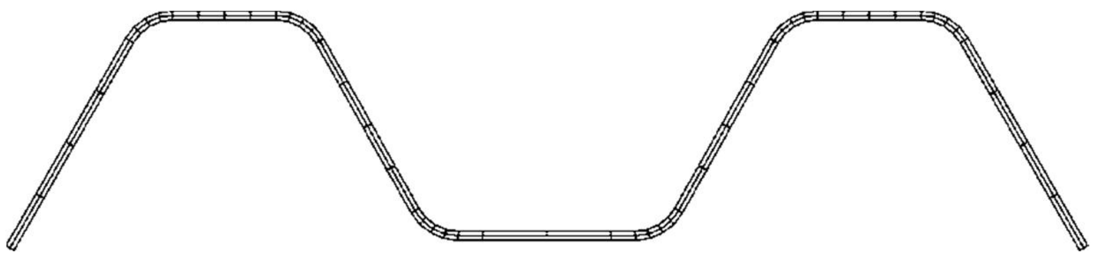

Figure 2. 'W'-shaped profile, structural steel S355J2, 2.8mm thickness.

Figure 2 also shows the middle surface representing the shell as well as the meshed shell elements. In order to get more control over the meshed part was well as to have the initial workpiece already put into the production line, the workpiece as well as the single blocks forming the whole workpiece were created by small excel scripts and imported into Abaqus/CAE. An additional benefit was the reduced influence of mass scaling as roll forming is a rather slow forming principle. Afterwards, the rolling tools were constructed within Abaqus/CAE as well as the assembly created. Both assemblies as shown in Figure 3 for the periodic media analysis and Figure 4 for the traditional analysis use the same rolling tool setup, speeds and boundary conditions.

Key features of both analyses:

- 4 type S4R elements along each straight section and each radius. $20\ mm$ sized elements in roll forming direction.
- 18 single forming steps +1 cylindrical feed stage, $900\ mm$ distance between two consecutive stages.
- Tool rolls are modeled as analytical rigid bodies.
- 'General Contact' algorithm excluding self-contact of the metal strip. This was necessary to eliminate the contact thickness reduction in order to achieve correct forming conditions.
- Eliminate initial overclosure: upper and lower rolls are initially $0.1\ mm$ away from strip surface. Upper and lower rolls move collectively into their final position within the first $0.1\ s$ simulation time.
- Initial velocity of $1000\ mm \cdot s^{-1}$ for the metal strip and initial rotating velocities of all tool rolls according to their mean diameter.
- Metal strip speed equals $1000\ mm \cdot s^{-1}$, resulting in $16.2\ s$ travel time to pass all stages.

2.1.1 Periodic media analysis

Initially there are 18 blocks between the 19 tool stages and one additional block at the outlet end and two more at the inlet end of the periodic media and is roughly illustrated in Figure 3. This results in a total amount of 21 blocks of 52x45 elements. According to the manual, there are a few things possible while setting up a periodic media and some others are mandatory. Details are listed in Table 1.

Table 1. Periodic media analysis - details.

Possible	Mandatory
Arbitrary positioning of inlet and outlet control nodes.	Existence of inlet, outlet and trigger-control node.
Blocks may be deformed prior to analysis start to speed up setup effects.	Periodic media setup: Blocks must be listed in direction from inlet to outlet node.
Arbitrary origin of the coordinate system.	Named coordinate system with positive z-axis pointing from periodic media inlet to outlet.
Arbitrary mixture at each node, e.g. Inlet:v_1+v_2+f_3, Outlet: f_1+f_2+v_3	Concentric force or velocity in all three directions at inlet and outlet control node.

Especially the mixture of velocity-boundary condition and concentrated force seemed to be very interesting, as the strip is stretched due to the roll forming process and applying velocities at both inlet and outlet control node would result in some sort of buckling, most likely at the beginning of the roll forming line. For some reason mixing up forces and velocities didn't work correctly. It looked like as if the velocity boundary condition would not be applied correctly after the first block is shifted for the outlet to the inlet. Some severe distortions like crashing at a solid surface occurred. As soon as velocities were applied at both control nodes, the simulation finished correctly.

Figure 3. Assembly of periodic media analysis.

2.1.2 Traditional analysis

The metal strip has a length of 42 blocks compared to the periodic media analysis. Like at the periodic media analysis, there is an equal of one block length in front of the last single forming step, the rest is either in between the roll forming line or at the inlet end of it. The assembly is roughly illustrated in Figure 4 including a zoom on the roll forming line. This results in just twice as many elements (98280 elements of type S4R) as in the periodic media analysis.

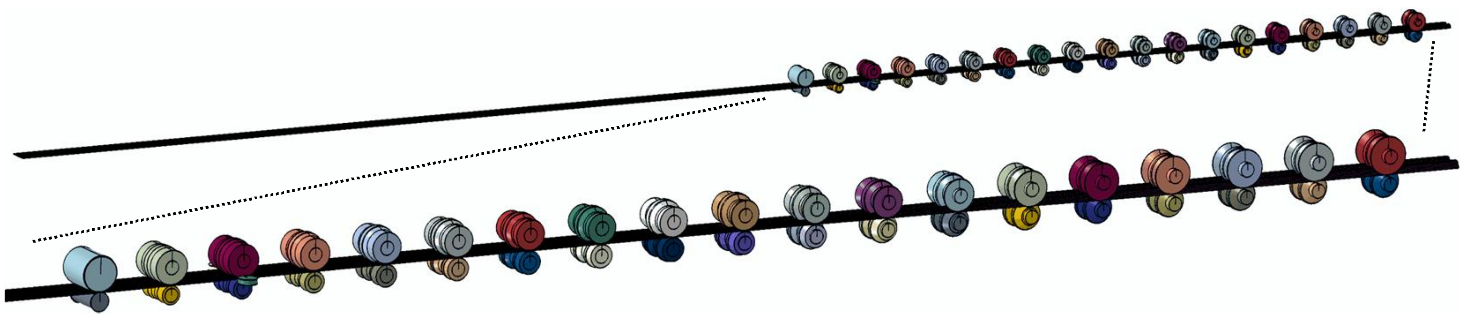

Figure 4. Assembly of traditional analysis.

Applying different boundary conditions at the front and back surface was easily possible. Therefore, just a pulling velocity at the front surface and a concentrated force at the back surface were applied.

2.2 Planetary rolling mill

Due to the strong demand of lightweight structures, many roll forming companies do extensive research on the inline production of either profiles with varying cross section along their length or cross sections with varying wall thickness. There is extensive literature showing at least the basic idea on how to achieve such a thickness reduction. Most of these documents are found while studying patent applications. Some ideas may require a number of single forming steps to achieve the necessary thickness reduction (e.g. USG Interiors Inc., 1990; Hilti, 2009), others use multi roll tools to work at one single forming stage (e.g. voestalpine Krems, 2012; Hitachi Ltd., 2000).

In this paper a planetary rolling mill is used to reduce the wall thickness in a small center region of the metal strip. The basic working principle is shown in Figure 5.

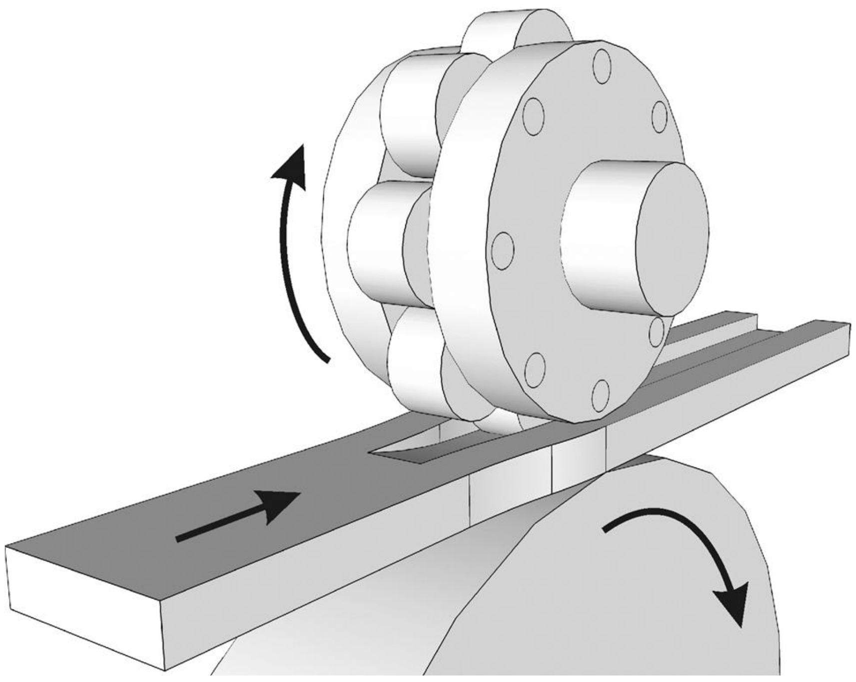

Figure 5. Principle of planetary rolling mill.

In theory, this is where the computation time should benefit most because of the new periodic media transport technology. For an explicit analysis the computation time depends on both problem size in terms of total degrees of freedom as well as simulation time in a more multiplicative way as given in Equation 1,

$$t_c \propto N \cdot T, \qquad (1)$$

where t_c represents the computation time needed to advance the solution until the desired analysis time T for all N degrees of freedom. For the feasibility study of the planetary rolling mill a steady state condition should be reached and the deformation as well as forces should be investigated. But when is this steady state achieved? It is hard to tell in advance of the analysis. If the planetary rolling mill is modeled without periodic media, one has to create a metal strip long enough to have no boundary effects within the region of interest. This requires the strip length to be related to the simulation time. As of now, these considerations are very simple. But what's the situation as one decides after the first analysis that the steady state was not achieved and e.g. doubling the simulation time is necessary? A reasonable assumption could be made by doubling the strip length, which will result in about twice as many degrees of freedom. Therefore, one can estimate the change of the computational costs for doubling the original simulation time T_0 for both analysis approaches. We approximate the computation time $t_{c,2}$ for the periodic media analysis,

$$\mathrm{t}_{\mathrm{c,2,PMT}} \propto \mathrm{N} \cdot (2 \cdot \mathrm{T}_0), \tag{2}$$

to be probably twice the original computation time $t_{c,0,PMT}$. Similar considerations for the traditional analysis lead us to

$$\mathrm{t}_{\mathrm{c,2,TRD}} \propto (2 \cdot \mathrm{N}) \cdot (2 \cdot \mathrm{T}_0), \tag{3}$$

where we get four times the original simulation time $t_{c,0,TRD}$. Therefore we see that on a traditional analysis the computational costs rise according to the longer strip compared to the periodic media analysis. Of cause these calculations are only valid if both analysis approaches have comparable computational costs in the first place but that depends on many other parameters, e.g. symmetry conditions, lead time, strip length necessary to keep the influence of the boundary conditions out of the region of interest, …

The feasibility study was performed with an equal set of parameters for both analyses:

- 8-Roll planetary rolling mill
- Planetary roll: $46\,mm$ diameter, $20\,mm$ width, $2x4\,mm$ chamfer
- Sun roll – not included: $84\,mm$ diameter
- Planetary holder: modeled as beam and hinge connectors, driven at $50\,rad \cdot s^{-1}$
- Metal strip: $60\,mm$ width, material: DD11, $4\,mm$ thickness, driven at $54\,mm \cdot s^{-1}$
- support roll: $180\,mm$ diameter, driven at $0.6\,rad \cdot s^{-1}$

2.2.1 Periodic media analysis

Since in a periodic media analysis no symmetry boundary condition can be specified, the complete process needs to be modeled. The first assembly setup was prepared with 5 blocks of $20\,mm$ length with 30x10x8 elements to form the periodic media. Due to some strange artifacts caused by a too small designed process area the results could not be considered trustworthy. Therefore, 3 blocks were added at the input and outlet end of the periodic media and some guidance rolls were added. Mesh size varied across strip width to be less coarse in the center region where the working area of the planetary rolling mill is located. The mesh was deformed by using a small Excel script to do all positioning in the assembly without any further translator movement of rolls or the strip at the beginning of the analysis. Therefore we have 12000 elements in the first assembly and 28800 elements of type C3D8R in our final model both with enhanced hourglass control and second order accuracy activated. Velocity boundary conditions were applied at both inlet and outlet control nodes. A rigid body boundary condition was enforced at the planetary rolls and the support roll. The both assemblies are shown in Figure 6, the first one on the left hand side, the final one on the right hand side.

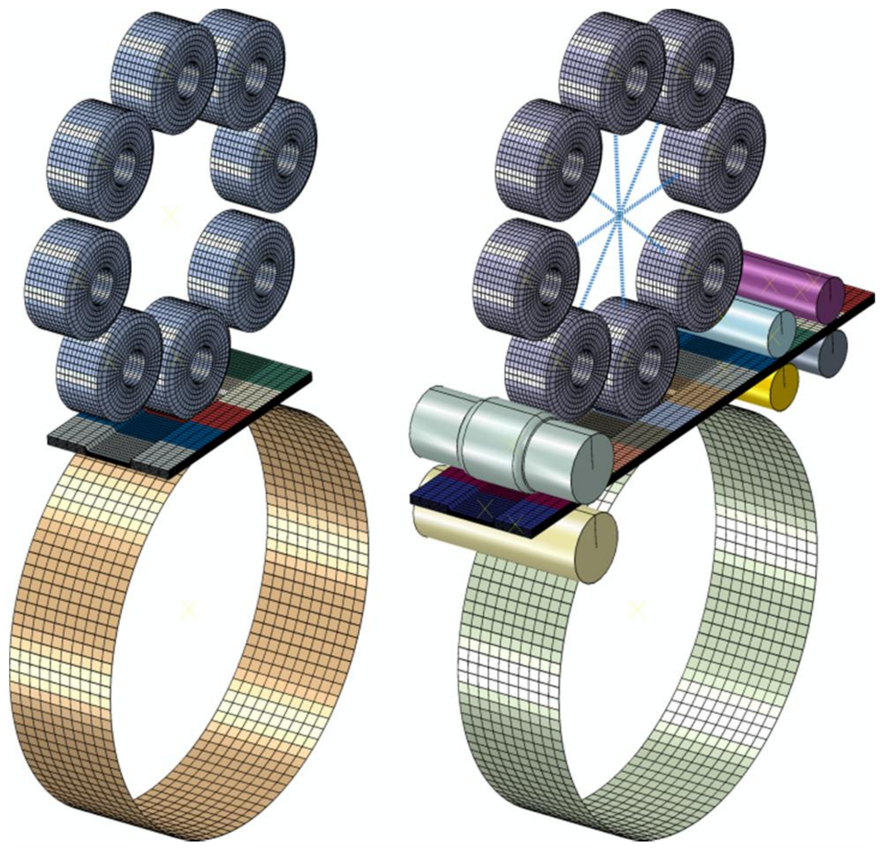

Figure 6. Planetary rolling mill assemblies featuring periodic media technology.

2.2.2 Traditional analysis

Because of the expected high number of elements only one half of the planetary rolling mill was assembled and a symmetry constraint enforced. As both analyses approaches were prepared almost simultaneously, there are 2 assemblies as well. The metal strip was prepared by aligning in the first approach 15 blocks (23 flocks for the final assembly) from the periodic media analysis and merging them in Abaqus/CAE to one single part. Afterwards half of the elements and thus unconnected nodes of the metal strip were deleted. Therefore the strip was finally meshed with 27600 elements of type C3D8R with both enhanced hourglass control and second order accuracy. The same guidance rolls are used as in the periodic media analysis.

A velocity boundary condition was applied at the front surface, while the back surface was constrained to a node carrying a concentrated force opposite to the strip velocity direction. The symmetry condition completed the set of boundary conditions on the metal strip. Rigid body boundary conditions were enforced at the planetary rolls and the support roll. The final assembly is shown in Figure 7 on the right hand side. Contrary to the periodic media assembly, the beam connector elements being part of the planetary holder modeling are not perpendicular aligned to the axis of rotation to allow a view on the hinge connectors parallel to the axis of rotation.

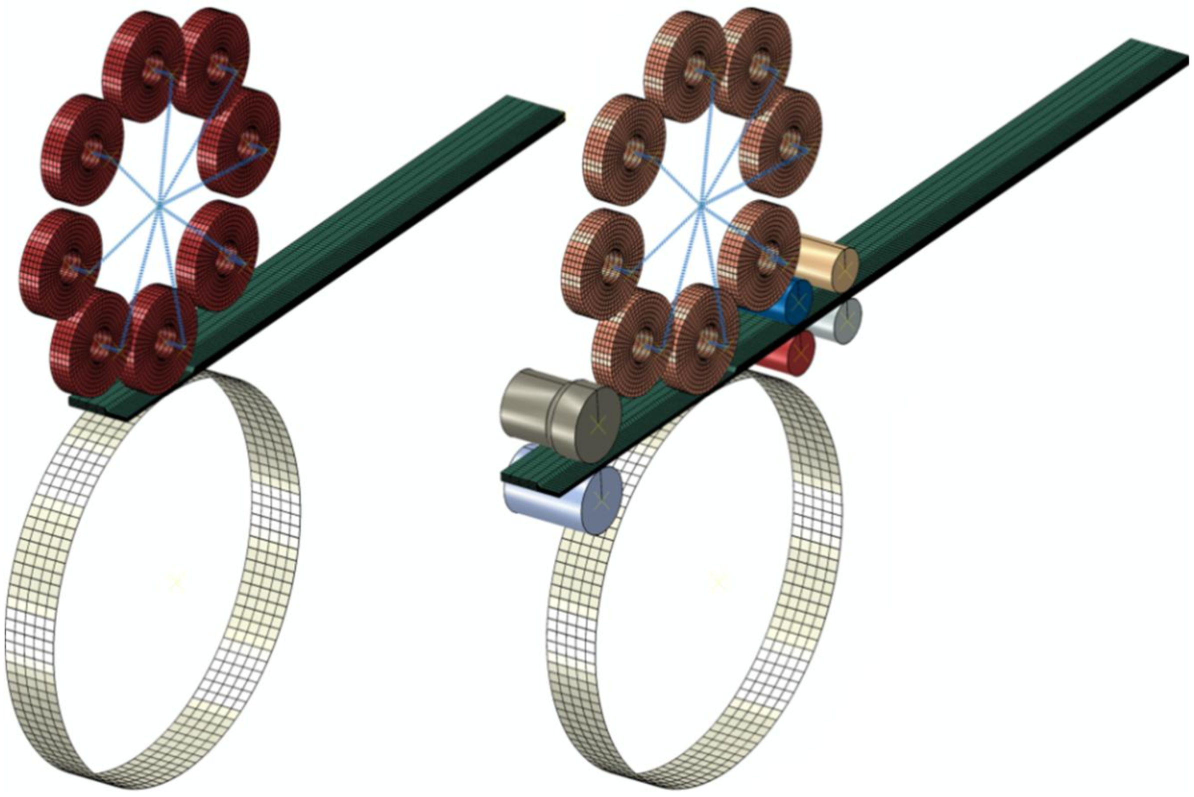

Figure 7. Planetary rolling mill assemblies without periodic media.

3. Results

3.1 Roll forming

At these large models the speed differential due to analysis technique was quite impressive. The traditional approach took 44530 seconds at 12 CPUs while the periodic media analysis ran for 25639 seconds at the same number of CPUs of the machine. Therefore, the periodic media Analysis took only 58% of the traditional approach's computational time.

Because of the huge dimensions und long computation time, mass scaling was used extensively. Therefore, deformation artifacts caused by the mass scaling, mainly in the region of huge deformations were reduced by deforming the mesh prior to the analysis. The results of both analyses can be observed in Figure 8 for the periodic media analysis and Figure 9 for the traditional analysis.

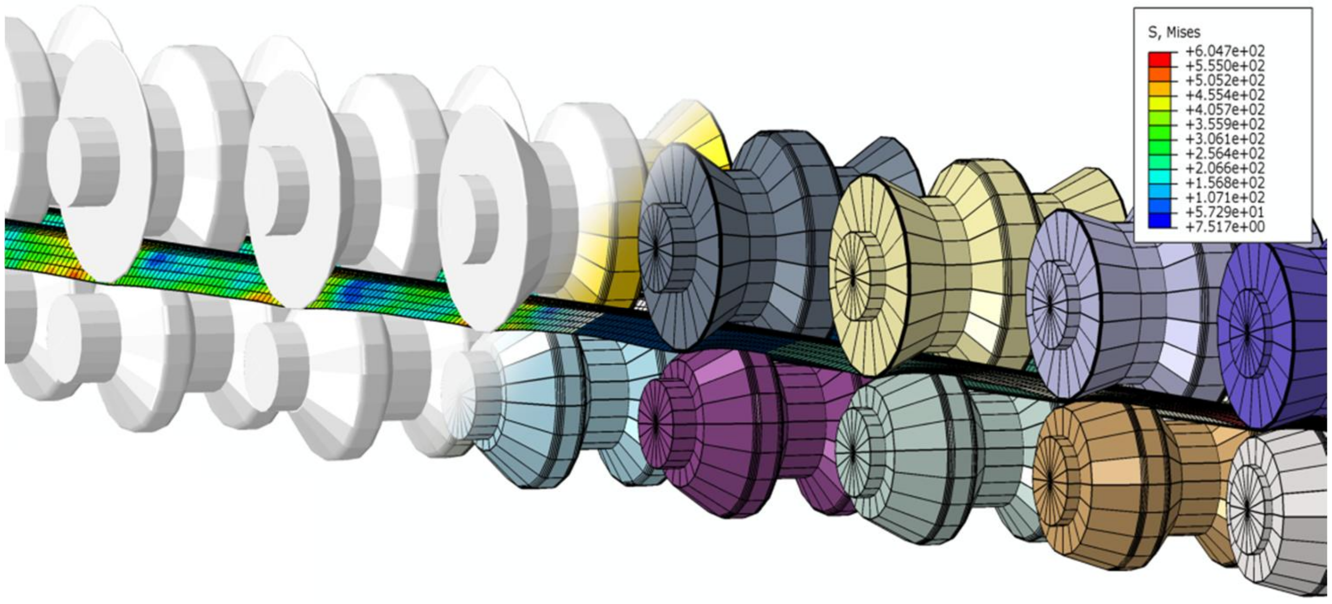

Figure 8. Periodic media analysis.

Because of the internal tie constraints which are used to build up the periodic media, there is often some kind of unphysical stress-jump visible at the interface between two consecutive blocks. Usually that problem is linked to mesh density and can be reduced by a refined mesh. On the left hand side of Figure 8 von Mises stress is plotted. Figure 8 shows nicely that due to the slow forming process of roll forming even a very coarse mesh like the one used isn't influencing the analysis' results too much.

Comparing the stress levels of both results shown in Figure 8 and Figure 9 we get good agreement between both analysis approaches.

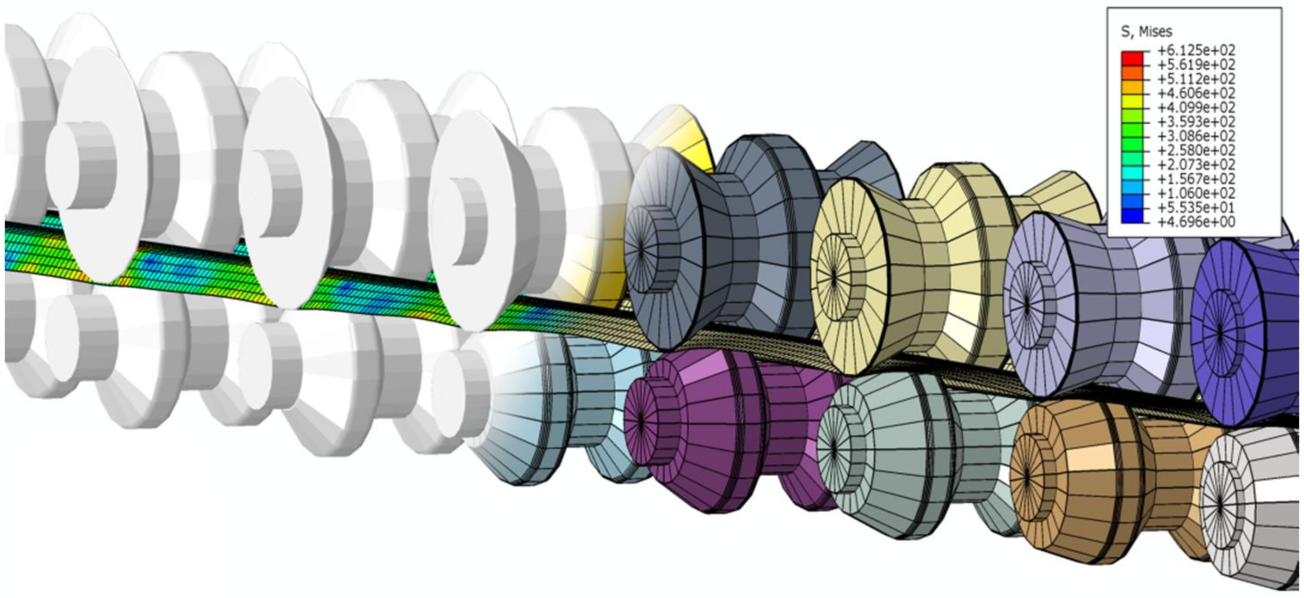

Figure 9. Traditional analysis.

Comparing the cross section development at constant intervals, e.g. 4 seconds shows good agreement as well. The cross section profiles are shown in Figure 10, where the continuous line represents results from the periodic media analysis and the dashed line the corresponding results from the traditional analysis.

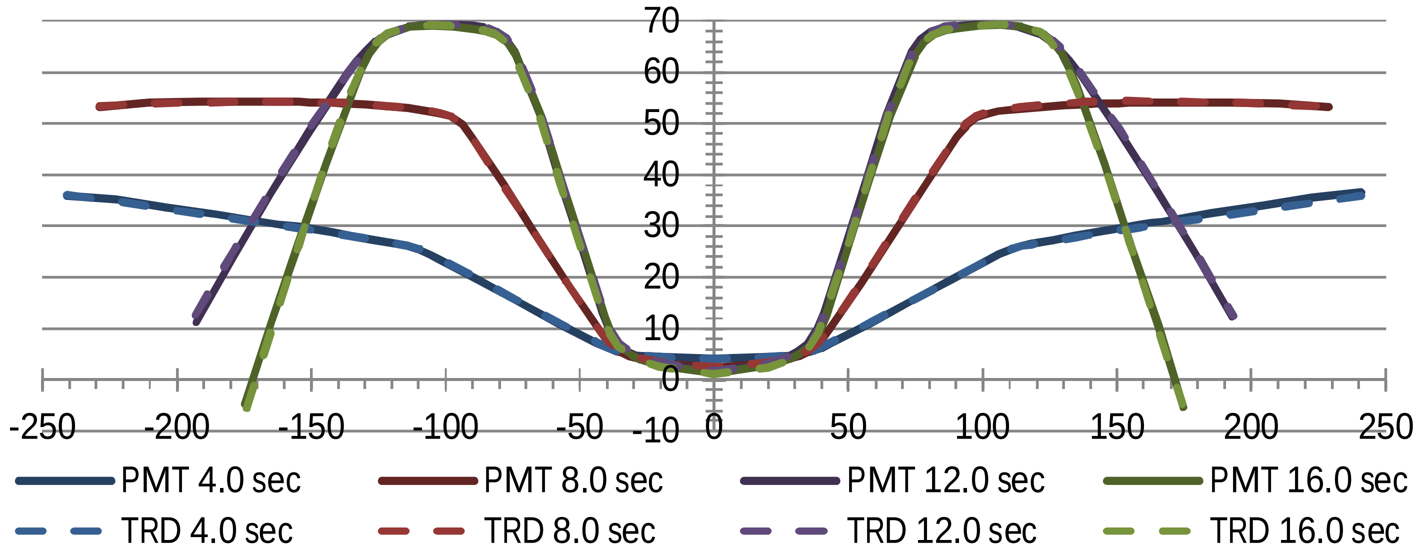

Figure 10. Comparison of cross sections at different time stamps.

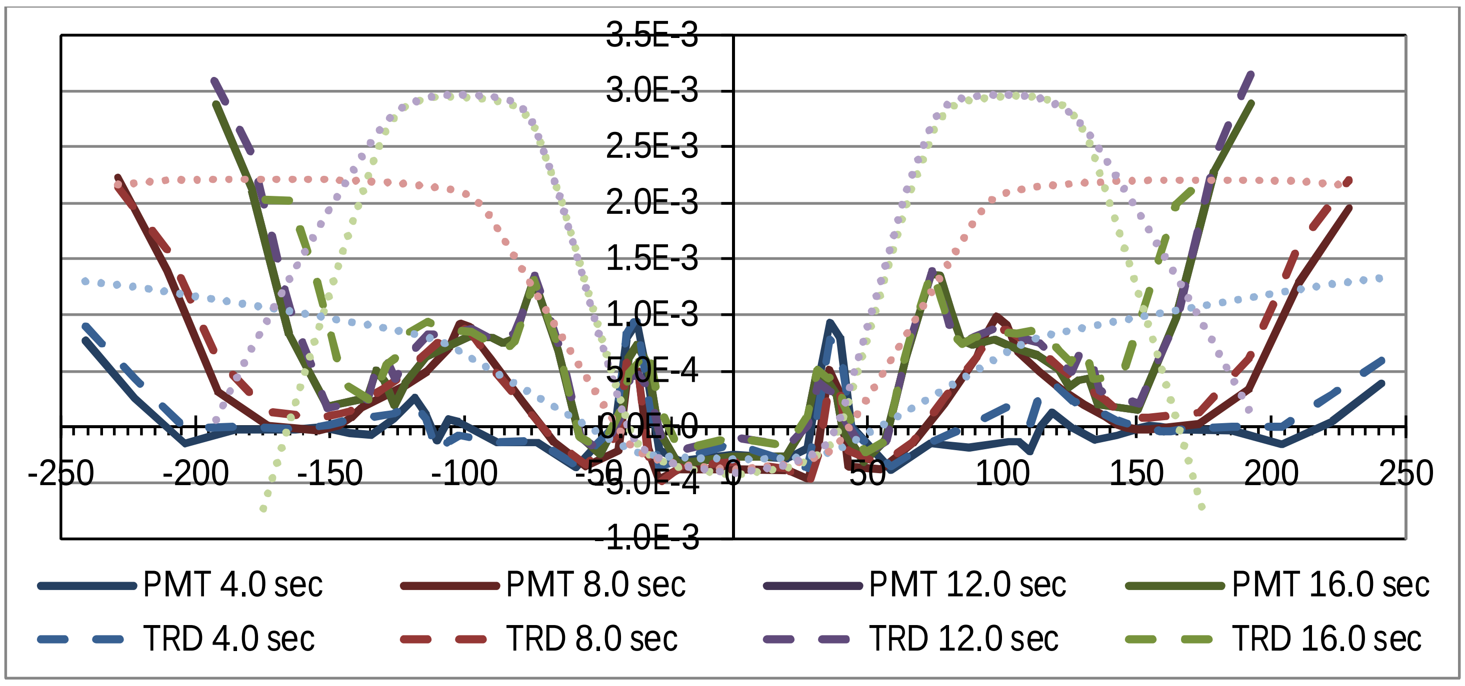

Figure 11. Plastic strain component in roll forming direction.

The next very important results which will be compared are plastic strain levels in process direction as these strains cause twist and deviation from straightness. The PE22 plastic strain component in roll forming direction is plotted in Figure 11, where the continuous line corresponds to the periodic media analysis and the dashed one to the traditional analysis. For orientation purpose the dotted line represents the cross section at the same time stamp. Other useful evaluations are the waviness at the strip edge, which is shown in Figure 12.

The best line fit which was used to create Figure 12 was calculated by means of Excel, using the solver module by minimizing the sum of the distances of each point to the best line fit. The best line fit L may be given by Equation 4

$$L = \vec{M} + \lambda \cdot \vec{t}_0, \tag{4}$$

with the center point $\vec{M}$, the parameter λ and the tangential unit vector $\vec{t}_0$. The distance was calculated by Equation 5

$$d = \left|(\vec{p} - \vec{M}) \times \vec{t}_0\right|, \tag{5}$$

where d represents the distance of point $\vec{p}$ to the best line fit defined in Equation 4. This procedure is illustrated in Figure 13 and helps for better understanding of Figure 12.

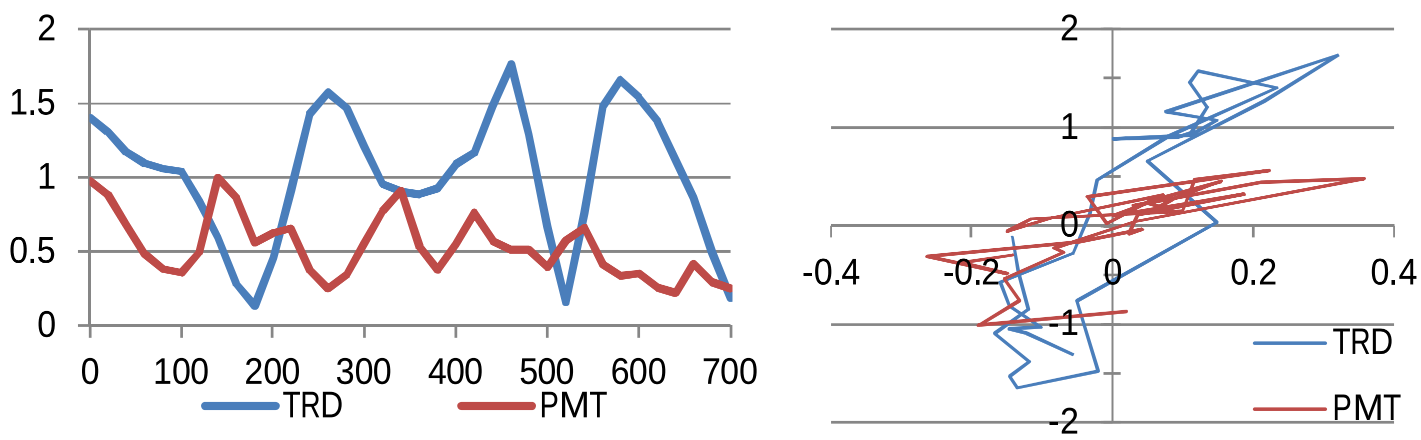

Figure 12. Waviness of strip edge compared to a best line fit.

With both figures at hand the interpretation of Figure 12 is much easier. On the left hand side all distances d_i are plotted over their position in strip feed direction. One can see that the result from the periodic media analysis is in general much closer to the best line fit that the result from the traditional approach. Of cause, since just the distances are plotted, all information regarding the kind of deviation is lost. On the right hand side of Figure 12 that information is retained as it is a view on the node position viewed along the best line fit unit vector $\vec{t}_0$. It is obvious, that the periodic media analysis scatters much less as all node coordinates are significantly closer to the origin which represents the best line fit.

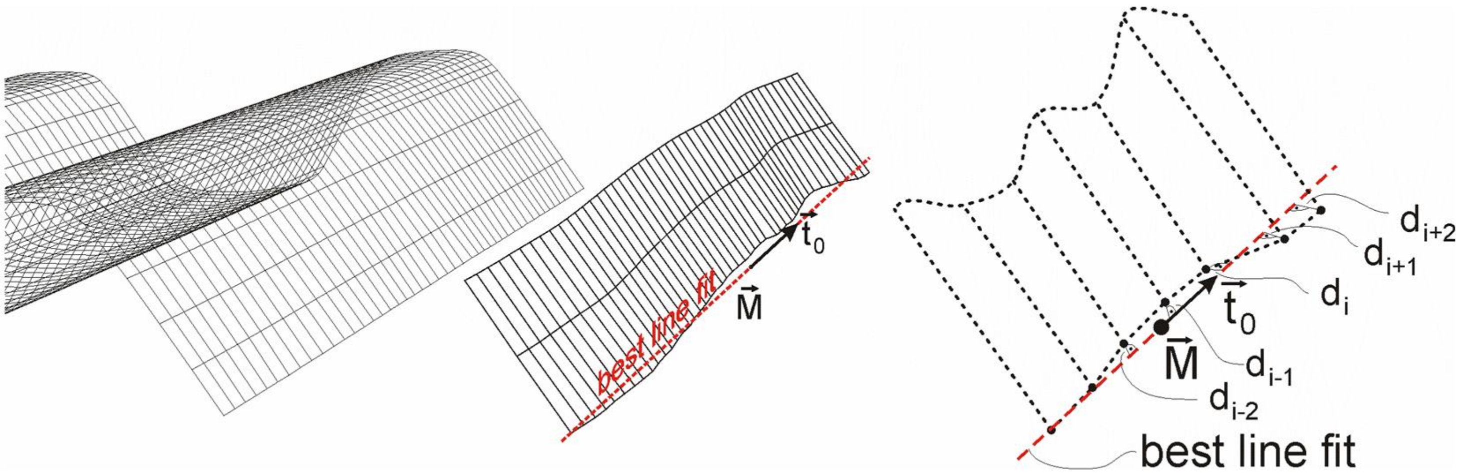

Figure 13. Best line fit.

Figure 14 illustrated the shell thickness distribution along the cross section to assess difficulties due to necking. The dotted lines represent again the cross section profile for orientation purpose.

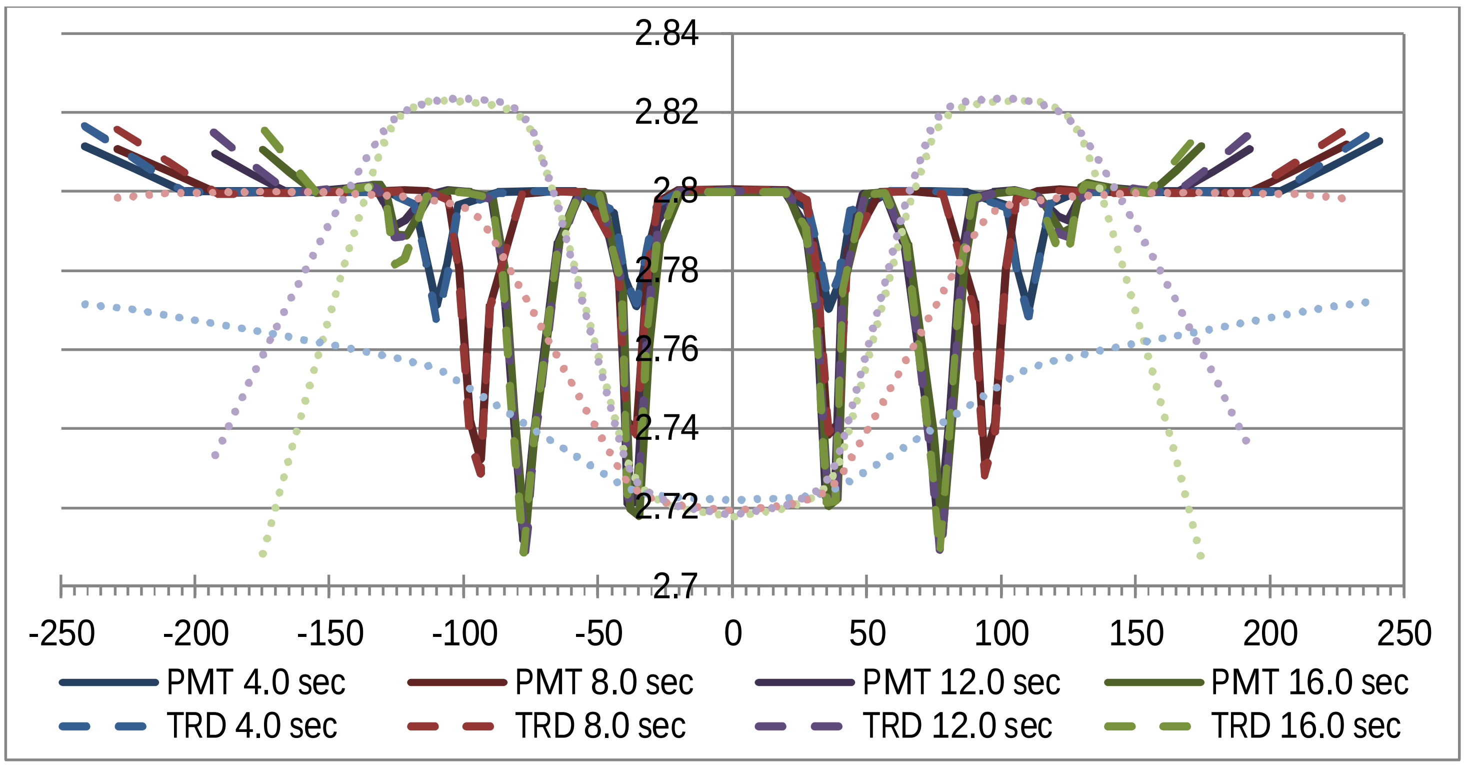

Figure 14. Shell thickness comparison.

3.2 Planetary rolling mill

At this model the speed differential due to analysis technique was very well observable. The traditional approach was more than twice as fast as the periodic media analysis. In addition, it was quite easy to handle within Abaqus/CAE and completed quite straight forward. The periodic media analysis on the other hand is prepared on input file level and some unexpected behavior occurred. Figure 15 gives an overview of the results of the traditional analysis. The results are very reasonable and mirrored in the visualization module at the YZ-plane.

Figure 15 clearly illustrates that the basic principle is working quite well. The wrapping of the metal strip is not acceptable so guiding rolls should be included in a further analysis. This was done in the second model to fit to the final periodic media analysis. Simulation time seems to be sufficient although almost one third of the strip shows run-in effects.

Contrary to these very promising results those of the periodic media analysis need to be assessed with caution. Figure 16 shows two plots of the results of periodic media analyses. On the left hand side incompatible mode elements are used with no mass damping, but the analysis aborted 2 frames later due to excessive wave speed / highly distorted elements. Additionally to that abortion, the results showed some unrealistic behavior as the strip edge is since the first shift operation no longer a smooth surface. It doesn’t necessarily depend on the internal tie constraints the strip edge is smooth at the interface between the three not yet shifted blocks in the front.

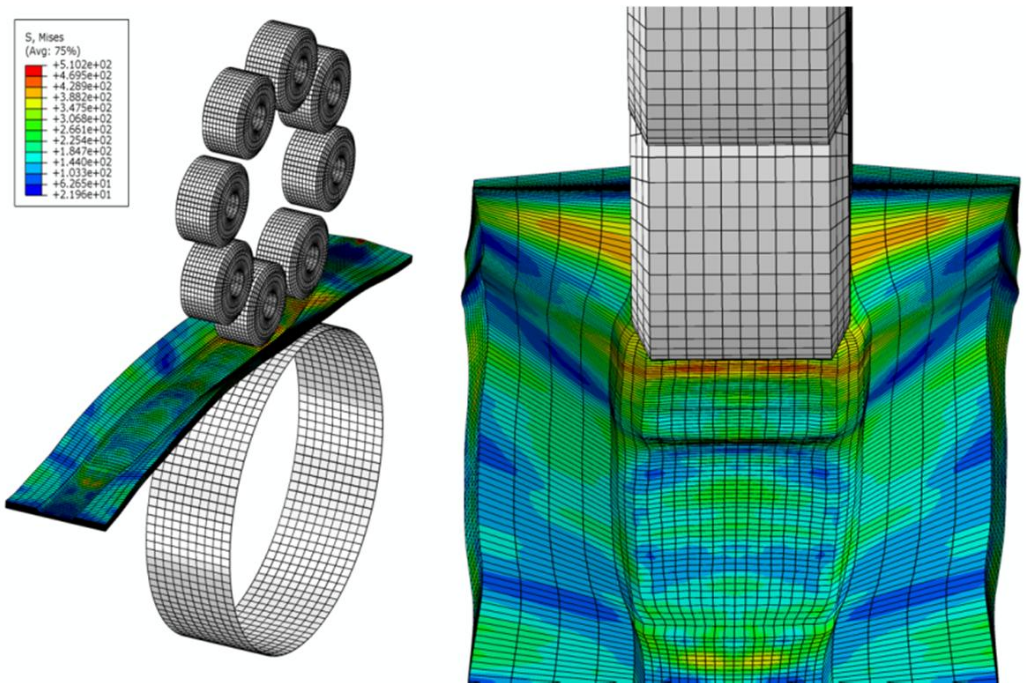

Figure 15. Planetary rolling mill – traditional results overview.

On the right hand side in Figure 16, reduced integration elements are used and mass damping was added. This was done as the manual recommends a small amount of mass damping due to shocks initiated from the shift and tie process related to the periodic media. Since the planetary rolling mill also may cause massive shocks, damping might help.

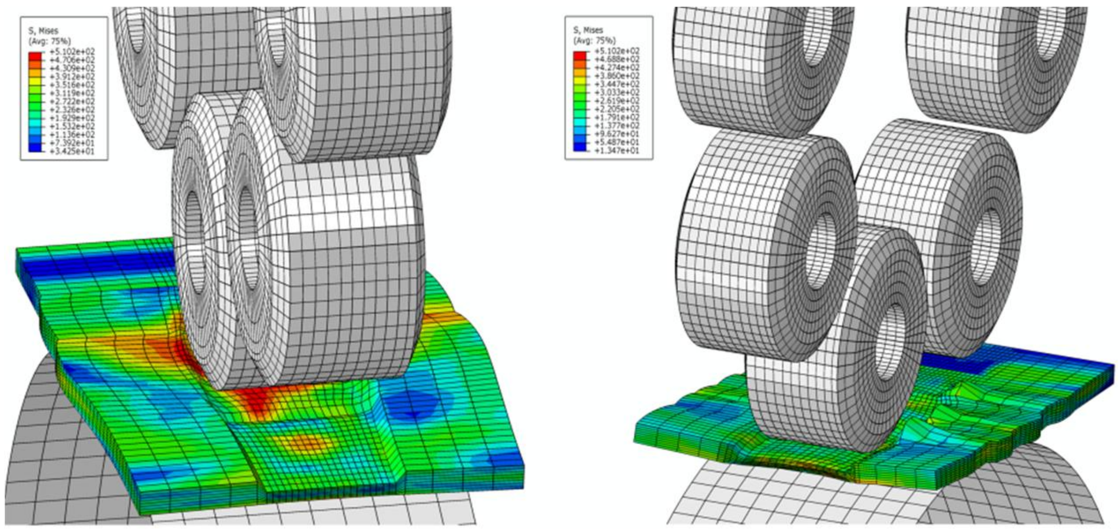

Figure 16. Periodic media analysis - simulation results.

This approach didn’t work well either. While the analysis didn’t abort this time and continued the calculation the results are still not satisfying. For some reason, right after the first shift operation, a small lump arose in the metal strip in the newly attached block right after the interface to the next block. These lumps grow in time to reach a stable size as seen in Figure 16 on the right hand side. Increasing the mass damping helps in keeping the lumps small but they arise anyway.

After intensive discussions with Simulia support the reason for the difficulties during the periodic media analysis were identified. The process area was way too small for the magnitude of deformation occurring within the model. Enhancing the model as shown on the right hand side of Figure 6 led to the results shown in Figure 17 for both analyses types. On the right hand side are the results of the periodic media analysis, on the left hand side those of the traditional analysis. Both deformed shapes are very reasonable and very similar to each other. Von Mises stress levels fit to each other quite well too.

The most interesting result despite of evaluating the working principal is the reaction force in direction of the strip thickness which is shown in Figure 18. There is a general difference in the maximum force amplitude of about 40% but the values of the force peaks scatter quite strongly. That may be caused by numerical imperfections as the measured distance in case of the periodic media analysis from the fulcrum to the center of any planetary roll averages $\bar{r} = 65.00465\text{mm}$ at a standard deviation of $\sigma = 0.0117\text{mm}$.

Averaging all peak amplitudes by integrating the reaction force and comparing the time integrated forces still shows a force magnitude approximately 11% bigger in the periodic media analysis.

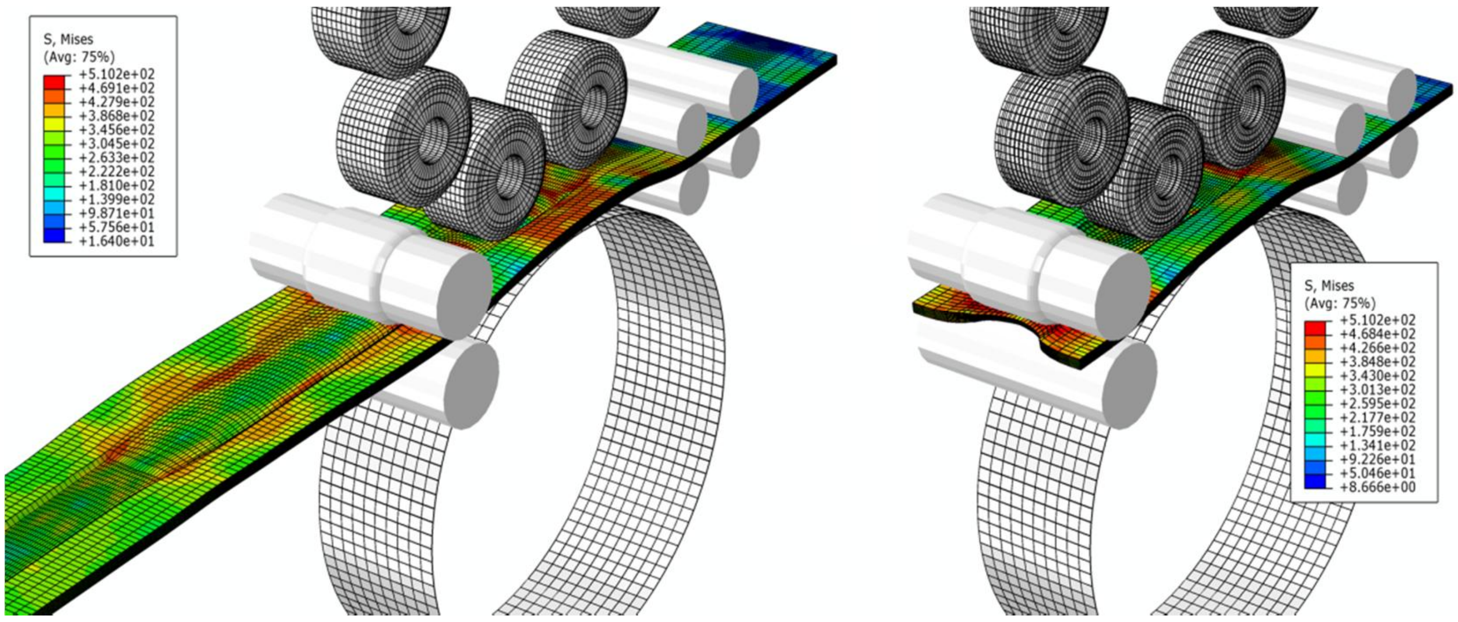

Figure 17. Final results of the feasibility study.

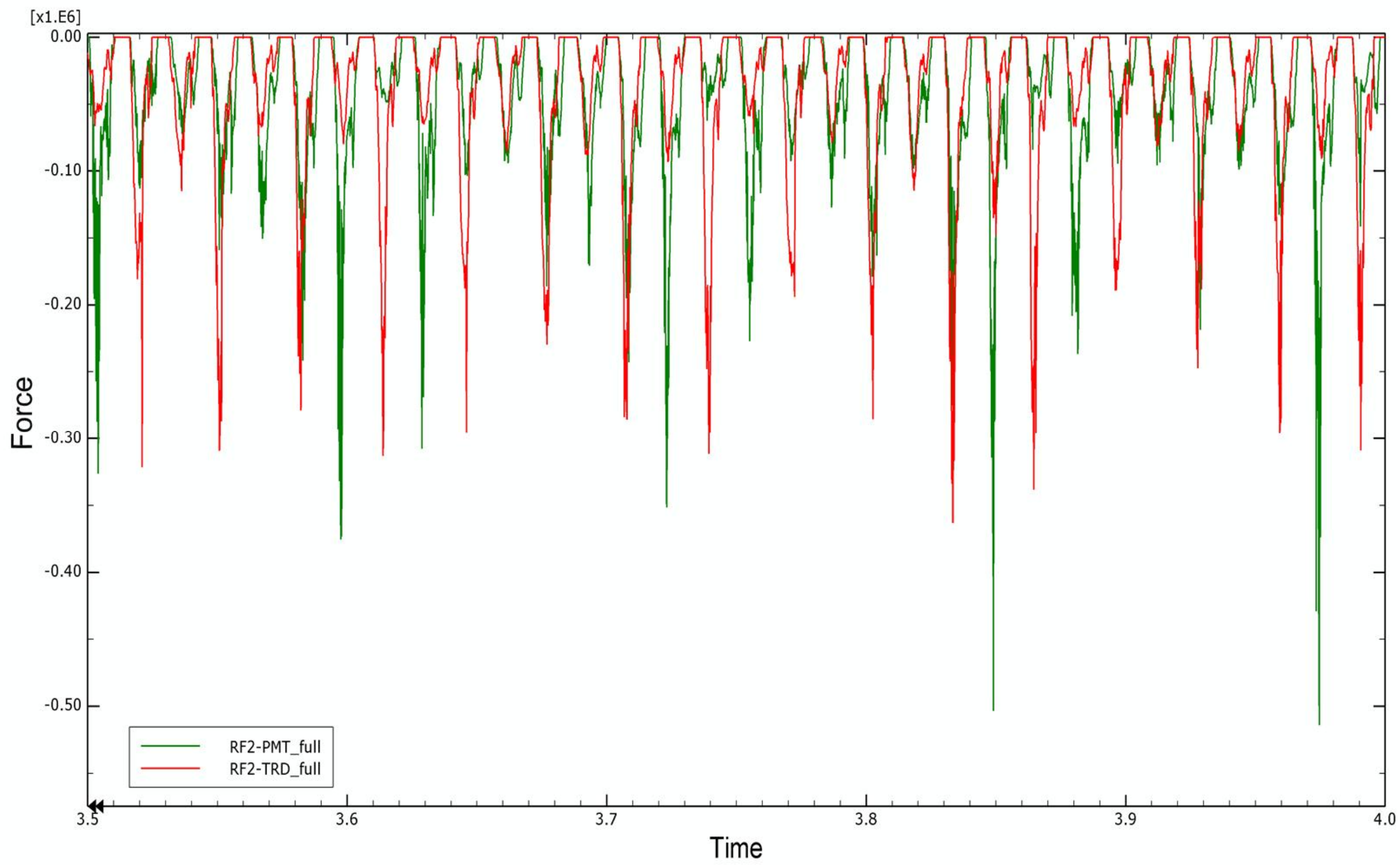

Figure 18. Comparison of the reaction force in strip thickness direction.

4. Summary

Periodic media transport is a new and very interesting analysis technique available in Abaqus/Explicit. Although it is a bit more complicated to set up as preparation work has to be finalized on input file level it is set up quite fast as soon as you get used to it. Right now there seems to be some discrepancy between features possible according to the manual and what will work in the analysis.

Restrictions of periodic media analysis:

- The process area has to be large enough to ensure that the shuffled block is tied to a perfectly planar node surface at the moment of shuffling. Deformations may not reach to the trigger plane, which is quite hard to define prior to the analysis. Fortunately, it is quite easy to add additional blocks at the inlet end to overcome that problem as soon as it is recognized.
- Stick to double precision explicit analysis. A single precision analysis might fail as the tie constraint can fail at the first shuffling operation without any warning. While the preprocessor reports such a distance between the opposing node surfaces of two consecutive blocks Abaqus/Explicit continues the analysis even with such a gap.
- Importing results of a pretension analysis should be done with the **`*import`** keyword instead of using predefined fields. Predefined fields do not work properly with shell elements.
- Exact bookkeeping while creating the periodic media: block sequence, front and back node-based surface created from unsorted node sets.
- Works well with velocity boundary conditions, mixed boundary conditions may be used with caution.
- No symmetry boundary conditions can be applied.
- Mesh density strongly depending on degree of deformation if unrealistic jumps in stresses should be avoided.
- Mass damping may help to analysis to overcome numerical problems.

Periodic media transport analyses will probably be chosen in case of roll forming analyses, especially if roll forming results should be processed in a further analysis. Solid structures analyses are quite rare as our products are made from sheet metal with usually no intend for massive forming procedures. Therefore, periodic media transport analyses will be taken into account for solid structures only on occasion.

Periodic media transport analysis might be of special interest as soon as it can be combined with electromagnetic analyses to simulate high frequency welding.

5. References

1. Abaqus Analysis User's Manual, Version 6.12-1, Dassault Systémes Simulia Corp., Providence, RI.
2. Roll Forming Handbook, George T. Halmos, CRC Press, 2005
3. US 4 969 349A – Apparatus for Producing Cold Roll-Formed Structures, USG interiors Inc., 1990, Chicago, Ill.
4. EP 2 025 420 A1 – Verfahren zur Dickenreduktion von einstückigem Walzgut, Hilti AG, 2009, Schaan, Lichtenstein.
5. JP 2000 000626 A – Device for Manufacturing Deformed Cross Section Bar Stock and Method Therefore, Hitachi Cable Ltd., 2000, Japan.
6. AT 510 957 B1 – Verfahren und Vorrichtung zur Herstellung eines metallischen Bandes, voestalpine Krems GmbH, 2012, Krems, Austria.

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