Internship report

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Table of contents

1. Introduction

Concluding my internship at Audi AG, I hereby present my report on the several jobs and tasks performed during a period of six months in Neckarsulm, Germany.

The focus of my internship is on simulation techniques. Especially simulation forming processes of thermoplastic fibre reinforced material. We can group these simulations under non-linear finite element method calculations. An important part in the process of performing these simulations, is the preparation of the required material data. Typically this is a time consuming process, at which great care is needed, since it plays a crucial role in the (successful) outcome of the simulation. Therefore a large time of my internship was invested in this area. The process towards the material data and the outcome will be presented in chapter 2.

The main objective during my internship was to draw comparison between two software packages for stamp forming simulations. PAM-FORM was compared with AniForm, and their potential to represent reality. Multiple simulations were performed using different materials and geometries. Therefore the performance of both software packages was researched under varying circumstances. The results and conclusion on this topic will be presented in chapter 3.

Additionally Cadmould, a software package for simulation injection moulding, was tested. Two filling studies has been performed and compared to reality. The results are presented in chapter 4.

The internship did not consist purely on simulations. Some designing in Catia V5 was performed too. For example two moulds for prototype car parts and the design of a mount for a heating element were constructed. The geometries are shown in chapter 5.

All the information, descriptions, diagrams and figures shown in this report are confidential. Therefore the scales are missing in the diagrams and no parameter values will be shown in this report.

2. Material calibration

When performing a finite element method (FEM) analysis it is great effort is put into material model calibration. We use material models to capture the material behaviour, and thereby get a proper description of our material during simulation. From these material models the mass- and stiffness matrix can be assembled. When these two matrices are known, we are able to solve the FEM domain.

Material data is gained by performing mechanical tests on the material of interest. For example, to determine the Young's and shear modulus, a tensile test respectively picture frame test can be performed. When using fibrous reinforced thermoplastics (FRTPs) there is an extra challenge: the forming process of these materials takes place at elevated temperatures. Here the polymer resin is in melt. Performing experiments at these temperatures is challenging. Often it is required to adapt the setup for elevated temperatures.

In the case of FRTPs, we distinguish three mechanisms which are dominant during the stamp forming process: in-plane shear, out-of-plane bending and friction. Each mechanism has its own test, from which an independent parameter can be determined. PAM-FORM uses material card 140 for draping simulations [1]. This material card can represent both a fabric and unidirectional fibrous material. The model contains a shear and bending material model. A more in depth description in the work of Donderwinkel [2]. Methods are provided by the ESI Group for determining the material parameters for the PAM-FORM material card using a picture frame test and cantilever bending test.

Typically we perform an experiment on the material in order to characterize a particular material behaviour. Additionally we simulate the experiment using the same conditions as in reality. The material parameters are adapted till they fit properly with the experimental data. This process will be described in this chapter for several experiments. Two materials will be presented, and their conversion from an experiment into a material card for PAM-FORM. The material calibration in AniForm is not discussed in this report.

2.1 Tepex dynalite 102

Tepex dynalite 102 is a composite material, which consists of 2x2-twill woven glass fibre yarns. The woven ply is impregnated with a nylon-6 resin. Figure 1 shows an automotive part where the Tepex material was used.

Figure 1 A stamp formed Tepex dynalite 102 laminate which was over-moulded after stamp forming.
Photo: Takata-Petri AG

A forming simulation is performed to predict the behaviour of the ply during the stamp forming process. We do this to indicate areas where problems might occur during stamp forming. Typical problems are wrinkle forming, critical fibre strain or high laminate compaction rates.

In order to calibrate the required material data, three tests were performed:

- A picture frame test to determine the shear behaviour of the laminate
- A cantilever test for the bending behaviour
- A tensile test to determine the tensile stress of the laminate

All tests were performed on a single ply of Tepex at temperature well above the melt temperature. All experiments and calibration processes are described in this chapter.

More information on the Tepex material properties can be found on the website of Bond Laminates [3].

2.1.1 Shear test

The shear behaviour of the laminate is measured using a picture frame test. The parameters we need to extract from the data are the shear modulus, the locking angle and the shear modulus after locking, since we use the fabric material model in PAM-FORM.

The experimental data is processed in the models provided by ESI. These analytical models provide us with a value for the shear modulus, locking angle and shear modulus after locking. These values are being processed into the material card 140, and the picture shear test is simulated in PAM-FORM. We try to reproduce the experimental data, and thereby checking whether the values provided by the ESI model are correct.

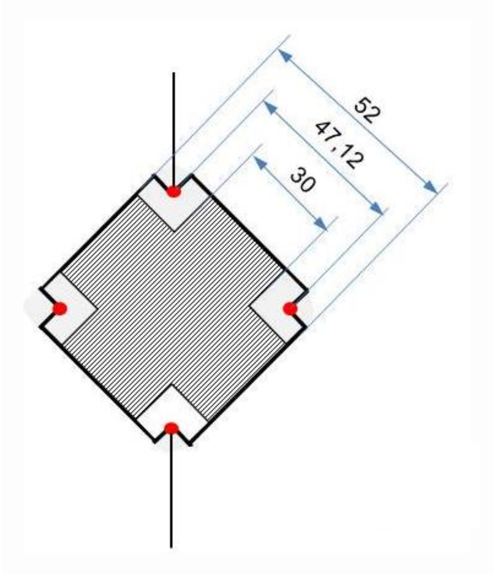


Figure 2 Picture frame setup

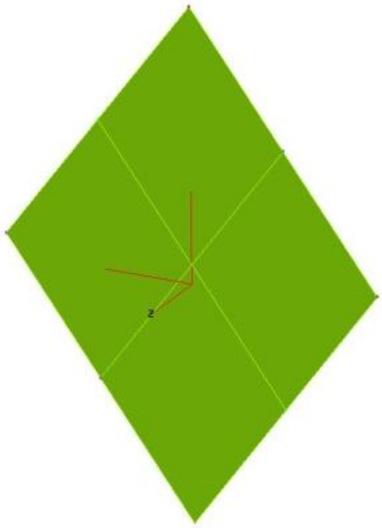


Figure 3 Picture frame simulation performed in PAM-FORM

The setup for the picture frame test is sketched in Figure 2, where the simulation of the picture frame is sketched in Figure 3. When looking at Figure 3, we can obtain a problem. The characteristic length for this test is unknown when simulating the test as shown in Figure 3. Should we take 30, 47.12 or 52 mm for this length? Therefore both 30 and 52 mm have been inserted into the ESI model to obtain an analytical solution. Both analytical solutions looked promising, therefore two PAM-FORM simulations were performed, one for the 30 mm setup and one for the 52 mm setup.

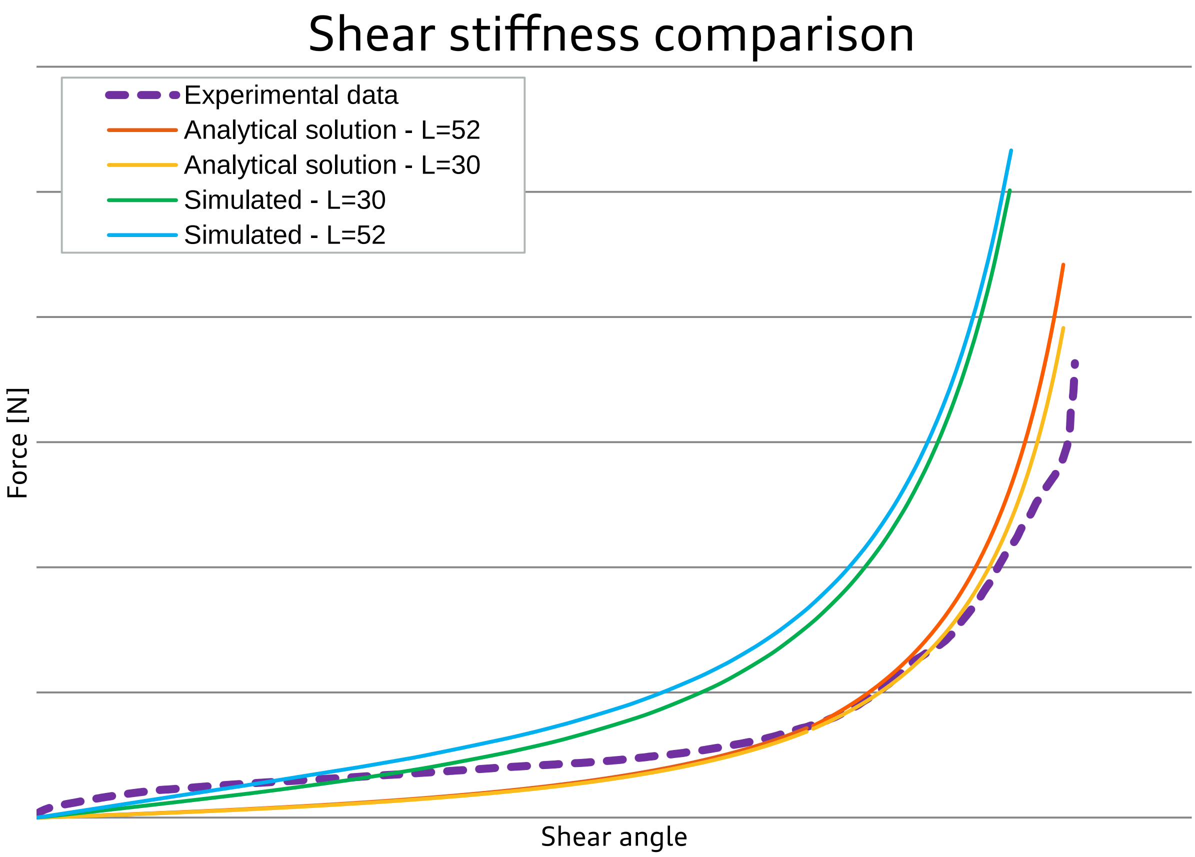


Figure 4 Shear force as a function of the shear angle for the 30 and 52 mm picture frame setup

Figure 4 shows the shear force as measured and simulated as a function of the shear angle. From Figure 4 was concluded the 30 mm setup is more promising than the 52 mm setup. The values suggested by the analytical model are implemented in the simulation. The simulation results show that the value for the shear force is not near the experimental data at the same shear angles. Therefore optimization is required to improve this result for high shear angles of 50 degrees and above, since this is our region of interest.

At first the shear modulus was modelled as a constant, but due to the fact that the nylon-6 matrix material is in melt and the high deformation grades, it is not quite sure how valid this assumption is. Therefore the shear modulus is implied as a function of the shear angle. The results of the implementation of a non-constant shear modulus are shown in Figure 5. The results look quite promising, especially when the material parameters are optimized to obtain a better fit with the experimental data. When we tried to take the non-constant shear value along in other simulations, PAM-FORM kept on crashing. From previous experience within the Volkswagen Group, it is known that PAM-FORM is not able to implement non-constant shear modulus values in simulation with many elements. Therefore a constant shear modulus was the next focus. The result for a constant shear parameter was optimized too, and showed promising results in the region of interest. Figure 5 displays the calibrated curves along with the experimental data and the analytical solution.

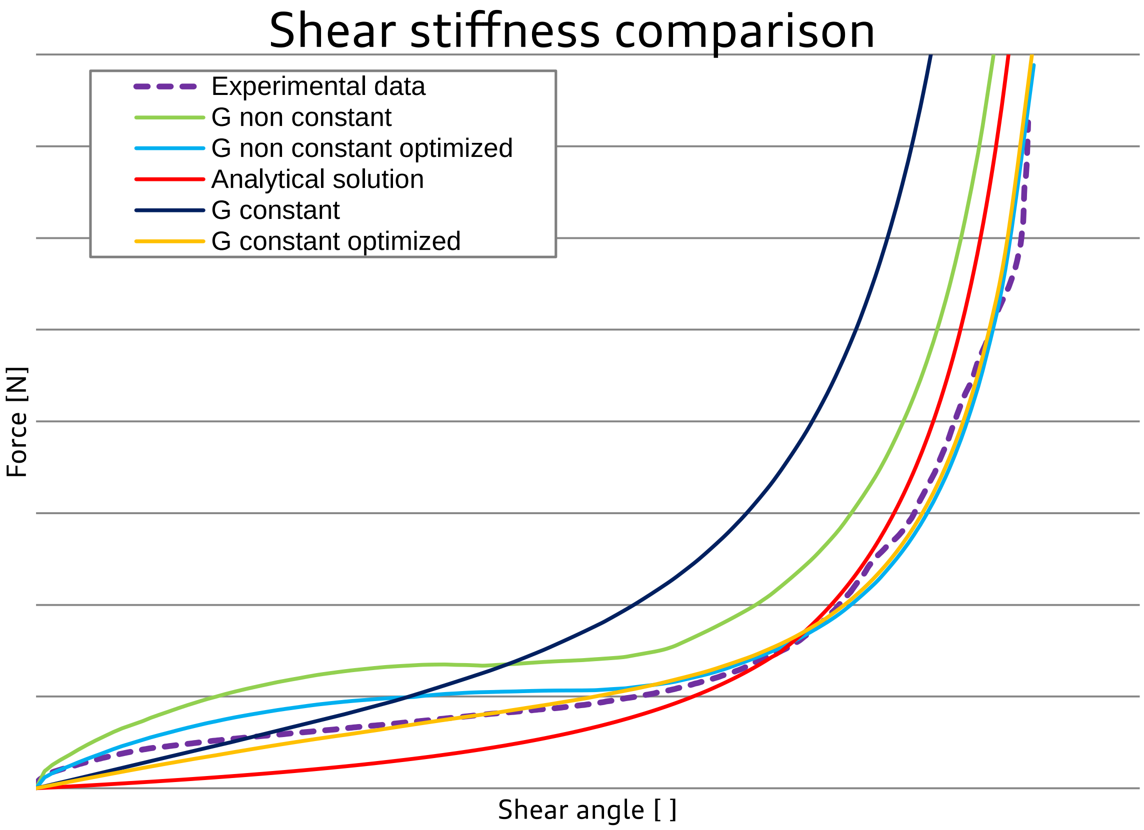


Figure 5 Shear stiffness comparison for the 30 mm picture frame setup using different shear modulus descriptions

In future simulations the optimized constant shear modulus will be used as shear modulus. This includes its accompanying locking angle and shear modulus after locking.

2.1.2 Bending test

To determine the bending parameters, ESI suggests using a cantilever test. A layer of material is melted in an oven, while being clamped on a cantilever. After a period of time, the laminate will bend due to the gravity force. The specimen is taken out of the oven after a certain period of time and photographed. We use PAM-FORM to approximate the image by adapting the bending parameter in the material card. The final simulation results of this iterative process are shown in Figure 6 and Figure 7.

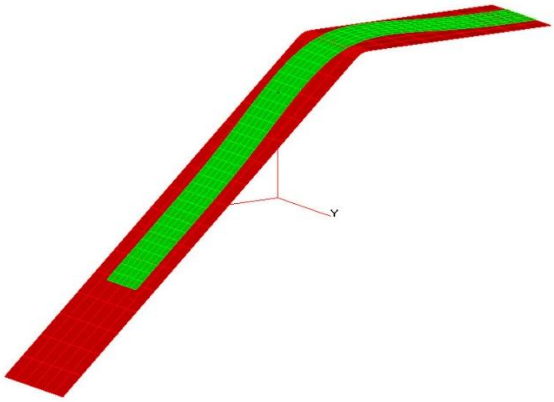


Figure 6 Simulation cantilever test 0°

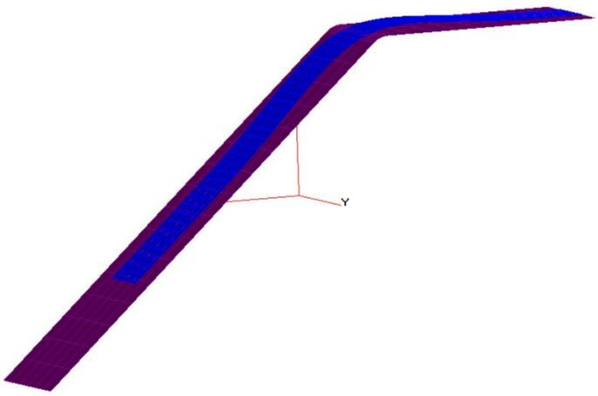


Figure 7 Simulation cantilever test 90°

This method provides us with a value for the bending factor, which describes the out-of-plane elastic behaviour. The cantilever test is time independent, therefore we are not able to calibrate the viscous contribution of the material.

2.1.3 Tensile test

In addition to the bending test, we need a value for the Young's modulus. Since the bending factor, as determined in paragraph 2.1.2, is a scaled value of the Young's modulus. To obtain this value, we use a tensile test. The specimen is brought in melt condition, and a tensile test is performed in both the fibre direction as perpendicular to the fibres. From this test we can obtain the Young's modulus, and additionally validate this value in PAM-FORM.

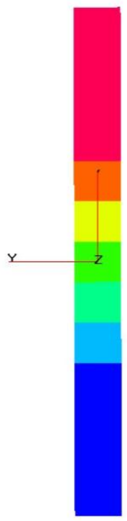


Figure 8 Displacement plot of the tensile test

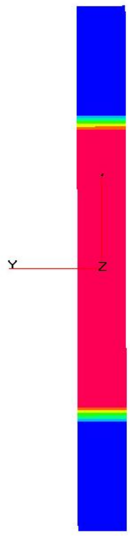


Figure 9 Strain plot of the tensile test

Figure 8 and Figure 9 shows the tensile specimens as simulated. The Young's modulus was determined from the experimental, and implemented in an analytical solution. Figure 10 displays the curves of the analytical solution and the simulation after calibrated.

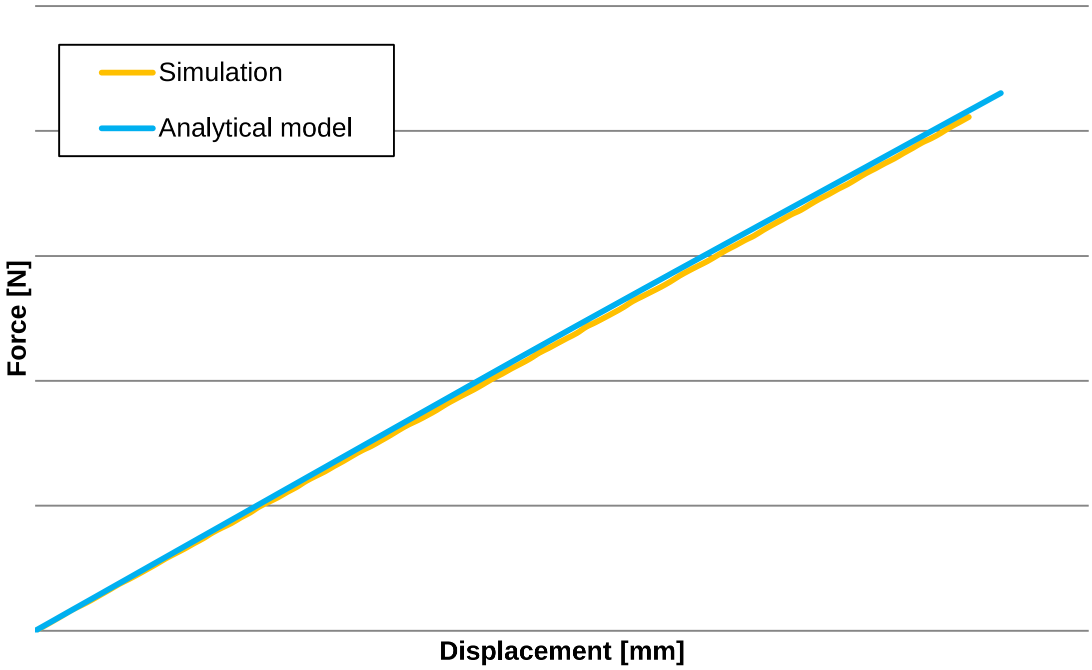


Figure 10 Tensile test analytical data and calibrated simulation

2.2 BASF Ultratape

One of the biggest challenges in the automotive industry is reinventing and improving cars at every iteration. The means changes in design, but also in material. Research and experiments are being performed on a new material called Ultratape from the BASF company. It is a carbon fibre unidirectional tape pre-impregnated with nylon-6 resin. The material datasheet is still confidential since the material is still in development.

In order to predict the behaviour of this material it has to be characterized first. The Dutch company ThermoPlastic composite Research Centre (TPRC) was asked to do this. Three different experiments were performed to characterize the tape material. These experiments are different than the ones described in the previous paragraph (2.1 Tepex dynalite). Typically we are not able to characterize tape-based composites using the same methods as fabric-based composites.

In this paragraph we will present a description of the tests used for material characterization. Moreover the calibration of the material data in PAM-FORM is described.

2.2.1 Shear test

The shear characterization is performed in a rheometer. We place a torsion beam in the rheometer. The rheometer is capable of applying rotational displacements on the clamps. The torsion beam is a stacked laminate of 60 layers of tape material. The specimen will be heated above the melting temperature of the polymer before the torsion test takes place. The setup of the test is shown in Figure 11.

Figure 11 Torsion test setup including torsion beam specimen. Photo: TPRC

This torsion test is simulated in PAM-FORM so we can fit the simulation results for a specific material card onto the test results and iterate the material card. Figure 12 shows the final iteration, from which the shear modulus can be determined. In Figure 13 we can see the beam as simulated in PAM-FORM.

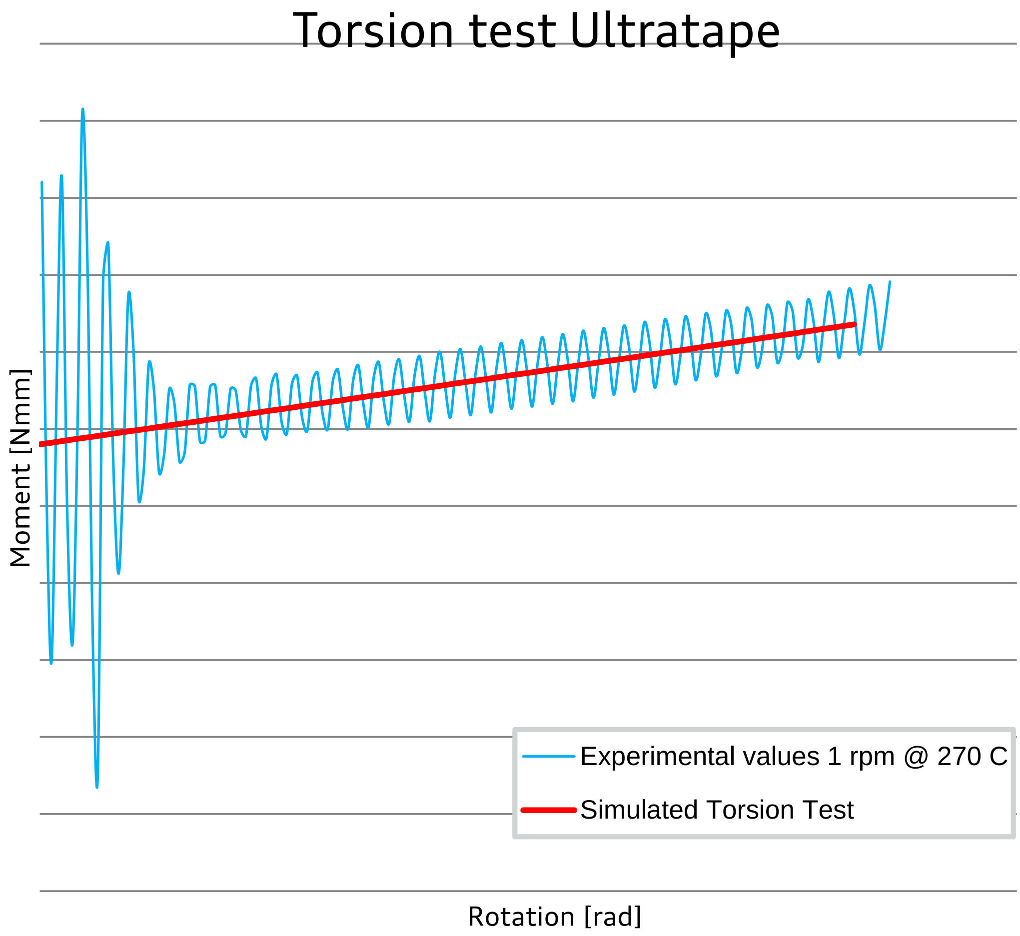


Figure 12 Torsion data fit of Ultratape

As is displayed in Figure 12, the reference test for the calibration of the material card is at 1 rpm and 270° Celsius. From previous tests, 270° Celsius appeared to be a sufficiently high temperature at which the laminate is in full melt. This was not always the case at lower temperatures, although we are past the melting temperature. The rotational speed of 1 rpm was the initial simulation setup. Simulations using 10 rpm as the rotational speed showed stability issues.

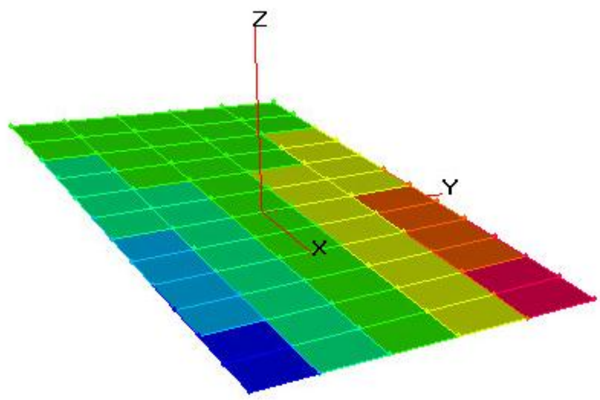


Figure 13 Torsion test simulation

2.2.2 Bending test

The bending characterization is performed by using a rheometer and a custom designed clamp. Using this method, we are able to measure resulting moments and forces while bending the laminate at several speeds in melting condition. This provides us with experimental data instead of a visual result as in the cantilever test. The setup is shown in Figure 14.

Figure 14 Bending setup using a rheometer. Photo: TPRC

The experiment is simulated in order to fit the simulation outcome on the experimental values. A shell mesh was created in order to simulate the bending test. Figure 15 shows the simulation.

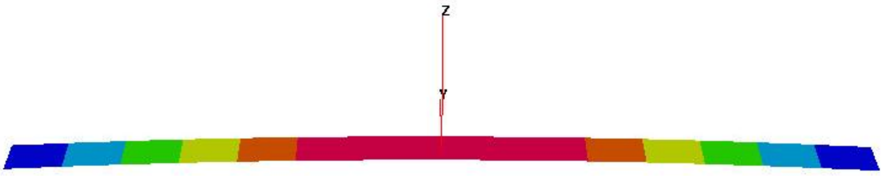


Figure 15 Bending experiment as simulated for calibrating Ultratape

In Figure 16 the results, after iterating towards a suiting bending parameter, are presented. Two laminate thicknesses are evaluated. Thereby we evaluate the influence of increasing thickness on the bending behaviour.

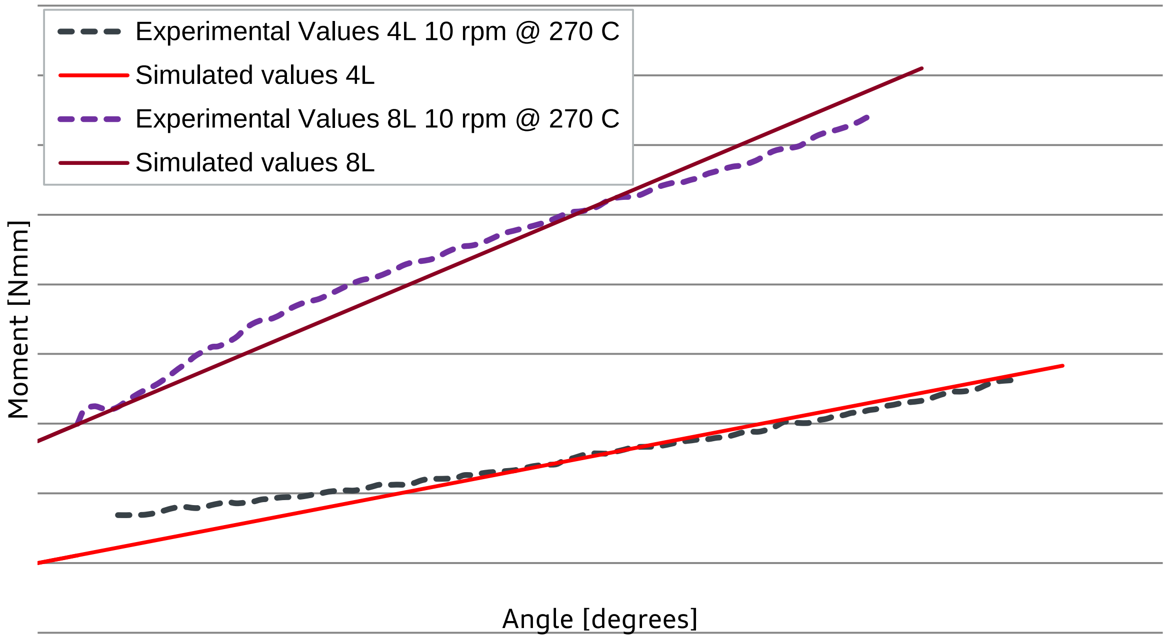


Figure 16 Bending calibration for Ultratape

2.2.3 Friction test

In order to obtain a proper description for the friction behaviour of the material, experiments were conducted on this behaviour as well. However this data was not used to calibrate the material card, since the friction model is not part of the material card. Friction behaviour is defined in a separate material model, which is defined in the contact definition of PAM-FORM. The parameters used in the friction model are based on previously performed simulations.

3. FEM simulations of thermoplastic fibre reinforced plastics

Several simulations were performed on the forming behaviour of fibrous material using different testing geometries. The goal of these simulations is to gain more insight in the stamp forming process when using fibrous material. Many of these geometries are preliminary designs of projects where Audi is involved in or in-house testing geometries for research purposes. The common thing amongst these simulations is the material: fibre reinforced thermoplastics (FRTPs). Primarily nylon-6 resin based FRTPs.

Software used for these simulations are PAM-FORM[4] and AniForm[5]. PAM-FORM is an explicit solver where AniForm in an implicit solver. Both come with a graphical user interface, including pre- and post-processor. Due to their similarity in simulation process, however using a different kind of solver, it would be interesting to compare these software packages. In this chapter we will present the results of several simulations performed in both PAM-FORM as AniForm. Additionally we will compare the simulation results with reality.

Due to the confidentiality of most projects, only two test cases will be discussed in more detail: the half sphere geometry and the “Universalprüfkörper”. Other projects will be mentioned briefly thereafter. The material models used and their parameters will not be mentioned in this report due to their confidentiality.

3.1 Half sphere

The half sphere is a geometry developed by the Production Technology group at the University of Twente. This part is used to test the forming behaviour of fibrous reinforced material during stamp forming. A dome is chosen since it is a non-complex geometry when looking at double curved geometries. Therefore the stamp forming process is easily reproduced, and no extensive numerical calculations are required when simulated. The half sphere is used to draw a comparison between simulations and reality. Due to its simplicity not only the global forming behaviour can be validated, moreover the material data as calibrated.

Five different laminate configurations were evaluated in this project. In which both woven fabrics and tape-based were used. The configurations were as following:

- Cross-ply using UD carbon tapes: $(0/90/0)_s$
- Quasi-isotropic using UD carbon tapes: $(45/0/-45)_s$
- Quasi-isotropic using woven glass combined with UD carbon tapes: $(0_f/0/90/0)$
- Quasi-isotropic using woven glass combined with UD carbon tapes: $(0_f/45/0/-45)$
- Quasi-isotropic using woven glass: $(0_f/45_f)$

The UD carbon tape material is BASF Ultratape: a carbon fibre tape impregnated with nylon-6 resin. The woven material is Tepex dynalite: a 2x2-twill woven glass fibre fabric impregnated with nylon-6 resin. More details on the material in paragraph 2.1 Tepex dynalite 102 and paragraph 2.2 BASF Ultratape.

The woven glass combined with UD carbon tapes configuration was not simulated, therefore a comparison with reality cannot be drawn.

For every configuration two pressings are performed. Full mould closure is one of the stages of interest, since it displays the final product. However, it is difficult to notice wrinkles and other forming effects in this stage. Additionally the press will be stopped when the mould spacing is 7 mm. At this stage the forming behaviour is displayed clearly. The same will be done in the simulations. We will compare both PAM-FORM as AniForm with the results after stamp forming at full mould closure and 7 mm mould spacing. The closing speed of the moulds is 50 mm/s at every simulation, since this is the closing speed during the press forming process.

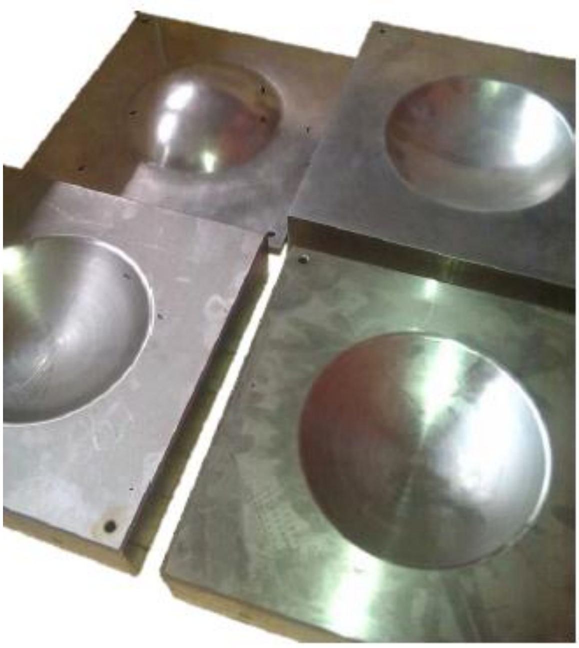


Figure 17 Half sphere moulds as used by TPRC. Photo: TPRC

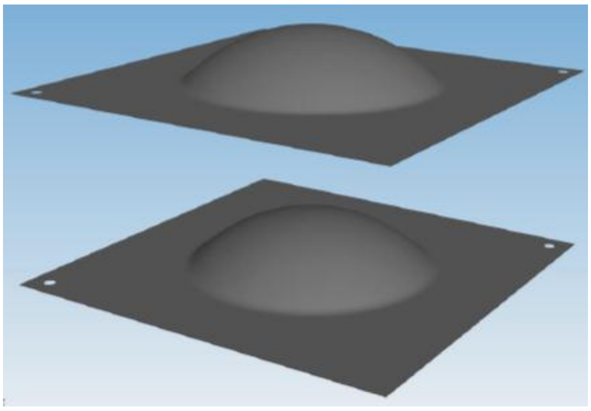


Figure 18 Half sphere moulds as simulated

When it comes to stamp forming, several steps are required for producing a half sphere:

- Individual plies are trimmed to their prescribed size.
- The laminate is stacked from the trimmed plies at room temperature and cured locally for handling purposes.
- The laminate is positioned in an oven and brought at melt temperature.
- The blank is positioned between the mould parts.
- The mould is closed and thereby the laminate pressed into shape.
- To prevent air entrapment and premature delamination, a high pressure is applied on the laminate.

The blank size is 300 mm x 300 mm. In the simulations every ply is modelled individually including its grippers, indicated by the circled region in Figure 19. A gripper is assumed over the full length of two opposing sides of the blank. The purpose of the gripper is to fix the laminate during pressing, and thereby limit the amount and size of wrinkles.

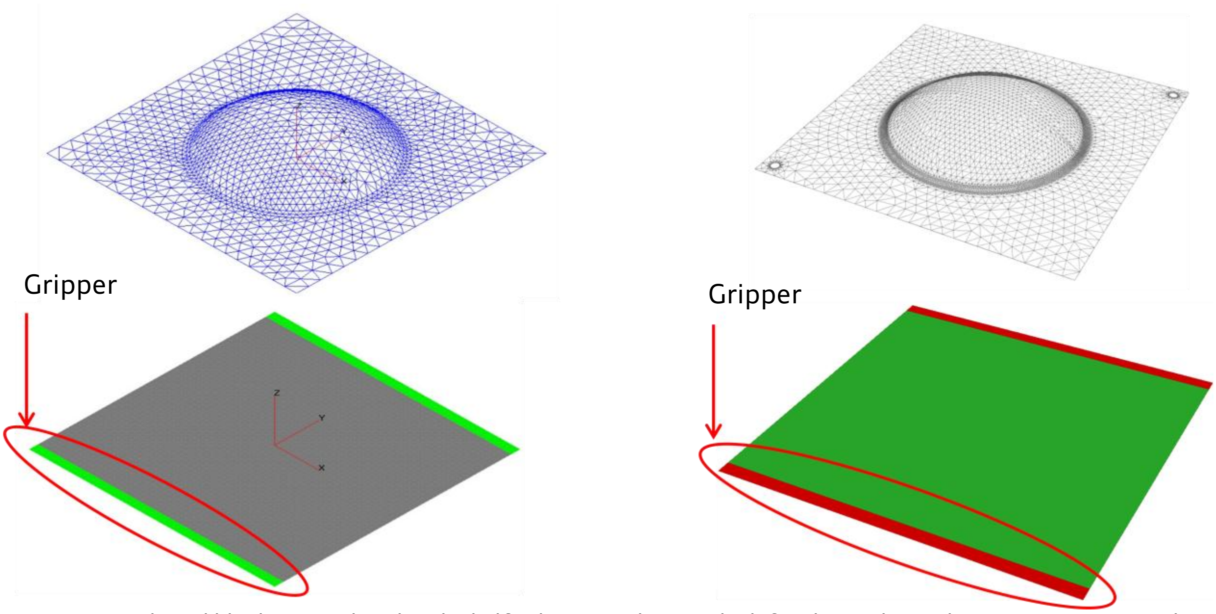


Figure 19 Tools and blank as simulated in the half sphere simulation. The left column shows the PAM-FORM setup, the right column the AniForm setup.

The grippers are simulated using the same properties as the blank; however the stiffness is ten times higher than the blank.

Every blank mesh is structured. This results in element edges aligned with the fibre direction of the laminate. Therefore a 0 and 90 degrees oriented ply automatically has an accompanying element edge, whether quadrilateral or triangular elements are used. However, the 45 and -45 degrees oriented ply does not have an accompanying element edge, when quadrilateral elements are used.

The element edge length of the blank mesh is 5 mm in PAM-FORM and 4 mm in AniForm. The Aniform meshdata was not available at the time the PAM-FORM simulations were performed; therefore there is difference in element edge length. The tools are meshed using linear triangular elements.

In the next section the forming results and simulation results will be presented. First the PAM-FORM simulation of a configuration will be shown, thereafter the AniForm simulation. At the same time the stamp forming results will be shown, thereby we are able to draw a comparison between reality and simulation for each software package and laminate configuration.

The computational time span between the PAM-FORM simulations and AniForm simulations cannot be compared, since the AniForm simulation, using the tape-based material, were performed on a different PC. However it shows that AniForm has the potential to solve simulations in a small time span despite using an implicit solver. The PAM-FORM simulations where performed on a Intel Xeon CPU quadcore @ 3.50 GHz system with 16 GB RAM., the AniForm simulations on a dual Intel Xeon hexacore @ 2.3 GHz system with 32 GB RAM. The simulations, where woven material was used, are performed on the same PC; therefore these computational times are comparable.

3.1.1 Cross-ply using UD carbon tapes: $(0/90/0)_s$

A cross-ply laminate was assembled using six layers of carbon UD carbon tape impregnated with PA6 resin. The layup of this laminate is $(0/90/0)_s$. First we will compare the results of the stamp forming with PAM-FORM. After that the AniForm results will be presented.

PAM-FORM

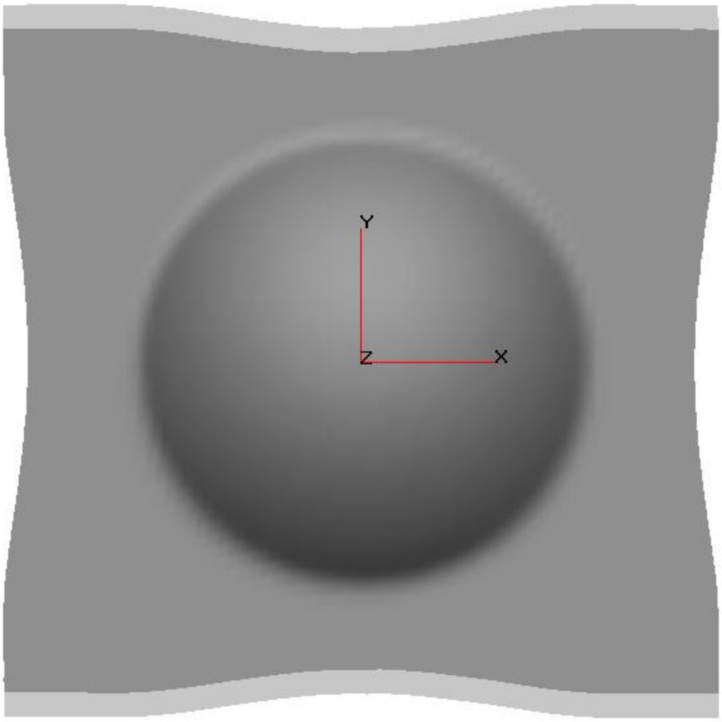


Figure 20 PAM-FORM simulation of cross-ply laminate at full mould closure

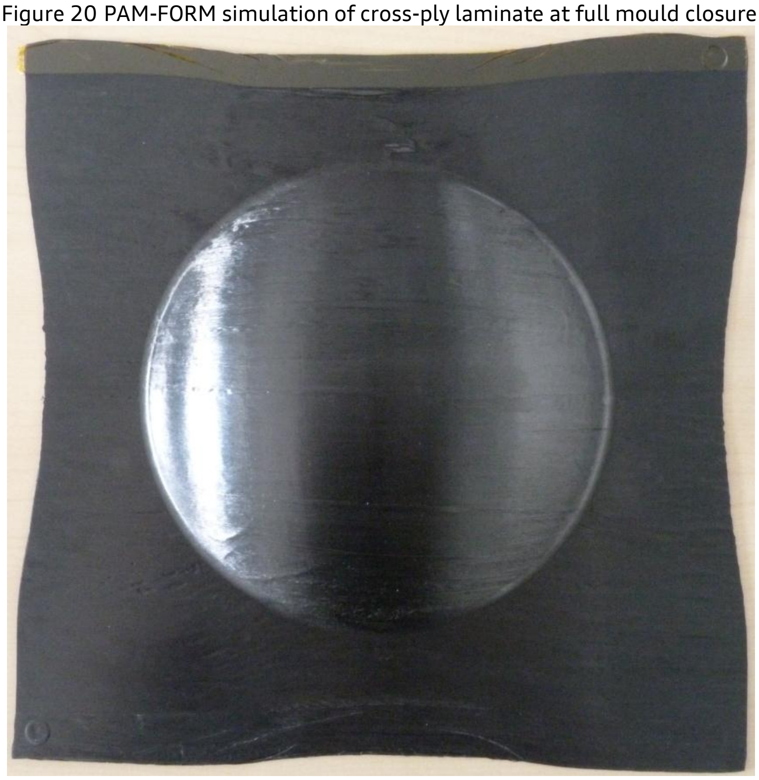


Figure 21 Cross-ply laminate after stamp forming at full mould closure

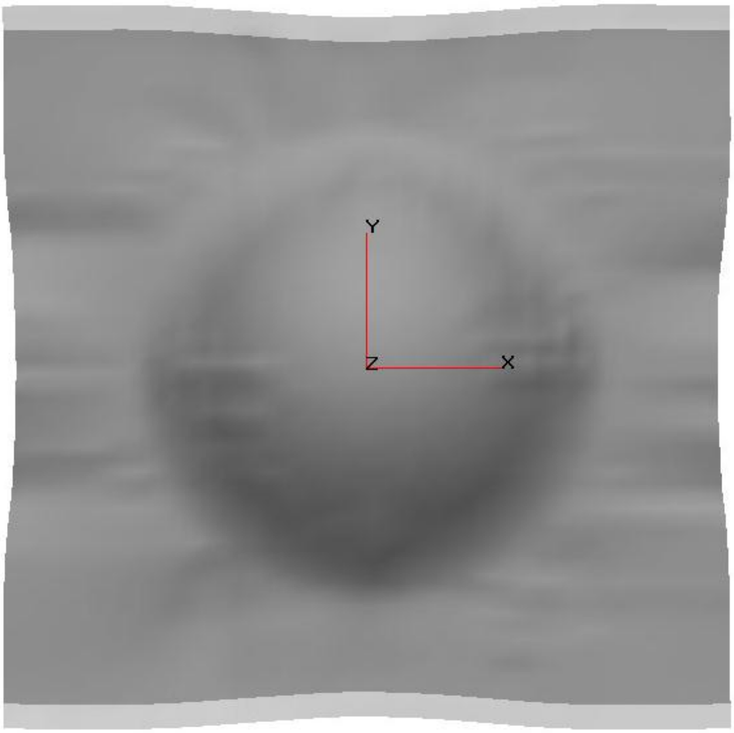


Figure 22 PAM-FORM simulation of cross-ply laminate at 7 mm mould spacing


Figure 23 Cross-ply laminate after stamp forming at 7 mm mould spacing

Both Figure 20 and Figure 21 display a smooth laminate. No wrinkles are occur in the laminate at full mould closure. The outer contours of the laminates seem much alike too. From Figure 22 and Figure 23 we obtain a comparable result for the outer contour. The wrinkles displayed in Figure 23 across the laminate are shown in Figure 22 too. The PAM-FORM material, combined with this laminate stacking, shows promising results when compared to reality.

Total computational time for this simulation was 31.8 hours.

AniForm

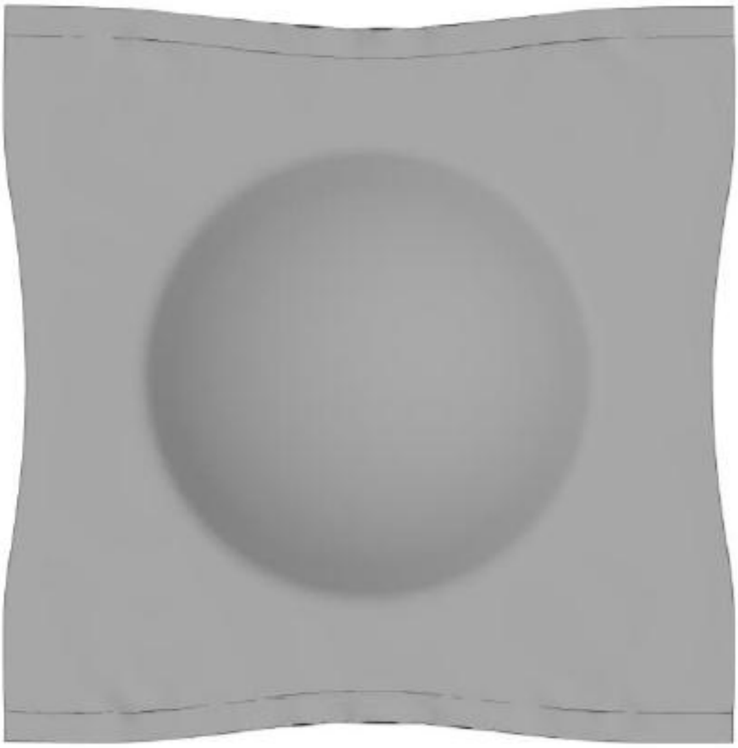


Figure 24 AniForm simulation of cross-ply laminate at full mould closure

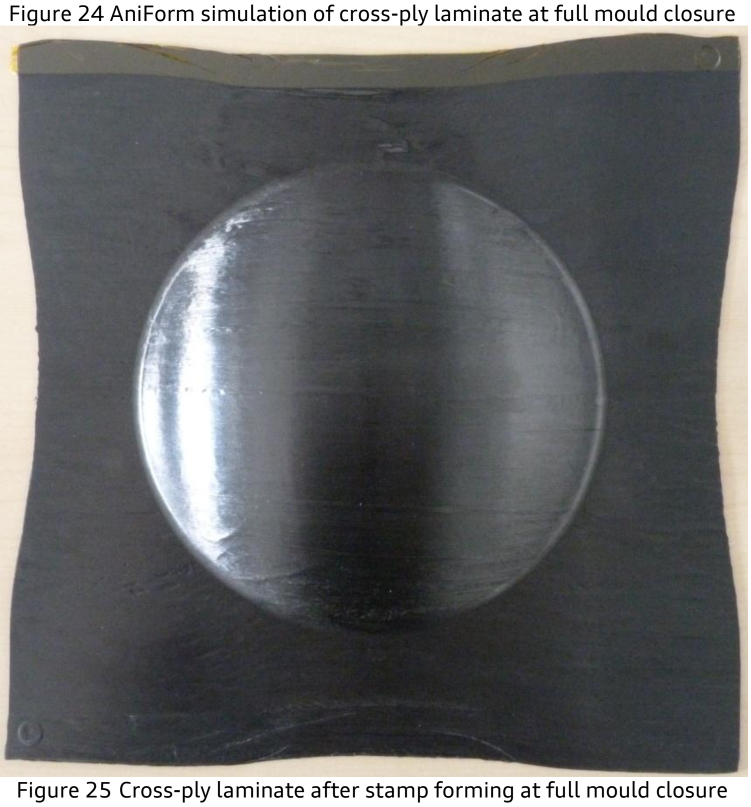


Figure 25 Cross-ply laminate after stamp forming at full mould closure

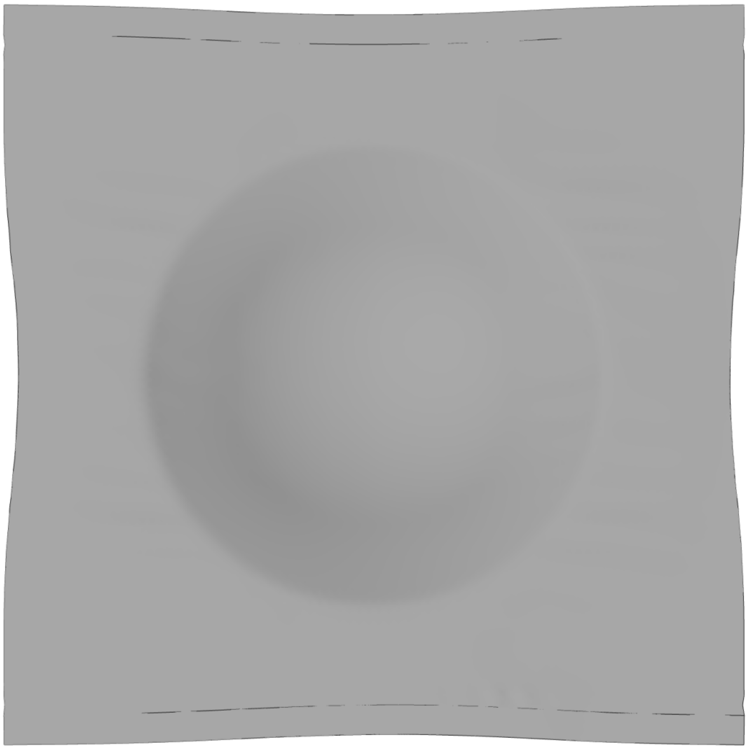


Figure 26 AniForm simulation of cross-ply laminate at 7 mm mould spacing

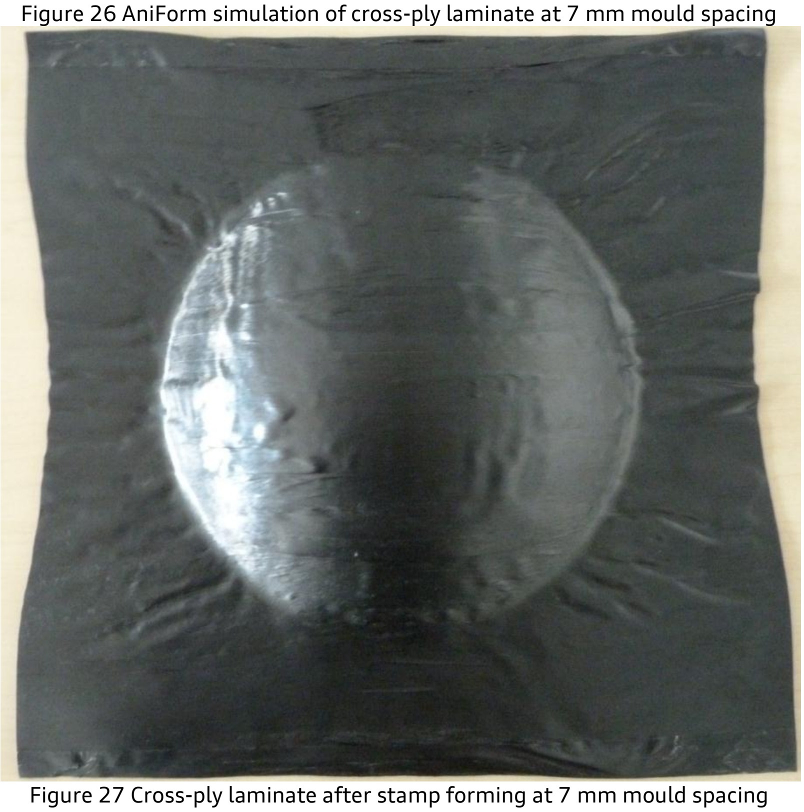


Figure 27 Cross-ply laminate after stamp forming at 7 mm mould spacing

Looking at figures above, a similar conclusion as for the PAM-FORM simulations can be drawn. Figure 26 seem to represent the outer contour of the laminate, as shown in Figure 27, more accurate than PAM-FORM. The wrinkles seem in less excessive in Figure 26 than in reality. They are not absent, but are difficult to notice from Figure 26. Moreover the wrinkles only appear near the grippers, where in reality the wrinkles are all across the laminate.

Total computational time for this simulation was 2.63 hours.

Conclusion
Both PAM-FORM and AniForm show promising results when cross-ply laminates are simulated. The outer contour and wrinkles are represented properly in both software packages. The computational times are not comparable with one another; therefore we cannot conclude which software package is the most suited for this situation.

3.1.2 Quasi-isotropic layup using UD carbon tapes: $(45/0/\text{-}45)_s$

A six layer laminate was stacked with a $(45/0/\text{-}45)_s$ layup. Every single layer consists of carbon fibre UD-tape pre-impregnated with PA6. It is expected that this layup will display more wrinkling than the cross-ply layup, since this layup will limit shear deformation more extensive.

Normally PAM-FORM uses quadrilateral elements when simulating blanks and moulds. However, due to intra-ply shear locking, as described by Wolthuizen et al.[6], excessive fibre stresses can occur due to this phenomenon. These stresses do not occur in reality, they are purely numerical. As was advised by Wolthuizen, triangular elements are used when simulating the laminate additionally. Therefore two simulations performed in PAM-FORM: one with a blank mesh using quadrilateral elements and one using triangular elements. In AniForm no quadrilateral elements are used, since this is not allowed in the software.

First the PAM-FORM simulation using quadrilateral elements are presented, after that the PAM-FORM simulation using triangular elements. Following the AniForm simulations are presented. AniForm strictly uses structured triangular meshes as blank mesh to prevent intra-ply shear locking. Additionally we will look at the fibre strain. This provides us with an indication where intra-ply shear locking might occur and its influence on the results.

PAM-FORM simulation using quadrilateral elements

Figure 28 and Figure 29 show the configuration where a $(45/0/-45)_s$ laminate is fully pressed. Figure 30 and Figure 31 show the results for the same lay-up, however the stamp forming process is stopped when the mould spacing was 7 mm.

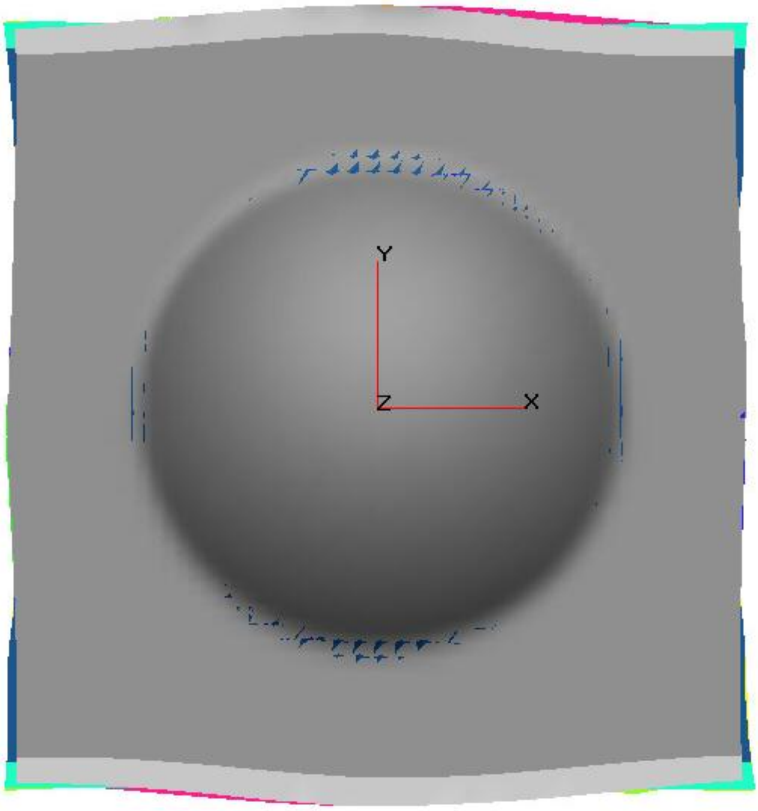


Figure 28 PAM-FORM simulation of a quasi-isotropic laminate using quadrilateral elements at full mould closure

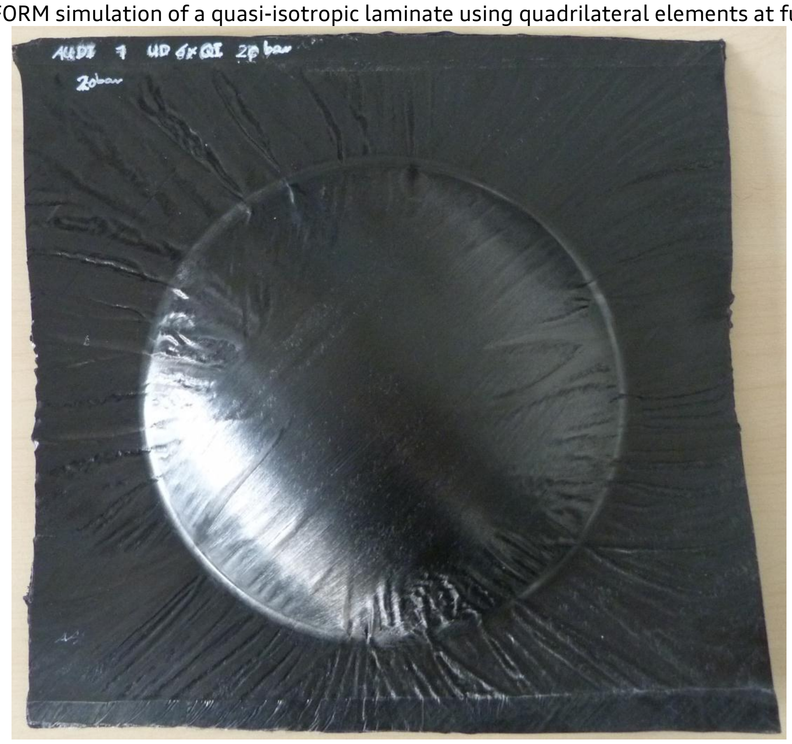


Figure 29 Quasi-isotropic laminate after stamp forming at full mould closure

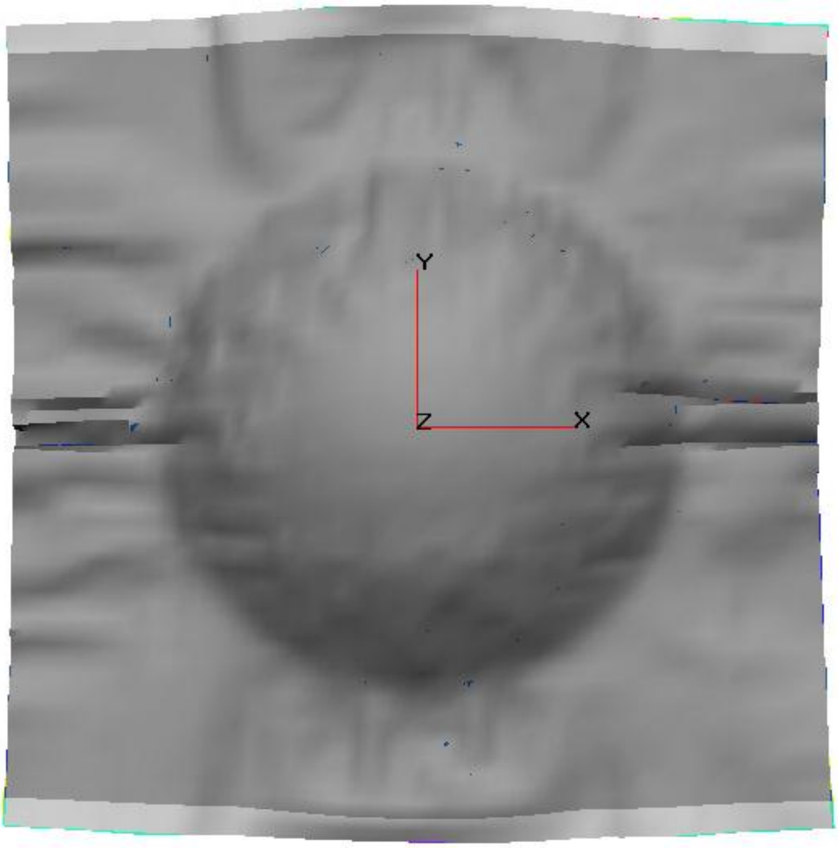


Figure 30 PAM-FORM simulation of a quasi-isotropic laminate using quadrilateral elements at 7 mm mould spacing

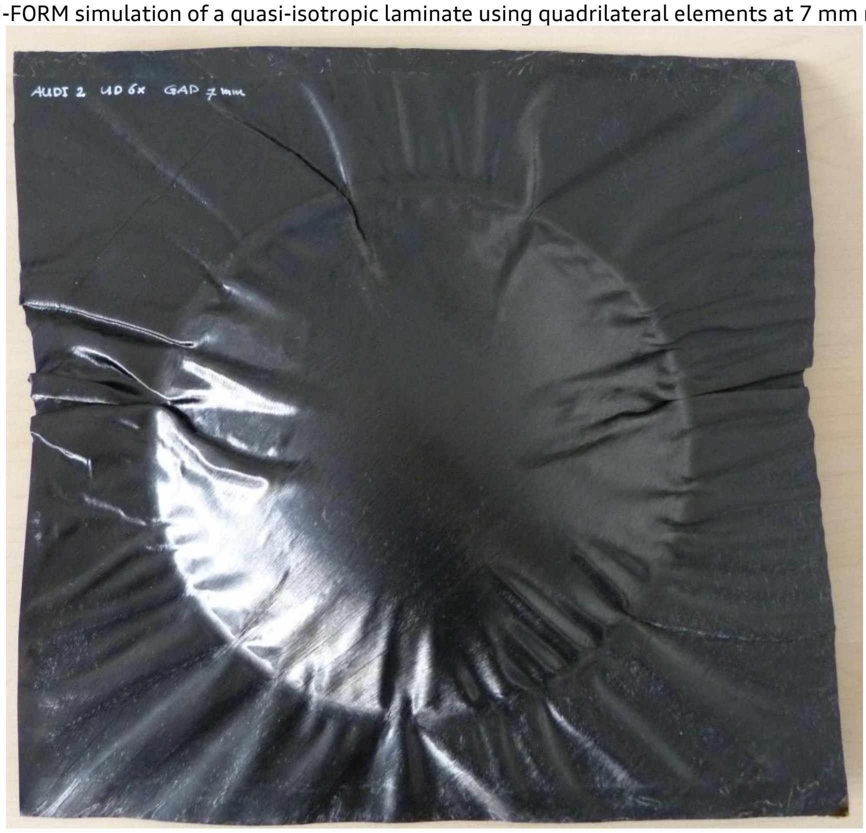


Figure 31 Quasi-isotropic laminate after stamp forming at 7 mm mould spacing

When the results of the fully closed mould are reviewed, we can notice several phenomena. The outline of the laminate as shown in Figure 29, is not properly displayed by its accompanying PAM-FORM simulation. The sides moving inwards are result of the contraction of the 0 degree layer. This contraction occurs; however the friction behaviour between the interacting layers is not described properly. Therefore the slip occurring in the simulation is excessive in comparison with reality. This can also be noticed from the different colours along the laminate edge; each colour represents a different layer.

Figure 29 shows wrinkles all across the laminate where Figure 28 does not. These wrinkles are too small for the blank mesh to display. Additionally no mould penetration is allowed; therefore a very smooth laminate is displayed by PAM-FORM after full mould closure.

Figure 30 displays the state where the mould spacing is still 7 mm. From this figure we notice more and larger wrinkles occurring across the laminate. This is in better agreement with Figure 31, which displays the state in reality. Inter-ply slip starts to occur in this phase; however it is not that excessive as displayed previously. Therefore the simulation's outline of the laminate is in agreement with reality. Moreover the wrinkles and their location look promising. In Figure 31 we can notice that the wrinkles on the left and right side are shifted upwards. This can be caused by the laminate being shifted sideways during stamp forming. The wrinkles in the diagonal direction are displayed more poorly than the vertical and horizontal wrinkles. The direction of the vertical wrinkles in the simulation show a different direction than reality does. This indicates that local layer buckling occurs in the simulation at a different location in the laminate, than it does in reality. This can be caused by the inter-ply slip, where wrinkles are shifted across the laminate more easily than it should according to the real pressings.

Total computational time for this simulation was 21.2 hours.

PAM-FORM simulation using triangular elements

As suggested by Wolthuizen et al. [6], the element edges should be aligned along the fibre direction. At a $(45, 0, -45)_s$ laminate this can be achieved be rotating a quadrilateral mesh for the ± 45 degree plies, or by using triangular elements. The latter is the more straightforward method; therefore it is implemented in the PAM-FORM simulation.

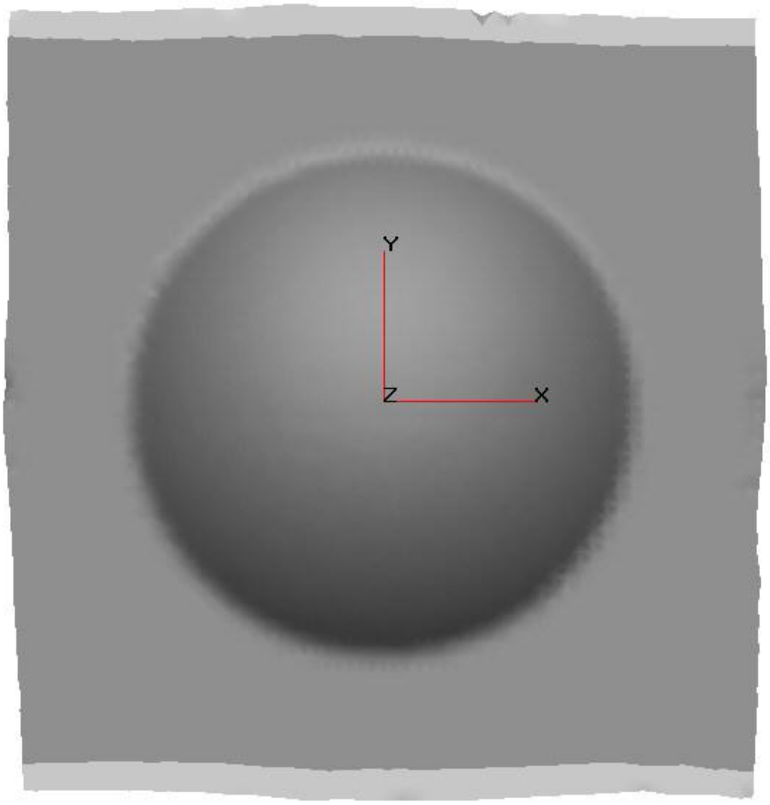


Figure 32 PAM-FORM simulation of a quasi-isotropic laminate using triangular elements at full mould closure

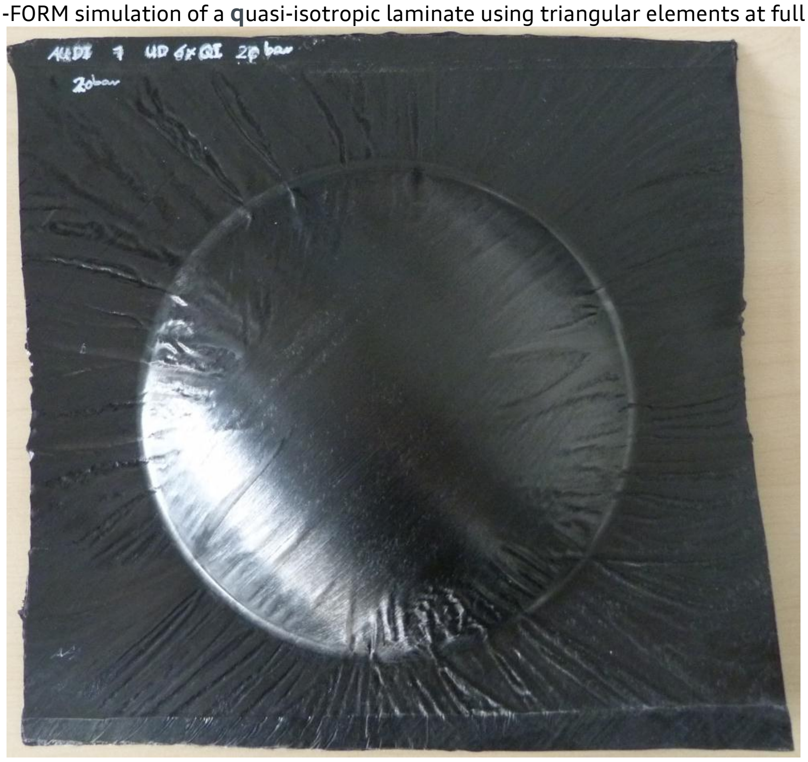


Figure 33 Quasi-isotropic laminate after stamp forming at full mould closure

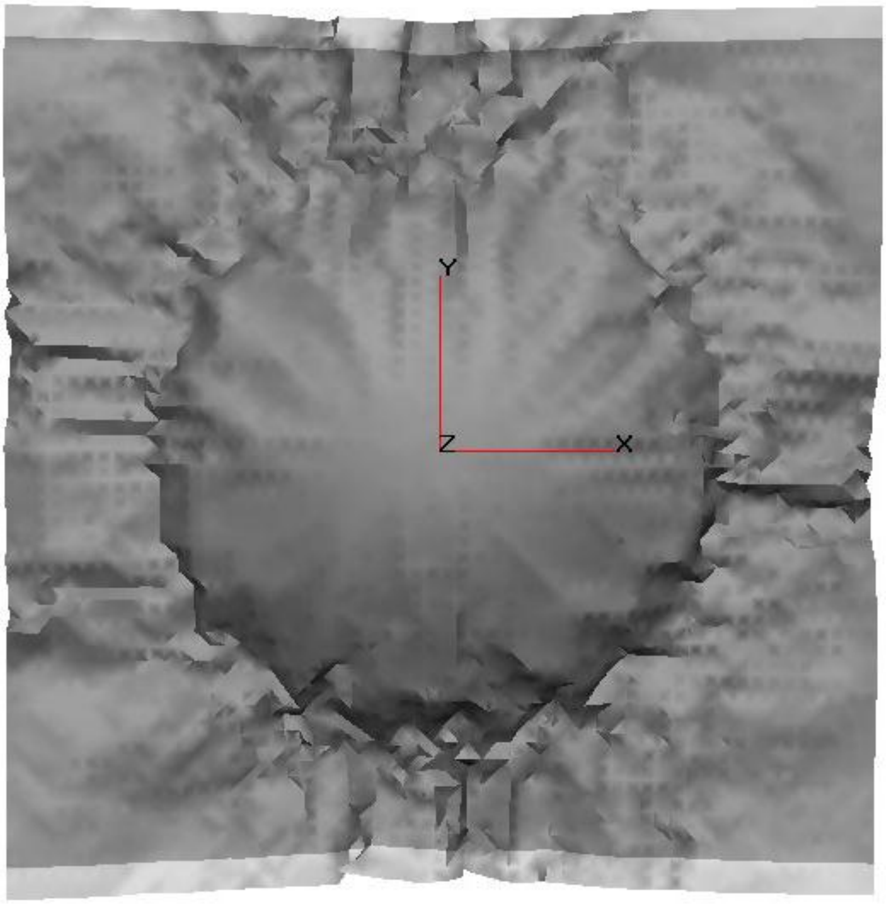


Figure 34 PAM-FORM simulation of a quasi-isotropic laminate using triangular elements at 7 mm mould spacing

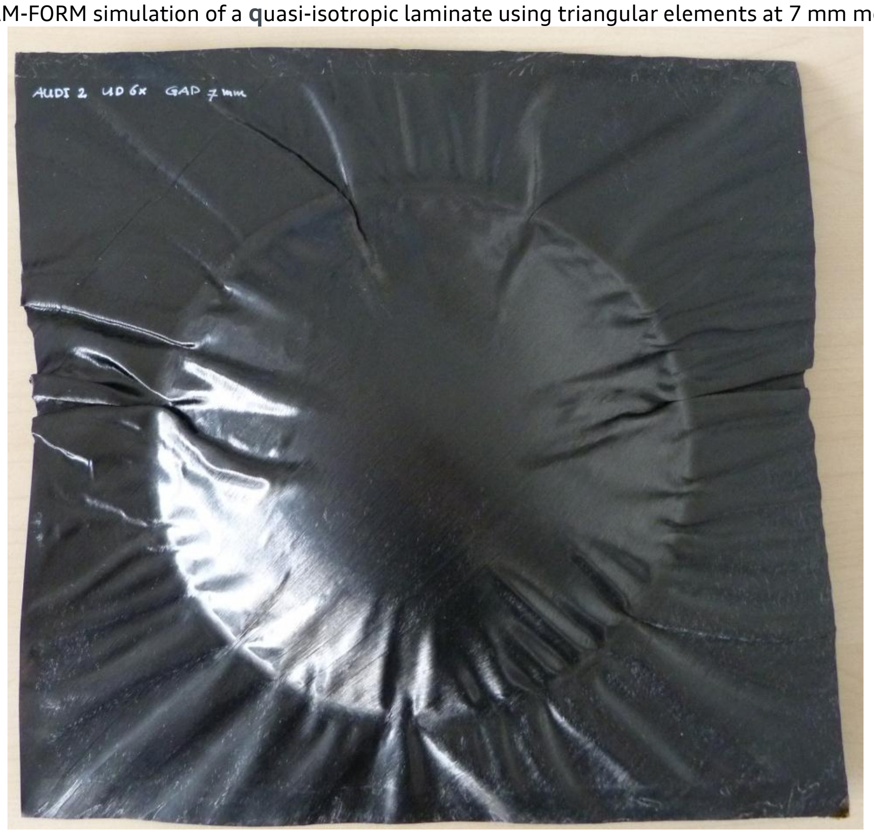


Figure 35 Quasi-isotropic laminate after stamp forming at 7 mm mould spacing

From Figure 34 we can notice that the blank looks heavily distorted. In comparison with the simulation where quadrilateral elements where used, the deformed shape looks different. The folds in vertical direction, as shown in Figure 34, are not present in Figure 30, although the same material properties were used. This gives us an indication that the bending stiffness decreases when using triangular elements are implemented in PAM-FORM. This can be explained by the fact that every quadrilateral element is split into four triangular elements. Therefore more complex deformations can be displayed, with a decreasing element size. The same effect was noticed in the PhD of Haanappel[7], but was not furthermore discussed. We could simulate a bending test to check this hypothesis.

This conclusion is only valid when the diagonal element edges of the triangular elements have an accompanying fibre direction. No simulations on a cross-ply laminate using triangular elements were performed.

When looking at the wrinkles in Figure 34 and Figure 35, the location of these appear to be similar. Although the wrinkles, as displayed in Figure 35, are shifted during stamp forming. Moreover the outline of the laminate at full mould closure seems to be represented more properly as well.

Total computational time for this simulation was 66.4 hours. We can improve this by using a larger element size. This will limit local buckling more. However the question remains to which size the element length should be changed into. No additional simulations were performed to elucidate this topic.

AniForm

In this section the results of the AniForm simulation of the half sphere will be presented. The lay-up is $(45, 0, -45)_s$: six layers of carbon UD-tape. The two displayed stages are at full mould closure and 7 mm mould spacing.

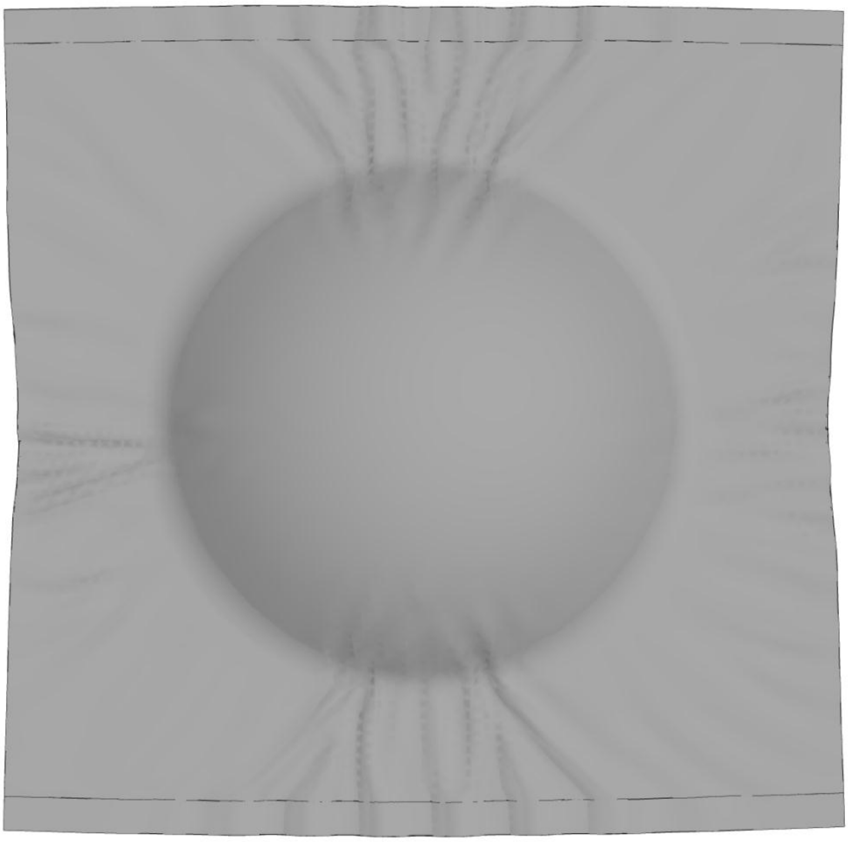


Figure 36 AniForm simulation of a quasi-isotropic laminate at full mould closure

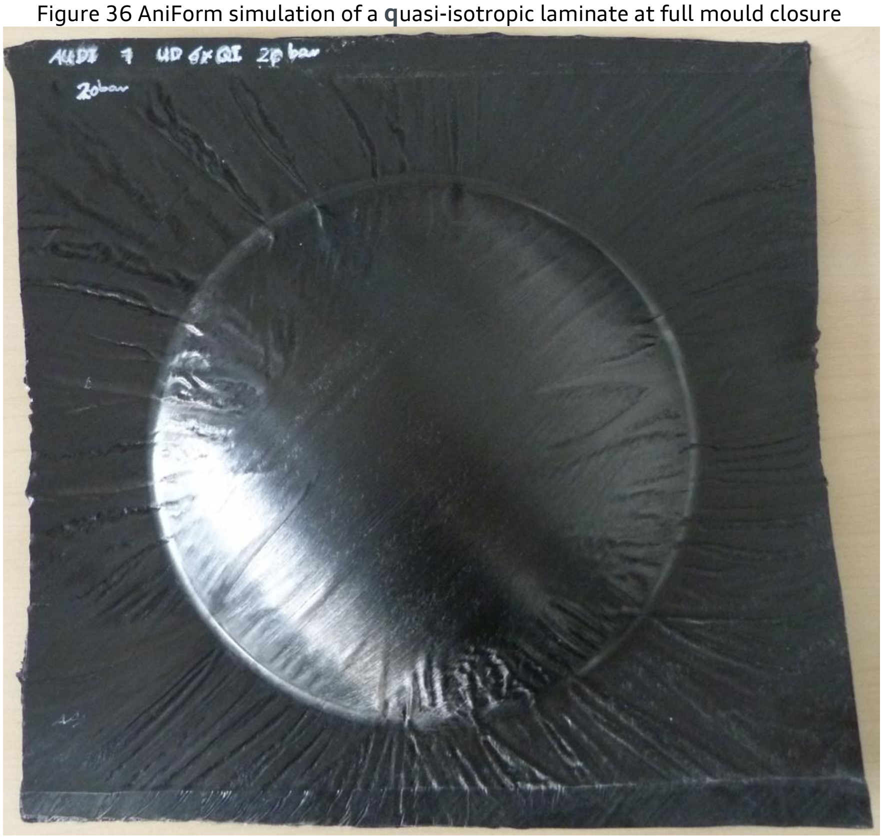


Figure 37 Quasi-isotropic laminate after stamp forming at full mould closure

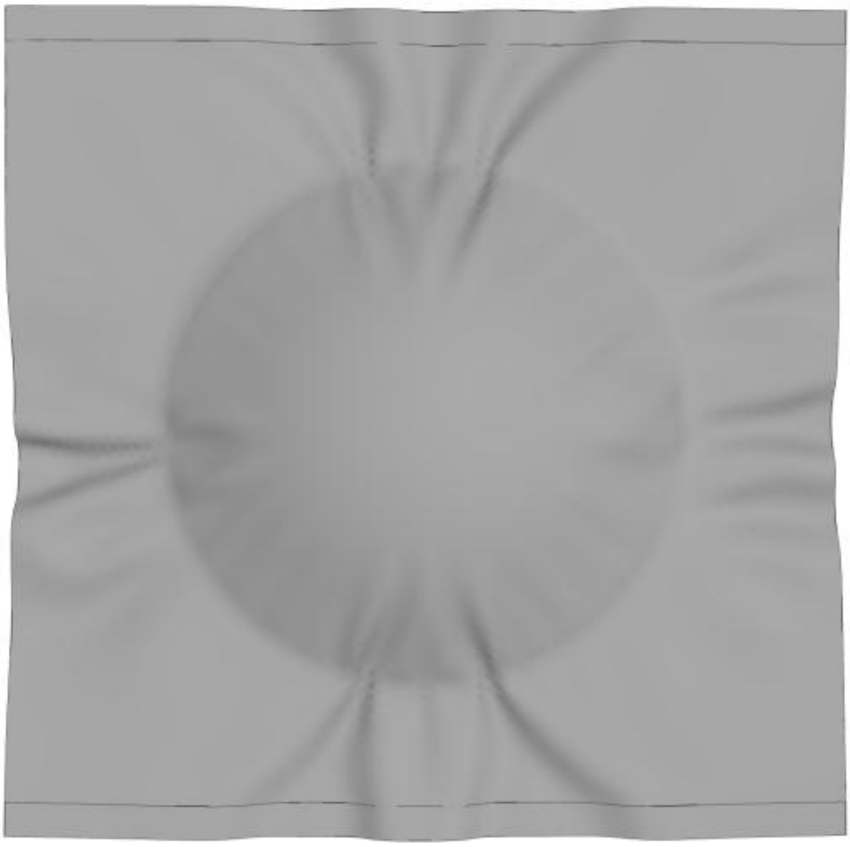


Figure 38 AniForm simulation of a quasi-isotropic laminate at 7 mm mould spacing

Figure 39 Quasi-isotropic laminate after stamp forming at 7 mm mould spacing

Figure 36 and Figure 37 show the half sphere at full mould closure. Figure 36 shows larger wrinkles than Figure 37 does; this is due to mould penetration by the laminate. Therefore the wrinkles are not compacted between the two moulds, thereby remain larger in size. Figure 37 shows small wrinkles all across the blank. Figure 36 show these wrinkles too, however smaller in size. The outline of the simulated laminate is in agreement with the pressed laminate. The gripper sides the laminate is curved outwards, where at the other two sides the laminate is pulled inwards.

Figure 38 shows wrinkles which draw a good comparison with Figure 39. The most dominant wrinkles present in Figure 39 are shown in Figure 38. Additionally the direction of the vertical wrinkles is better displayed than in the PAM-FORM simulation is. The direction is in better agreement with reality. The diagonal wrinkles are displayed by the AniForm simulation but not in the amount present in reality.

Total computational time for this simulation was 3.35 hours.

Fibre strain

The half sphere is not a very complex geometry, therefore it can be predicted where the largest fibre strain will occur: primarily across the top of the dome shape. We will look at the $(45, 0, -45)_s$ layup since intra-ply shear locking might occur here. For the top ply the maximum fibre strain will be in its fibre direction (45 degrees with respect to the blank edges), across the top of the dome. We can check if this is happening in every simulation. The mould will not be fully closed in these results, since that might change the results due to compaction. Therefore the mould will still be opened 2.5 mm. The results will be presented in the figures below.

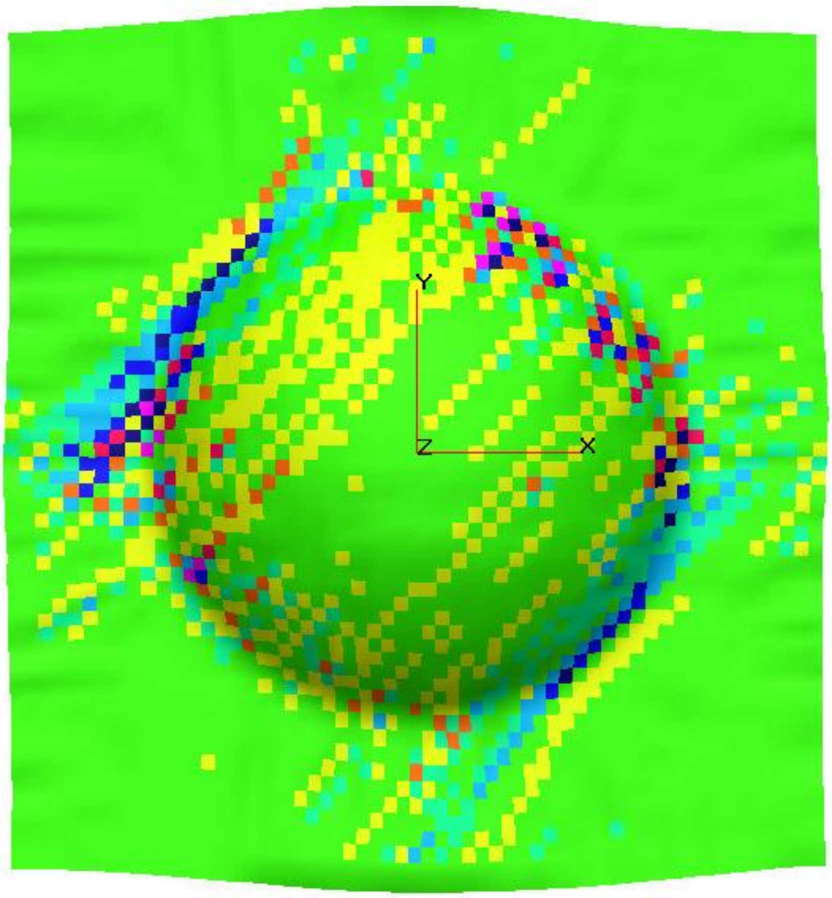


Figure 40 PAM-FORM simulation of a quasi-isotropic laminate using quadrilateral elements, fibre strain in top ply $[-5\cdot10^{-4}, 5\cdot10^{-4}]$, (min = $-14.2\cdot10^{-4}$, max = $7.6\cdot10^{-4}$)

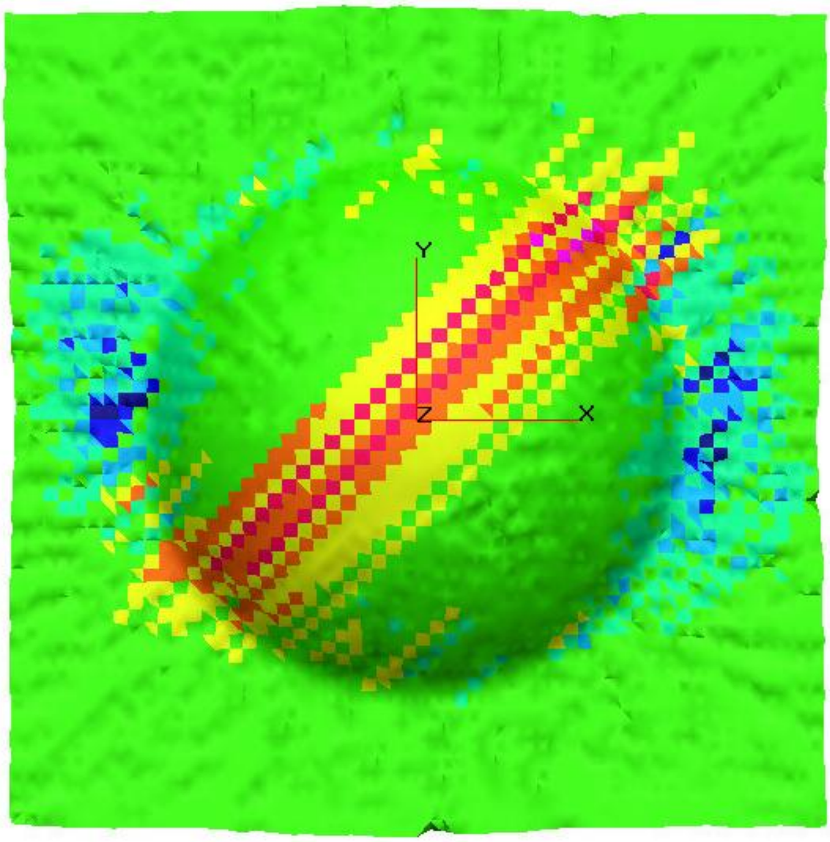


Figure 41 PAM-FORM simulation of a quasi-isotropic laminate using triangular elements, fibre strain in top ply [$-5\cdot10^{-4}$, $5\cdot10^{-4}$], (min = $-8.3\cdot10^{-4}$, max = $5.7\cdot10^{-4}$)

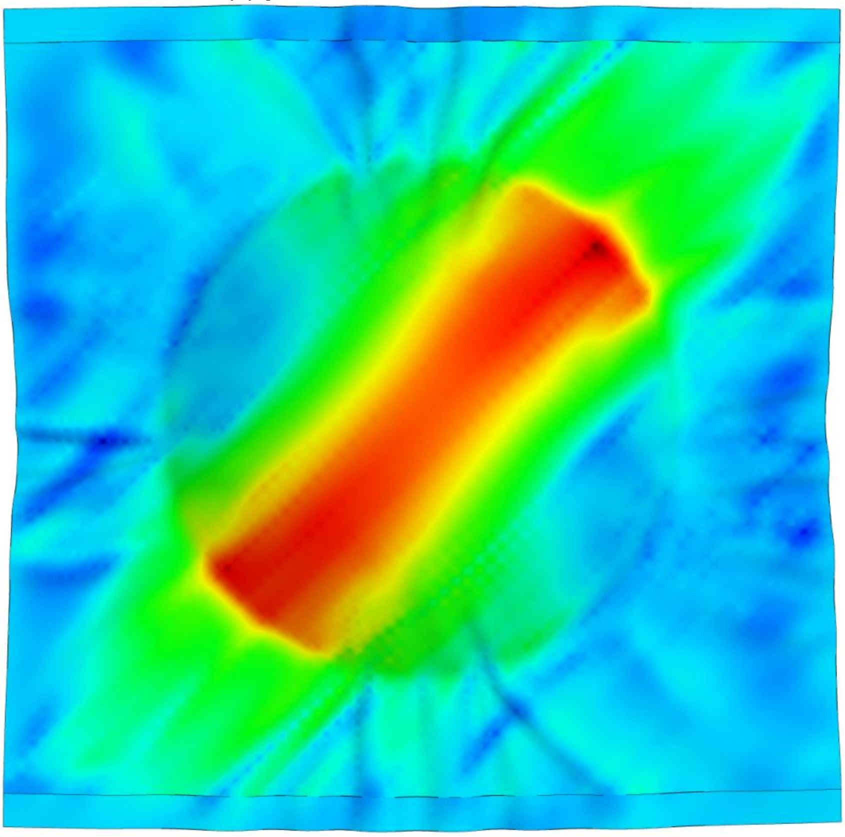


Figure 42 AniForm simulation of a quasi-isotropic laminate, fibre strain in top ply [$-2.5\cdot10^{-2}$, $6.8\cdot10^{-3}$]

From the figures above, we can obtain that triangular elements describe the region of maximum fibre strain properly. However the values of the fibre strain are far apart, this is due to the elasticity modulus assigned to the fibres. These are about a factor 100 apart, when this is taken into account the results are comparable. The interesting point here is the strain distribution across the half sphere when using quadrilateral elements. The strain field is distributed along the edge of the dome, instead of across the dome. This indicates that intra-ply shear locking is occurring in these elements along the edge of the dome. However excessively high strain values that typically accompany this phenomenon are not displayed in the simulation.

The regions which experience compressive strain is almost in accordance with the triangular element simulations. We can conclude that when the fibre strain (and thereby stress) is of interest, one should use triangular elements.

Using an unstructured blank mesh, as generated by most meshers by default, will always result in unaligned element edges with respect to the fibre direction. Therefore intra-ply shear locking will occur here, no matter the fibre orientation.

Conclusion
The results as presented in this paragraph conclude a few points. The friction model as used in PAM-FORM does not suffice the situation. Changing the parameters to unrealistic high values did not improve the inter-ply slip behaviour. AniForm uses a different model, therefore the results are different, and seem to be better fitting for the carbon tape material.

The wrinkles as displayed by PAM-FORM when using quadrilateral elements are only in horizontal direction in agreement with the real pressings. The other wrinkles differ from reality. When the mould is fully closed the simulation is not capable of displaying the wrinkles properly.

Using triangular elements in PAM-FORM results in a more fitting global result, however the influence on the bending stiffness is noteworthy. More research is needed to check the influence of the element size on the bending stiffness.

The AniForm simulations display better results when it comes to tape based materials. The friction model used is in better agreement with reality, therefore the wrinkles probably are too.

The wrinkles as displayed by AniForm at full mould closure are in better agreement in comparison with reality, than the totally flat laminate as shown by PAM-FORM. In PAM-FORM the wrinkles have disappeared, they are fully pressed into the laminate. This can be of influence on the stresses in the laminate in the last forming step.

Moreover AniForm was able to take the viscous behaviour of the material into account, where PAM-FORM was not.

When it regards laminates with ±45 degree plies orientation, one should always consider using a structured triangular mesh. Although the global results seem to be in agreement with reality when quadrilateral elements are used, the more in-depth results show a disagreement. Directly splitting the quadrilateral elements results in unacceptably high computational times in PAM-FORM. More research is required on the triangular element size when applied in PAM-FORM.

3.1.3 Quasi-isotropic lay-up using woven glass: $(0_f/45_f)$

In this paragraph the stamp forming and simulation results will be presented for the woven material. The laminate consists of two layers of Tepex dynalite material as presented in paragraph 2.1 Tepex dynalite 102.

PAM-FORM

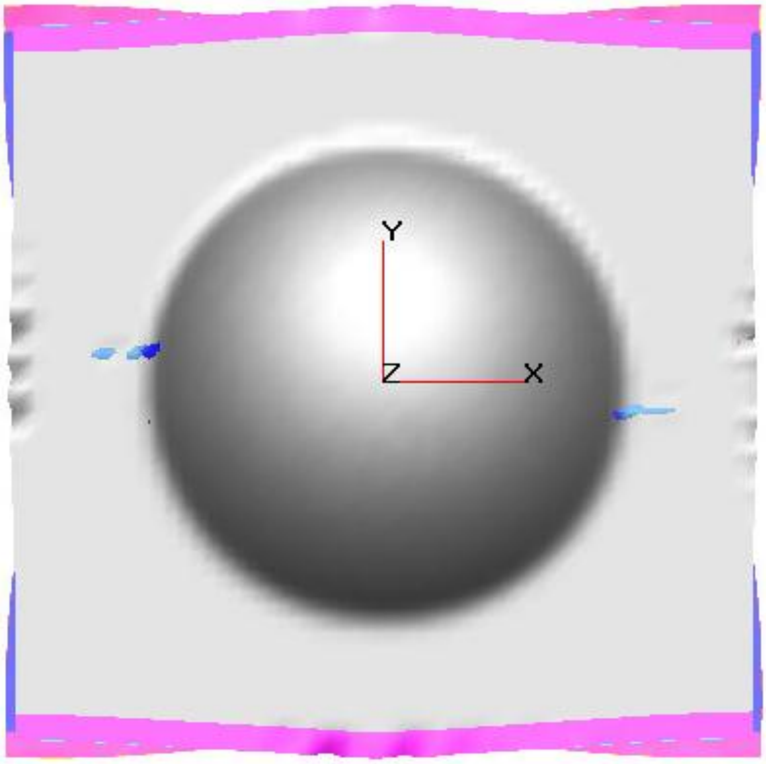


Figure 43 PAM-FORM simulation of a quasi-isotropic laminate at full mould closure

Figure 44 Half sphere at full mould closure using a quasi-isotropic laminate

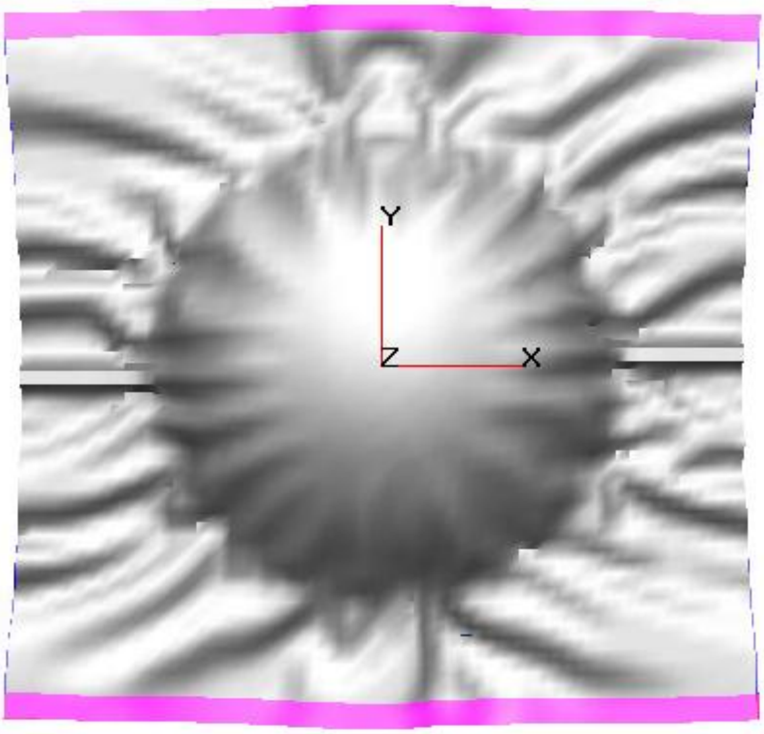


Figure 45 PAM-FORM simulation of a quasi-isotropic laminate at 7 mm mould spacing

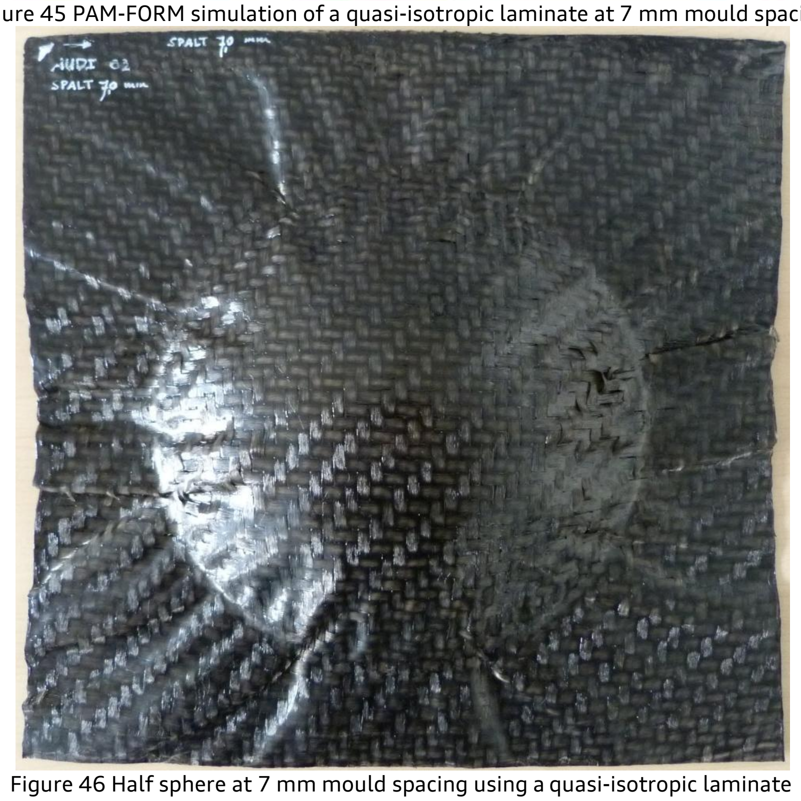


Figure 46 Half sphere at 7 mm mould spacing using a quasi-isotropic laminate

Figure 43 till Figure 46 display the results of the laminate pressing for both the simulations as in reality. When comparing Figure 43 to Figure 44, the figures look much alike. The little wrinkles as shown on the left and right side of the laminate as present in both the simulation as in reality. Across the laminate itself no wrinkles are present, which is displayed by both too. However PAM-FORM displays another issue, there is much inter-ply slip occurring between the plies. This slip mechanism is not present in reality and therefore displays another outer contour than the simulation does.

When we look at the time step where the mould spacing was 7 mm, as shown by Figure 45 and Figure 46, we notice that the results are comparable. As is displayed in Figure 46, the laminate seems to have shifted downwards during the stamp forming process. Therefore the wrinkles on the left and right side are not displayed fully symmetrical. The wrinkles as simulated are comparable with those in reality. Smaller wrinkles on the top and bottom side, larger wrinkles on the left and right side. In the corners diagonally oriented wrinkles are displayed in both figures. The outer contour of the laminate is comparable too. PAM-FORM is able to predict the outcome of the stamp forming process accurate when this material card is used.

The computational time needed to solve this simulation was 4.77 hours.

AniForm

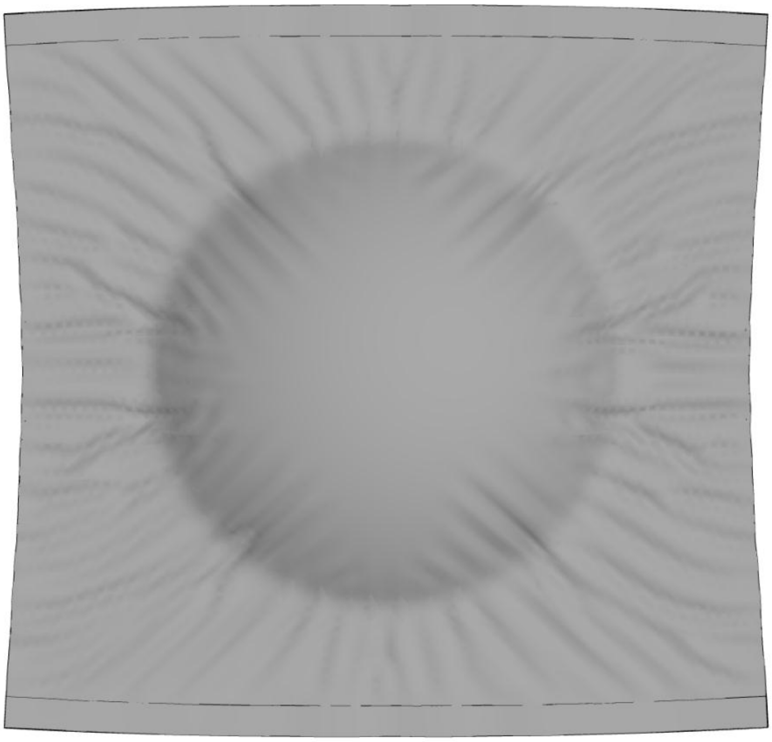


Figure 47 AniForm simulation of a quasi-isotropic laminate at full mould closure

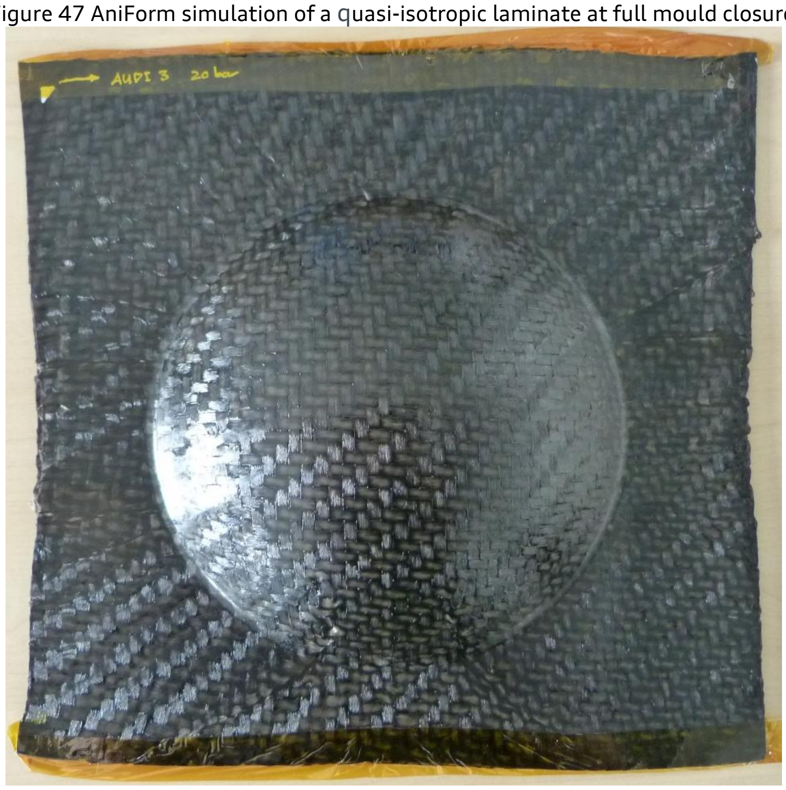


Figure 48 Half sphere at full mould closure using a quasi-isotropic laminate

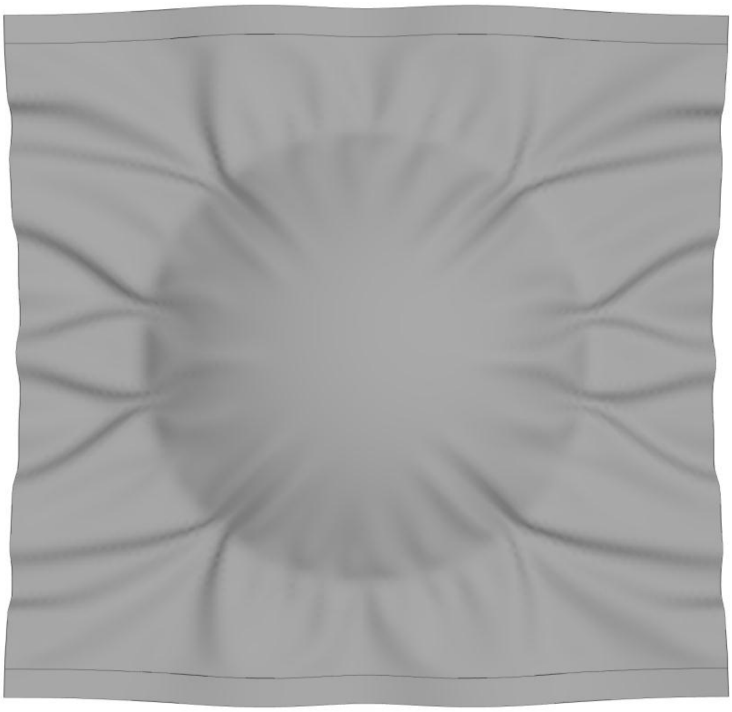


Figure 49 AniForm simulation of a quasi-isotropic laminate at 7 mm mould spacing

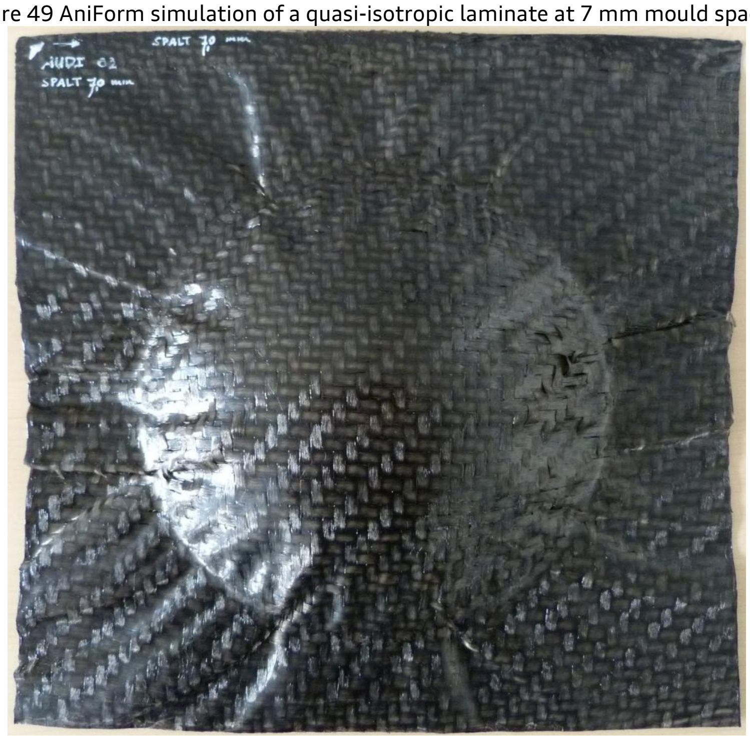


Figure 50 Half sphere at 7 mm mould spacing using a quasi-isotropic laminate

Figure 47 and Figure 48 display a similar outer contour, the top and bottom edges are curved outwards where the left and right edges are curved inwards. The AniForm simulation displays many little wrinkles all cross the laminate. These wrinkles are present in reality too, which is difficult to obtain from Figure 48.

Figure 49 and Figure 50 appear to be much alike. The wrinkles occur all around the dome, in all directions. In Figure 49 the wrinkles appear to be less straight than in reality.

The total computational time was 11 hours and 12 minutes. Most of the computational time is consumed near the end of the simulation. The time step where the mould spacing was 7 mm, was reached after approximately 5 hours.

Conclusion
Both PAM-FORM as AniForm show promising results when it concerns thermoplastic woven material. The results are comparable with reality, therefore both simulation packages show the potential to be applied when it concerns woven fabrics.

As was noticed too in the simulations for tape-based material, the friction model in PAM-FORM does not represent reality properly in the final pressing step. Much intra-ply slip is occurring in the final phase. This can be caused by the fact that the wrinkles are pressed into the laminate. The stresses introduced by this phenomenon cause the plies to slip. Adapting the friction parameter did not have any influence on this behaviour. Adapting the penalty stiffness may improve the result, this was not tested however.

The large wrinkles are represented well in both software packages. Whereas the tiny wrinkles across the laminate at full mould closure, have fully disappeared in PAM-FORM. These wrinkles can be seen in the AniForm simulation.

The contour of the laminate is represented well by both software packages at 7 mm mould spacing. At 0 mm mould spacing PAM-FORM solution deviates from reality, whereas the AniForm simulation does not.

The computational times are comparable till the last 15% of the simulation. AniForm shows larger computational times, due to increasing convergence difficulties near the end of the forming process.

3.1.4 Conclusion half sphere
The AniForm simulations when using tape based material, were in better agreement with reality. This can be caused by the friction model which showed a better performance in AniForm than PAM-FORM did. This excessive inter-ply slip behaviour is noticed too in the simulations where woven material was used. Although they do not appear to be of large influence of the final shape of the laminate when it concerns wrinkles.

Concluding, it is advisable to use AniForm when tape based material are applied. When woven materials are used, both software packages show proper results. However, in PAM-FORM one should look at the previous time-step instead of the final one.

The trade-off, when using AniForm, is in the increasing computational times. This can be overcome by using a powerful PC, as shown in the half sphere simulations performed by AniForm Engineering.

3.2 Universalprüfkörper

As a car manufacturer, the goal is always to produce as many parts in as little time possible. An interesting development of the last few years is the rise of hybrid technologies, such as the combination between forming technologies with injection moulding: over-moulding. Figure 1 shows a part which has been produced by this technology. During the inmould-forming-overmoulding process a blank of thermoplastic material reinforced with fibres is stamped into a certain shape by a press. Normally one would take this deformed blank out of the mould and trim it into the right shape to suffice the products function. When using the over-moulding process, the blank is a bit smaller than its final product shape typically. After forming the mould stays closed and a resin is injected into the mould. The space which was not filled by the blank in the first place, is now filled with resin. When the resin has cooled down, and we can open the mould. The result is a fibre reinforced product, which is already in its final shape, so no extra trimming is needed. Using this process we can combine the advantages of using fibrous material with the advantages of injection moulding.

The “Universalprüfkörper” (UPK) is a part developed by Audi, where this hybrid technology can be performed and afterwards tested on its mechanical properties. The UPK can be used in a lot of testing equipment; therefore it is suited for a broad range of research subjects. In this case the material used during forming is a glass fibre material combined with a nylon-6 resin. It goes by the name of Tepex, material data can be found on the website of Bonds Laminates[3] and more information on the calibration of this material in paragraph 2.1 Tepex dynalite 102.

In April 2014, the UPK was produced at Krauss Maffei in Munich. The injection moulding process will be tested later on. Using the results after forming, a comparison between the simulation and reality can be made. By this the calibrated material data can be verified and adapted if necessary.

Figure 51 “Universalprüfkörper”

3.2.1 Forming process

The forming step of the process is the first step in creating the actual part. The laminate is heated above melting temperature in an oven, while being fixed in a frame. When the temperature is right, the laminate is transferred to the mould. This has to be done rapidly since the polymer will solidify again at room temperature. Therefore the laminate will be heated well above melt temperature.

The laminate is transported in a frame by a robot to the mould. Here the frame is positioned between the two mould parts (male and female), as can be seen in Figure 52. When the positioning is completed, the laminate is fixed by the four pins. Now the frame is no longer necessary and is removed from the process area.

Figure 52 Positioning of the laminate

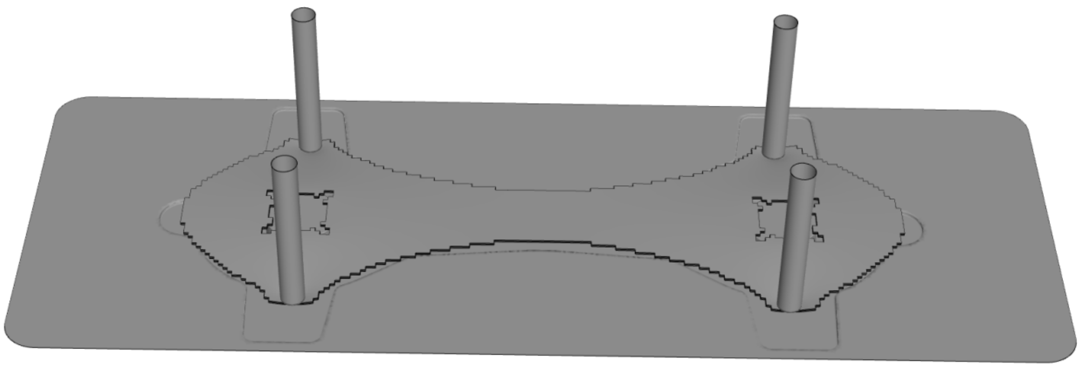


Figure 53 Positioning of the laminate and fixing by four pins as simulated

When the blank is positioned, and fixed, the actual forming step begins. We move the male part onto the laminate and press it into shape. The pressing continues until a certain distance is reached between the two moulds. Figure 53 till Figure 55 show the forming process of the UPK as simulated.

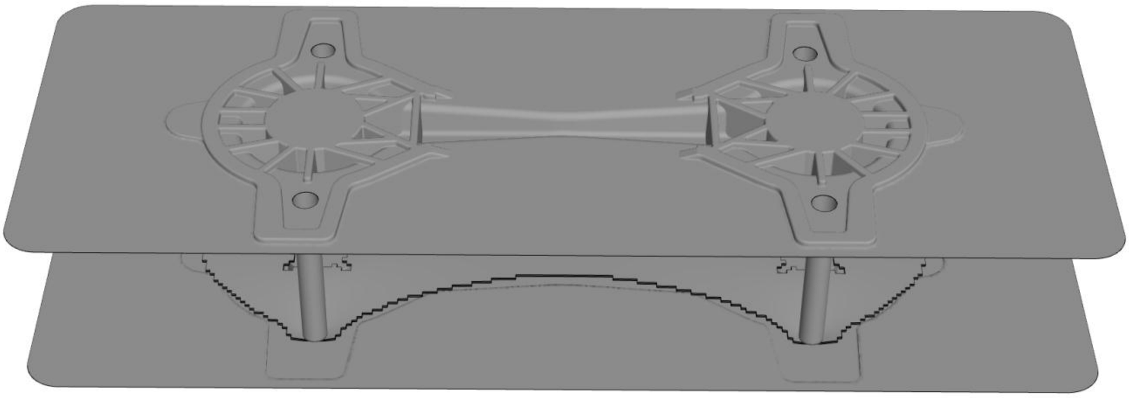


Figure 54 Initial position of the setup before closing the mould as simulated

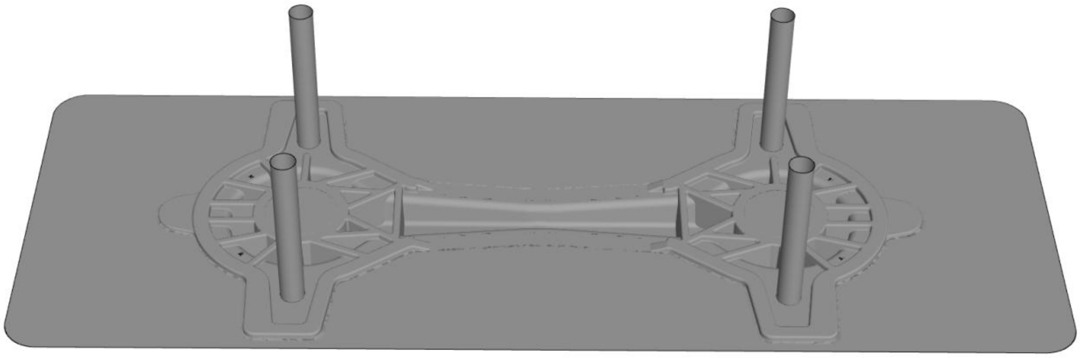


Figure 55 Setup after closing as simulated

Altogether the forming process, from clamping the laminate using the pins till the moment the mould is fully closed, is taking under three seconds.

It should be noted that all the simulations are without gravity. The real process is vertically oriented, since the bending of the laminate in melting condition is too high for proper positioning. One would bump the laminate against the mould when the current setup is used in horizontal orientation.

3.2.2 Mould and tool meshes and properties

To produce the UPK, three tools are necessary. We use a male and female mould to form the blank, but before we do, the blank is positioned and fixed by four pins. The moulds and pins were modelled using triangular linear elements. The size of these elements varies over the geometry due to contact effects. If contact is of larger interest in a certain region, for instance at a corner, the number of elements is increased locally.

All meshes used in the simulations are created in ANSA[8]. In every simulation the moulds and pins are modelled as rigid bodies. Therefore the only object in the simulation that can be deformed is the laminate.

3.2.3 Laminate meshes and properties

The laminate used in the simulations is not always the same. However the lay-up of the laminate does not change. The laminate consists of three layers of Tepex with a thickness of 0.5 mm. The lay-up is $[0]_3$ in every simulation. Therefore the total thickness of the laminate is 1.5 mm.

At first the laminate was modelled using three separate mesh layers, thereby every blank has its accompanying mesh layer. In this case we are able to simulation the behaviour of every single ply and take intra-ply friction into account. Later on, the laminate was also modelled using only one mesh layer for a three layered laminate. This will result in lower computational times. The laminate thickness is still 0.5 mm in one mesh layer; however the contact distances are adapted. Thereby the laminate appears to have a thickness of 1.5 mm. However in this case some assumptions on the material data have to be made, since the behaviour of the laminate changes with increasing thickness. The in-plane properties of the laminate and the mass are extrapolated linearly. The out-of-plane properties are more difficult to scale, since every material behaves differently when the thickness is increased. From previous experience it is known that the out-of-plane properties behave somewhat linear with respect to increasing laminate thickness. We lack experimental data to validate this assumption, but it is the best we got.

Previously, most of the simulations at Audi were performed in PAM-FORM. Quadrilateral elements were used in an unstructured mesh. For isotropic materials, this is nothing to worry about, however when using highly anisotropic materials, this can cause intra-ply shear locking. Wolthuizen et al.[6] has shown this in his work more extensively. Question remains of how much influence this phenomena is on this specific simulation. Therefore the UPK laminate is modelled with both structured as unstructured meshes.

Altogether the following simulations have been performed:

One-layered mesh	*Software*	**Three-layered mesh**	*Software*
Structured	AniForm	Structured	AniForm
Structured	PAM-FORM	Structured	PAM-FORM
Unstructured	PAM-FORM	Unstructured	PAM-FORM

3.2.4 Material data

The data as calibrated in PAM-FORM was used in the PAM-FORM simulations. A description of the calibration can be found in paragraph 2.1 Tepex dynalite 102. A fully elastic material description was used in PAM-FORM since we were not able to calibrate the material data for viscous behaviour. The same material data was used in the AniForm simulations.

Audi is not the only company to use this material, therefore there are more values available for this material. The bending test, as described in paragraph 2.1.2 Bending test, does not conclude at lot on the bending stiffness since its response on a change in bending factor is low. Our calibrated bending factor appeared to be high in comparison to the results of other companies. The people of Volkswagen were willing to share their calibrated material card for PAM-FORM, and their bending factor has been implemented. When the tests were performed in April, the results were compared to the simulation results. These results will be presented in paragraph 3.2.5 Simulations.

Due to confidentiality of this material and the project, the exact parameters which are used in the simulations cannot be shown.

3.2.5 Simulations

In this paragraph the simulation results are presented. A comparison with reality will be presented as well. For every simulation the laminate is shown at 7 mm mould spacing, 3.5 mm mould spacing and full mould closure. These results will be compared with the actual parts produced at Krauss Maffei.

All parts with come into play during the simulation are meshed using linear triangular elements. The tools have an unstructured mesh. Some of the blanks were simulated using a highly structured mesh to prevent intra-ply shear locking. This blank mesh has element edges aligned with fibre directions. They have been prepared for 45 and/or -45 degree directions as well, therefore triangular elements are used. Figure 56 displays a blank mesh used in the UPK simulations.

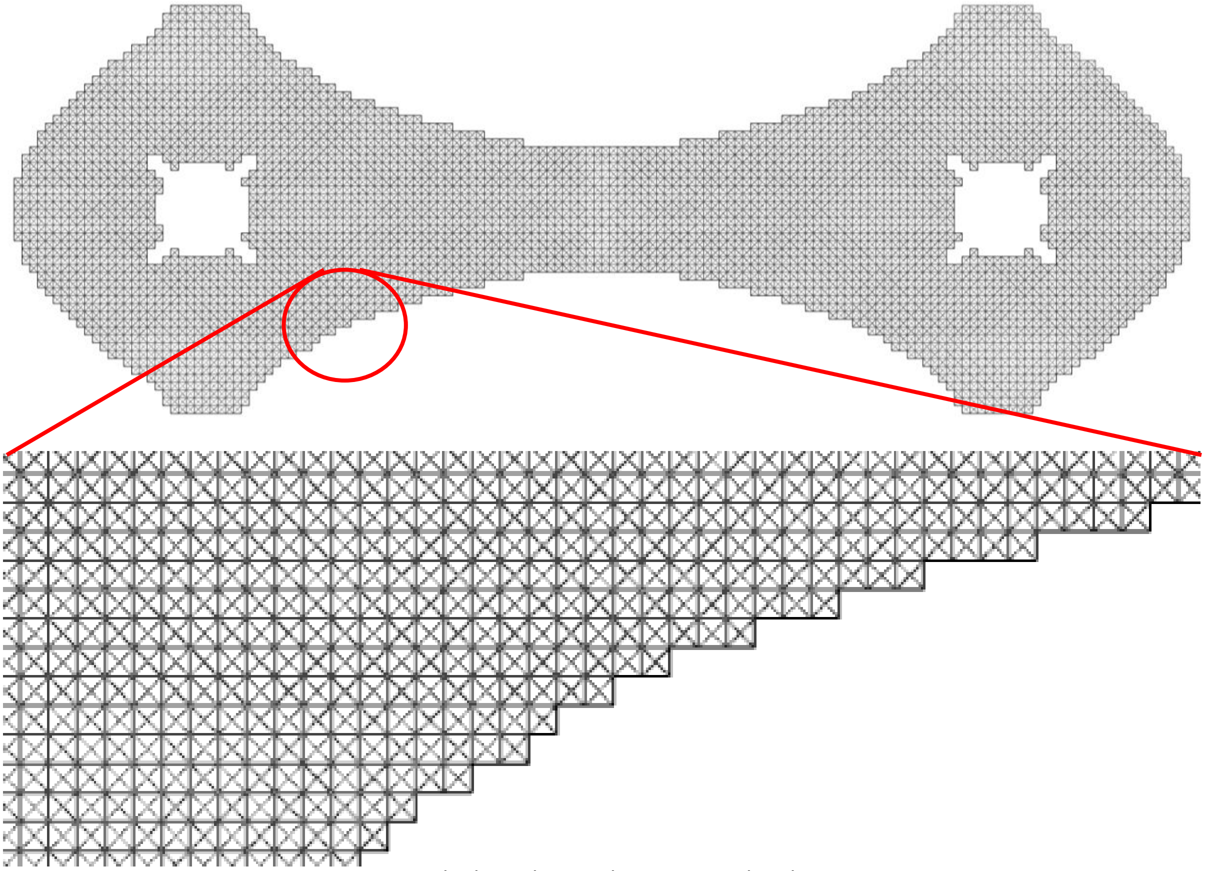


Figure 56 Blank mesh using linear triangular elements

One-layered structured mesh (AniForm)

The material data in this simulation has been extrapolated to a three layer configuration. This causes the contact to occur at correct distance, but it does not overestimate the material properties.

The loading is determined by looking at previous experiments on the setup and measuring the time. The closing time for the pins is set to 0.25 seconds, and the closing time of the mould was set to 0.5 seconds.

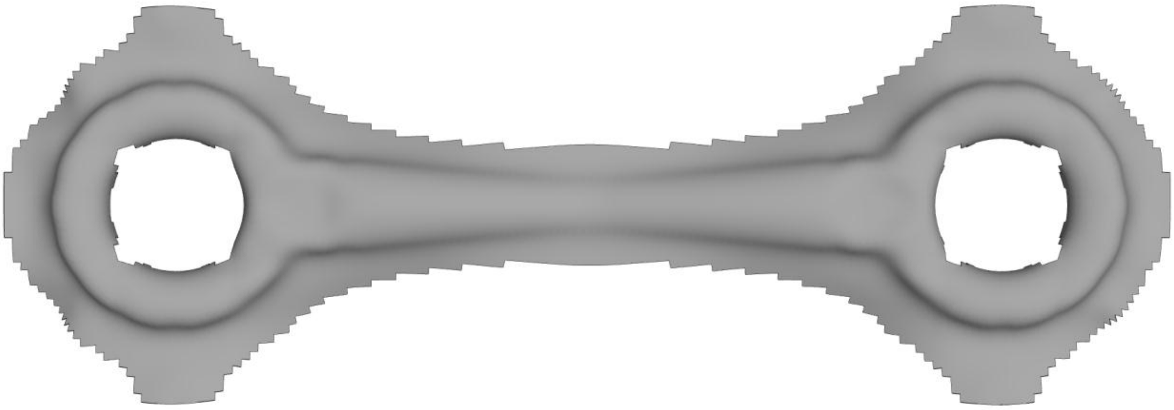


Figure 57 AniForm simulation results using a one-layered mesh when the mould spacing is 7 mm

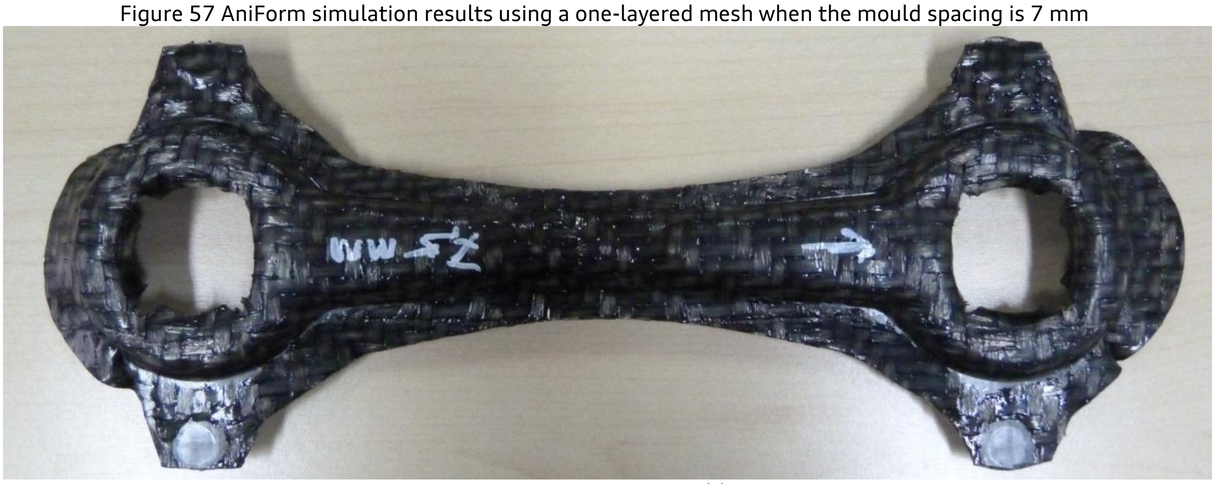


Figure 58 UPK at 7.5 mm mould spacing

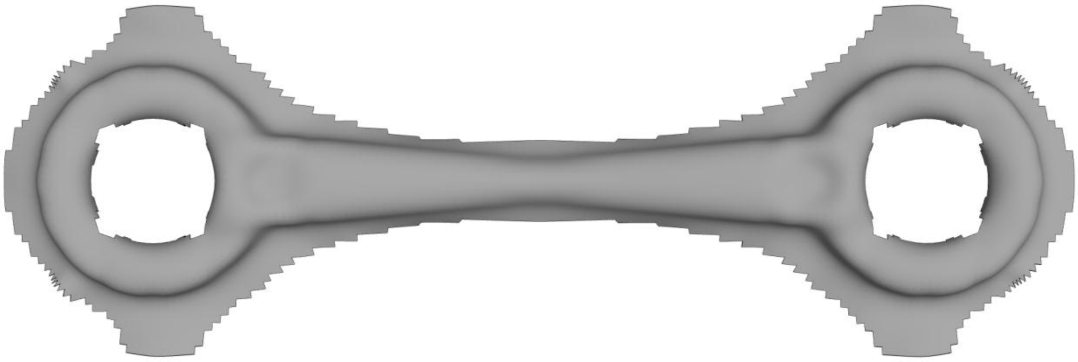


Figure 59 AniForm simulation results using a one-layered mesh when the mould spacing is 3.5 mm

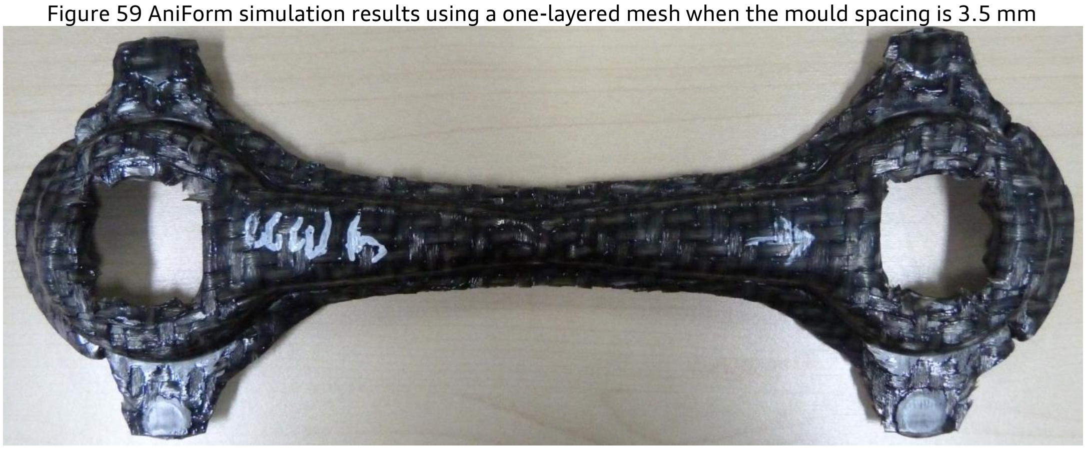


Figure 60 UPK at 4 mm mould spacing

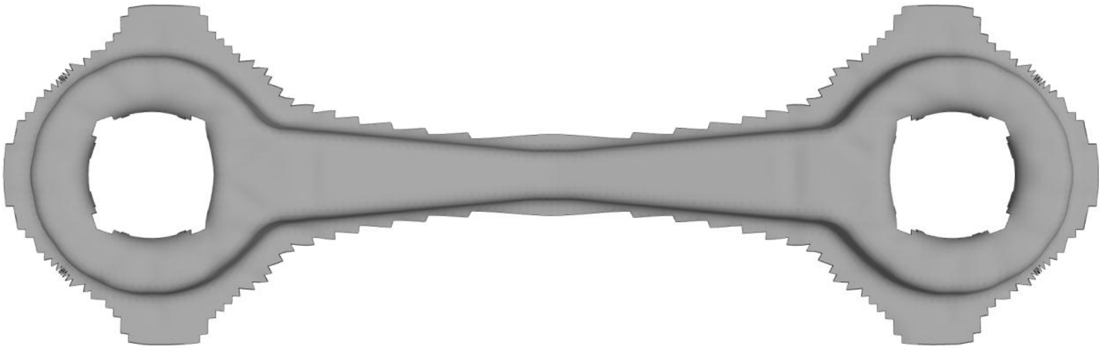


Figure 61 AniForm simulation results using a one-layered mesh at full mould closure

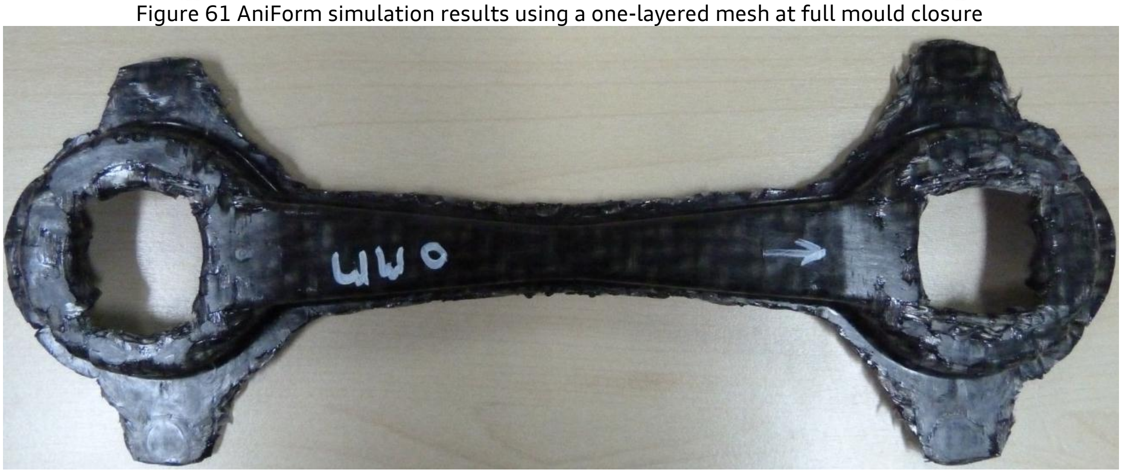


Figure 62 UPK at full mould closure

In the AniForm simulation at 100% mould closure, the results shows a tiny fold on the flange of the UPK. On the vertical part of the UPK no fold is visible. This is not fully in consensus with the actual forming results. In the middle of the UPK the simulation seems to be in agreement with reality. However on the ends, the simulations do not display any folds, while they are there in reality. The same phenomenon can be noticed when it concerns the outer contour of the laminate. The contour is in agreement with reality in the middle part, where it is not near the ends. It is suggested that the material behaviour is different in the middle part of the UPK, then it is near the ends. The laminate appears to be more stiff, which is results by a higher shear modulus. This can be caused by non-uniform heating, which results in different material properties across the laminate. When we look at the pressed laminates, as shown in Figure 63, we notice that the resin is not properly molten near the ends, and therefore confirms our notion. This phenomenon is noticed too on laminates that came straight out of the infrared oven.

Figure 63 End of a heated laminate which displays a glassy look

From PAM-FORM simulations performed in the past, a shear modulus is known which does display these wrinkles. This shear modulus is applied in AniForm to check whether the folds near the end of the laminate are displayed. If this is the case, our hypothesis is confirmed.

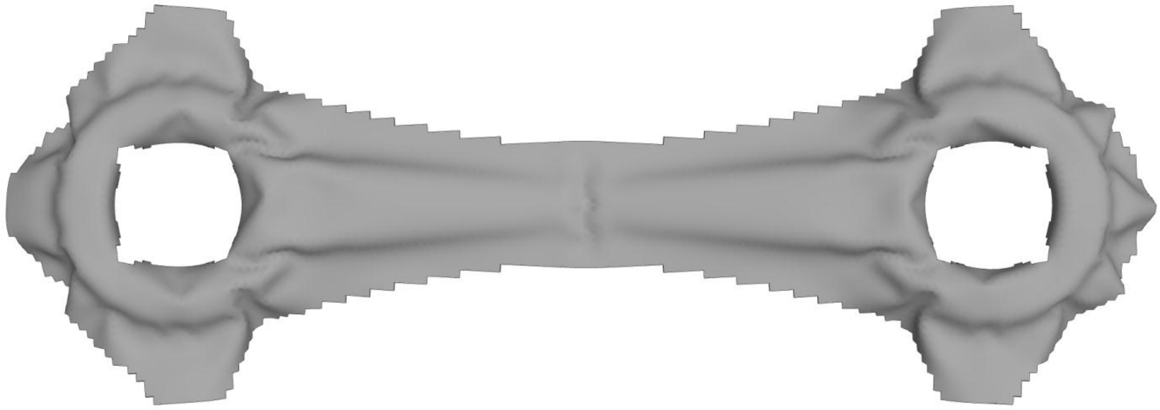


Figure 64 AniForm simulation results using a one-layered mesh when the mould spacing is 7.5 mm - higher modulus

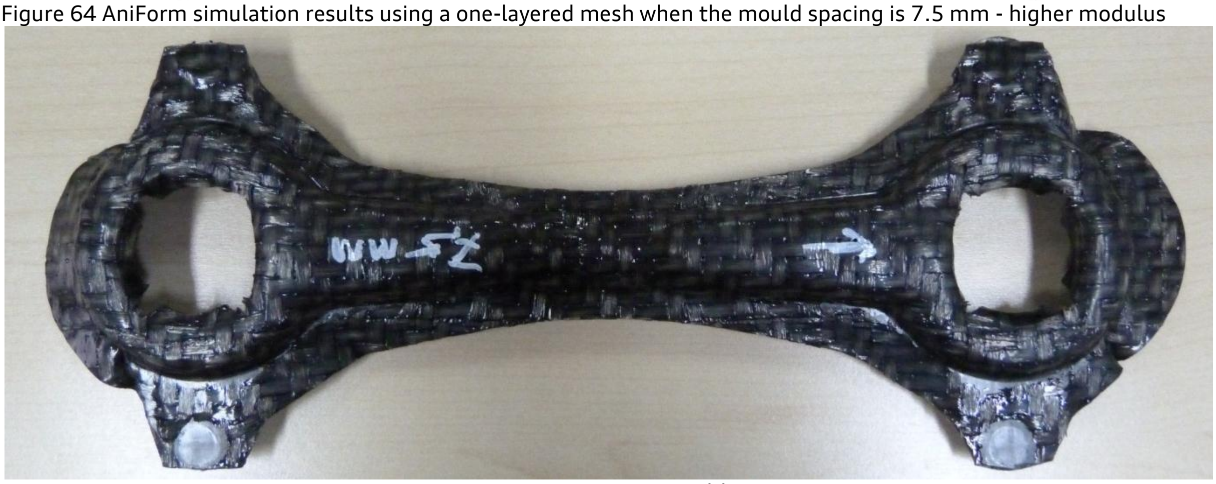


Figure 65 UPK at 7.5 mm mould spacing

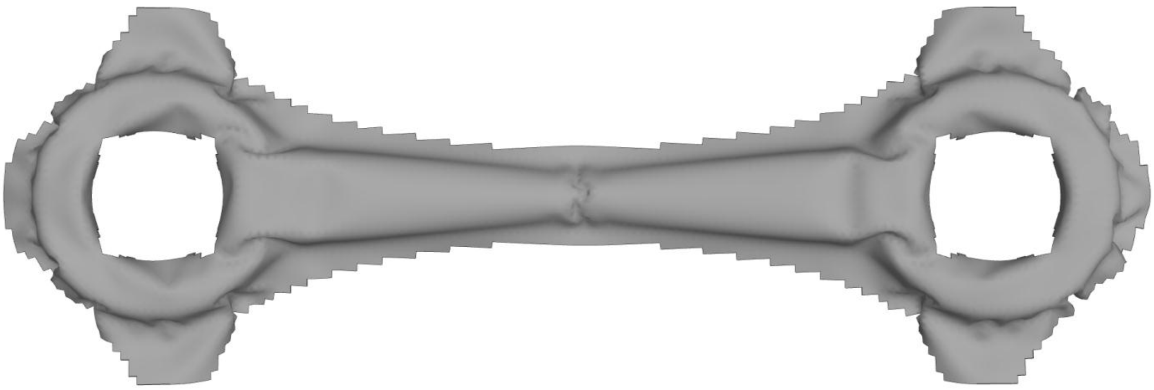


Figure 66 AniForm simulation results using a one-layered mesh when the mould spacing is 4 mm - higher modulus

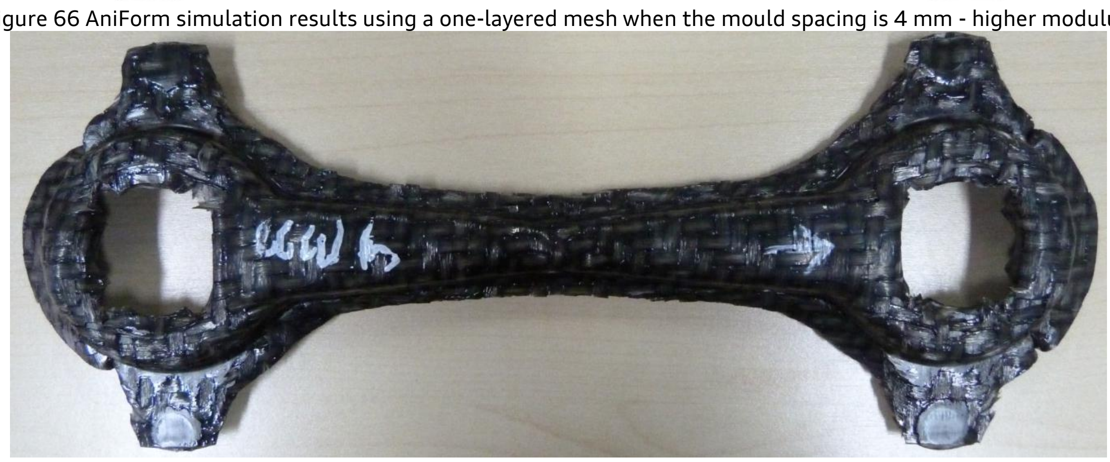


Figure 67 UPK at 4 mm mould spacing

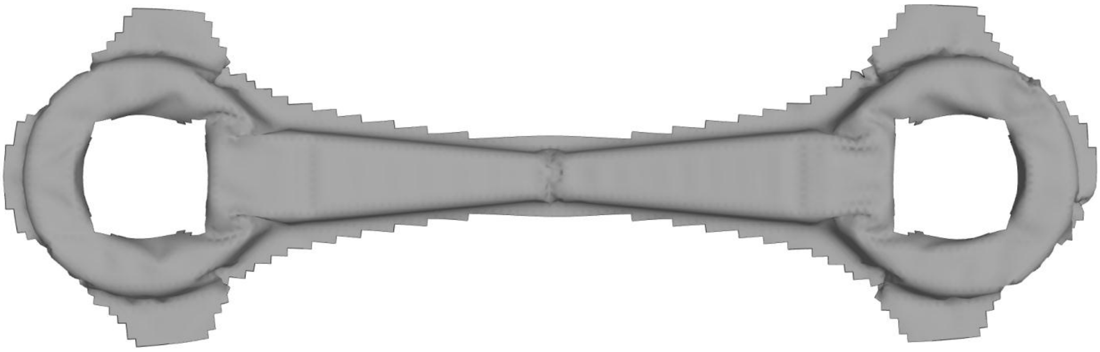


Figure 68 AniForm simulation results using a one-layered mesh when the mould spacing is 0 mm - higher modulus

Figure 69 UPK at 0 mm mould spacing

In Figure 64 till Figure 69 we notice the wrinkles at the end of the laminate in the simulations. The position of the wrinkles is not in accordance to reality during the forming process. The outline in the middle of the laminate is in good agreement with reality too. At the flaps, where the laminate is fixed by the four pins, the laminate appears to have been shifted. The simulation displays wrinkles near the flaps, which are not present in reality. The small fold in the middle of the laminate is neither present in reality. This suggests that the shear modulus was higher in these areas than it was in reality and thereby the temperature lower. Generally the wrinkles are rather large when compared to reality. This suggests that the applied shear modulus is probably too high.

Due to the temperature dependency, it is advisable in future work to include a temperature dependant material model for the in-plane shear properties. It appears that the temperature influence is rather large on the forming behaviour of the laminate. By using a temperature dependant material model we will to approximate the forming process more properly, since the laminate does not have a uniform temperature distribution.

Another option is to introduce a better heating control during laminate heating. When a uniform temperature field is reached, the laminate is transported. For practical reasons, this is rather difficult, since the process involves many motions. The laminate is transported during the process from the oven into the mould, therefore temperature alterations occur. Therefore reaching an uniform temperature distribution in the laminate whilst being positioned in the mould is (almost) impossible.

The computational time of the simulation using a small shear modulus is 1.13 hours. Where the computational time of the simulation using a higher modulus was 6.75 hours. Multiple simulations were running at the same time when the simulation using the higher modulus was performed.

One-layered structured mesh (PAM-FORM)
In PAM-FORM a forming simulation using a single mesh was prepared. In this simulation the material data is extrapolated in the same way as was done in the AniForm simulation. An problem occurred during this extrapolation. The same meshed blank as in the AniForm simulation is used. If size of the elements is small with respect to the material thickness, problems occur in PAM-FORM. The element edge length is 2 mm, the material thickness is 0.5 mm. The ratio between the element edge length and the material thickness must be kept at a high value, preferably around 10 or higher. The material thickness was chosen at 0.1 mm since this results in a stable simulation, whereas a thickness of 0.5 mm did not. It is important to keep this in mind when extrapolating the material properties, since we are still simulating a three layer laminate with a thickness of 1.5 mm.

The loading is here a bit different than in AniForm. Since we use only an elastic material description in PAM-FORM (viscous behaviour is instable for this geometry in combination with the material data), we are able to use very high velocities for the mould closing speeds without influencing the material behaviour. The closing time for the pins is here 4.5 ms. Closing the mould takes 22.5 ms.

Parallel to the previous paragraph, the results for the UPK simulations in PAM-FORM are shown in the figures below, and compared with the forming results.

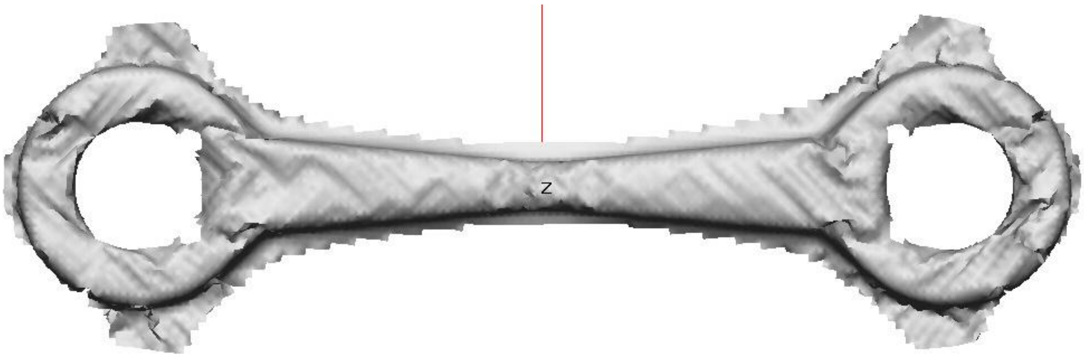


Figure 70 PAM-FORM simulation results using a one-layered structured mesh at 7.5 mm mould spacing

Figure 71 UPK at 7.5 mm mould spacing

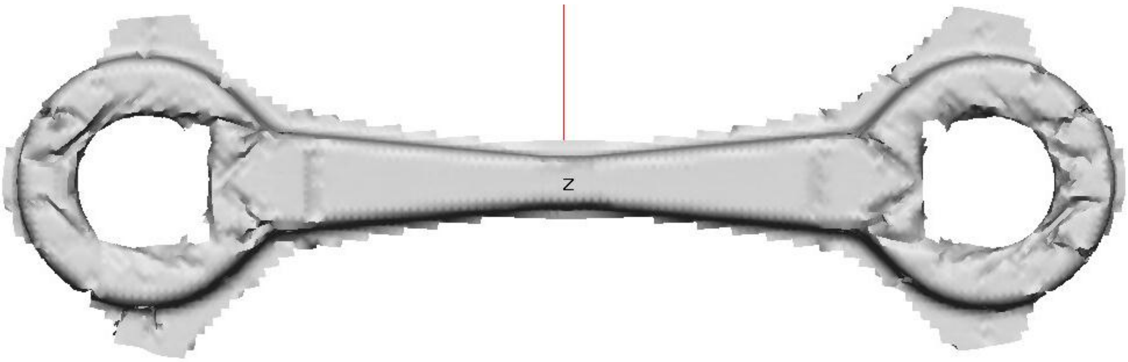


Figure 72 PAM-FORM simulation results using a one-layered structured mesh at full mould closure

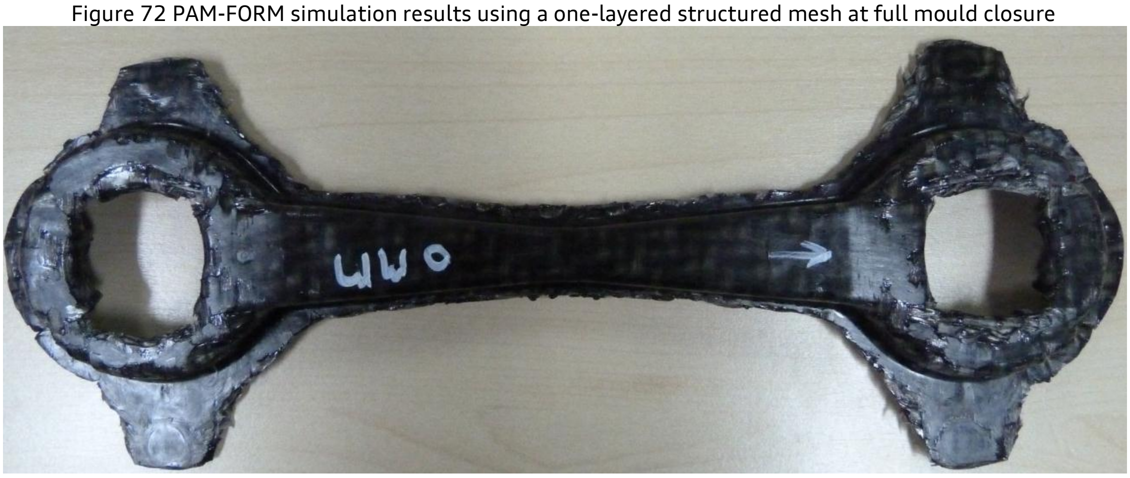


Figure 73 UPK at full mould closure

When looking at the inner side of the UPK, we can see big folds near the ends. These folds are only present in the PAM-FORM simulation.

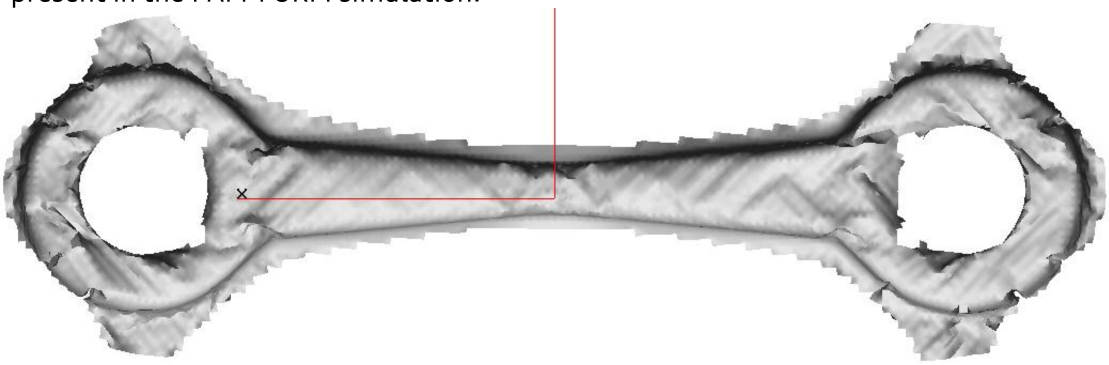


Figure 74 PAM-FORM simulation at full mould closure shows large folds at the inner side

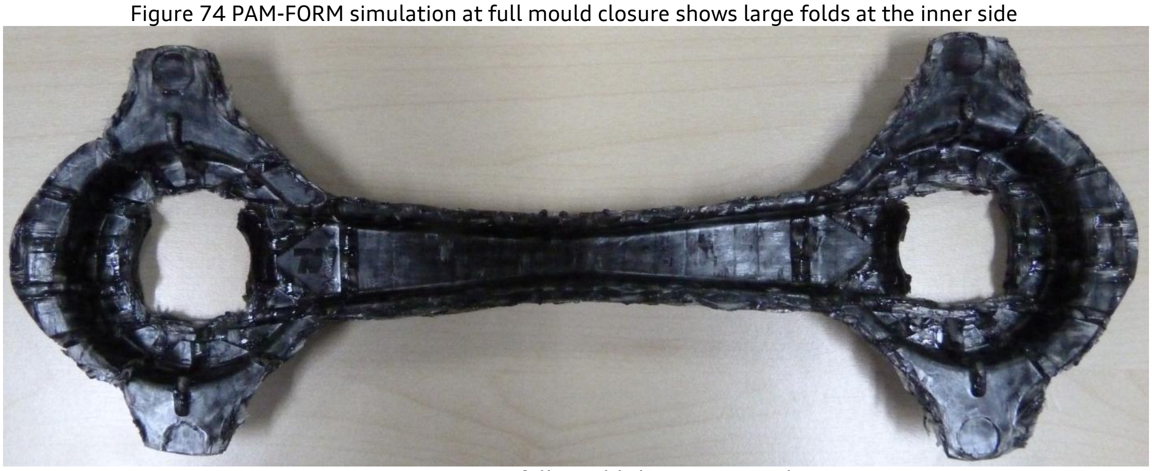


Figure 75 UPK at full mould closure inner side

As can be seen in the figures shown above, the laminate as simulated does look like the laminate as pressed when we look at the outer contour in the middle. The outer contour, during forming at the ends of the laminate, looks different than in reality. The laminate appears to have shifted inwards. At the flaps the contour behaves different too: they appear to have shifted where they should be fixed by the pins.

The wrinkles however, as shown by PAM-FORM, are a bit exaggerated. In reality not that many wrinkles occur in the laminate, and they are not that large.

The shear modulus is equal to the one used in AniForm at the “higher modulus” configuration.

The bending stiffness appears to be (too) low in this simulation. To check whether this is caused by the triangular mesh, a simulation was performed using a structured quadrilateral mesh, since PAM-FORM uses quadrilateral elements typically. In this simulation the same element size was used as was used in the triangular mesh. The results of this simulation did not show a noticeable difference compared with the triangular mesh. Therefore the difference between AniForm and PAM-FORM is not caused by the elements.

The simulation results where the mould spacing was 4 mm is missing, since there was not a result output at that point. The total computation time of this simulation is 8.11 minutes.

One-layered unstructured mesh (PAM-FORM)
When using the meshing feature in PAM-FORM, a quadrilateral element mesh will be created on an imported CAD (computer aided design) file. This mesh can be used in the simulation. However, when simulating fibre reinforced materials, anisotropic material behaviour plays a great part. As explained by Wolthuizen et al.[6], it is important to align the element edges with the fibre orientation to prevent intra-ply shear locking. This effect is not taken into account in the mesh feature of PAM-FORM, since PAM-FORM is not only used for simulating composite materials. It would be an interesting study, to see what happens to the simulation of the UPK when a non-structured mesh is applied. Therefore the UPK simulation is also performed using an unstructured mesh, with the same element size as the meshes used in the structured mesh simulations. The laminate thickness is 0.1 mm, as it was in the structured mesh simulation too.

The results of the PAM-FORM simulation, where an unstructured quad mesh was used, are shown in Figure 76 till Figure 79.

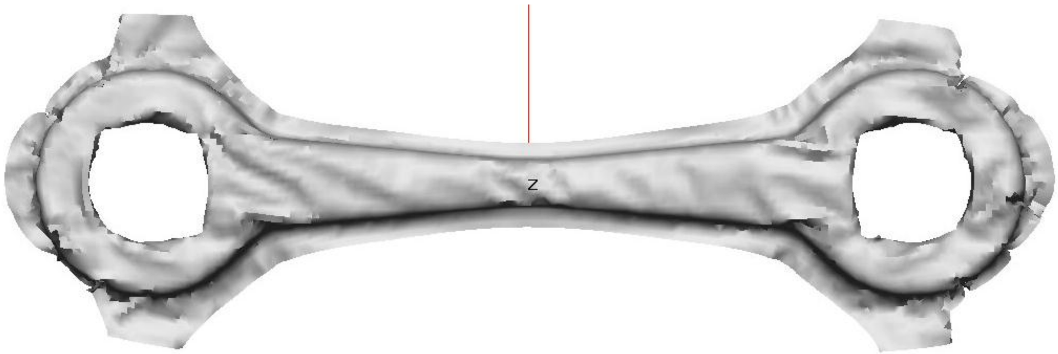


Figure 76 PAM-FORM simulation results using a one-layered unstructured mesh at 7 mm mould spacing

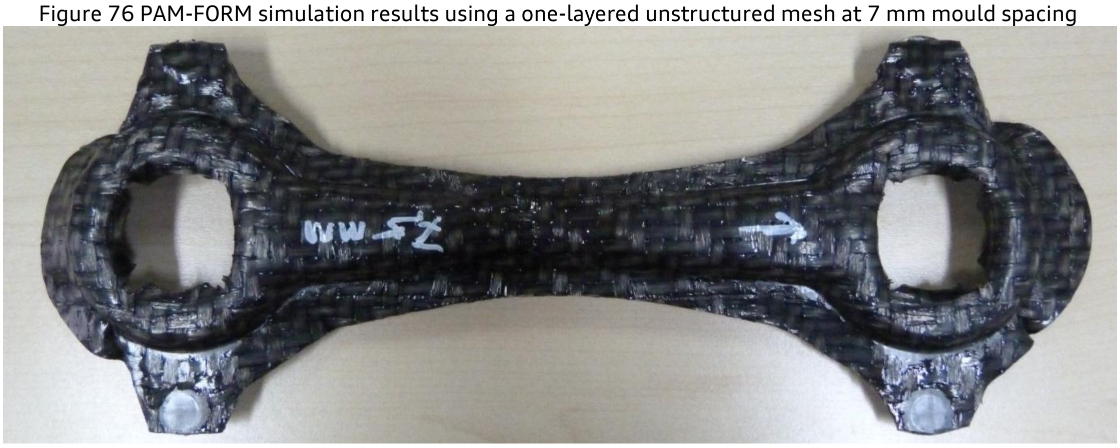


Figure 77 UPK at 7.5 mm mould spacing

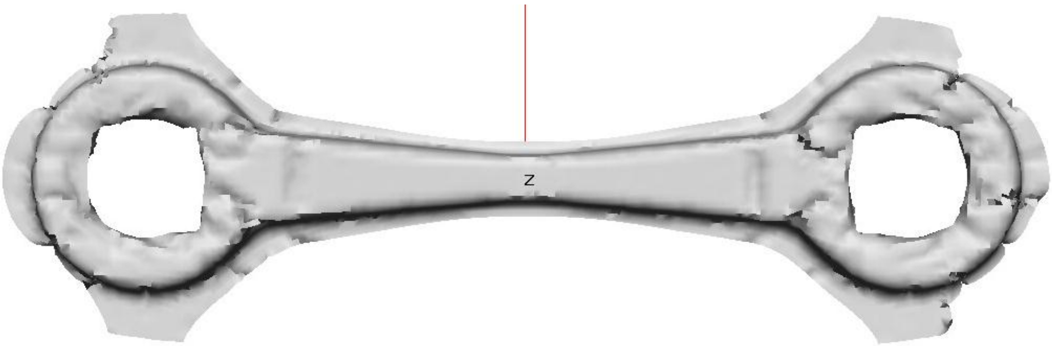


Figure 78 PAM-FORM simulation results using a one-layered unstructured mesh at full mould closure

Figure 79 UPK at full mould closure

The results as presented in the figures above look promising. The contour looks good in both cases at the ends of the laminate, however asymmetric. This makes sense since the mesh is asymmetric too. In the middle the contour is slightly too small when compared to reality. The flaps have shifted too. Altogether we notice the same behaviour as when using a structured mesh in PAM-FORM.

The total computational time for this simulation was 10 minutes and 29 seconds.

It would be interesting to see if there is excessive fibre strain occurring in the laminate due to intra-ply shear locking. Since the mesh is not aligned with respect to the fibre orientation, this is to be expected. We will compare the unaligned mesh to the aligned mesh, in both PAM-FORM as AniForm.

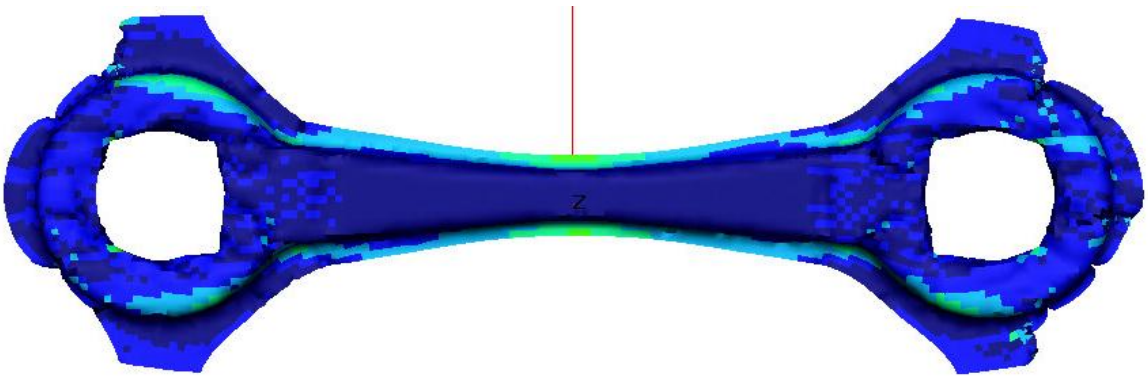


Figure 80 Fibre strain in a laminate using unstructured quadrilateral mesh in PAM-FORM.
Strain domain = [0, 0.1] (min = -0.11, max = 0.09)

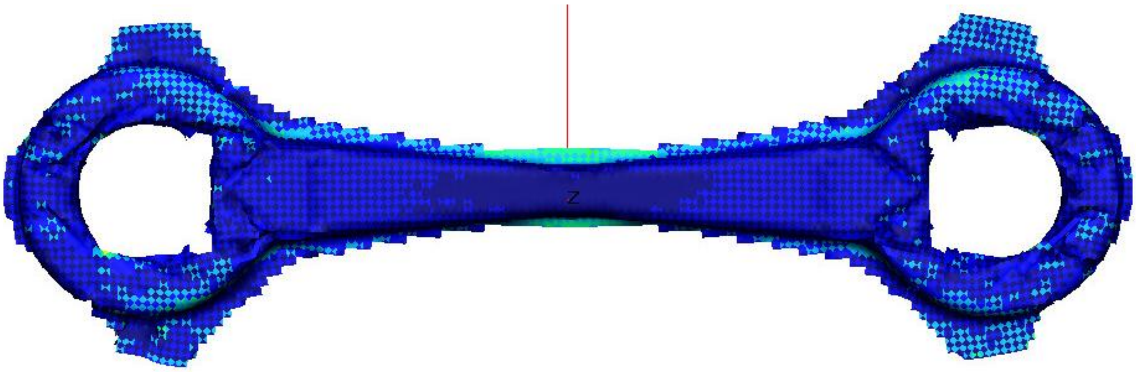


Figure 81 Fibre strain in a laminate using structured triangular mesh in PAM-FORM.
Strain domain = [0, 0.1] (min = -0.05, max = 0.10)

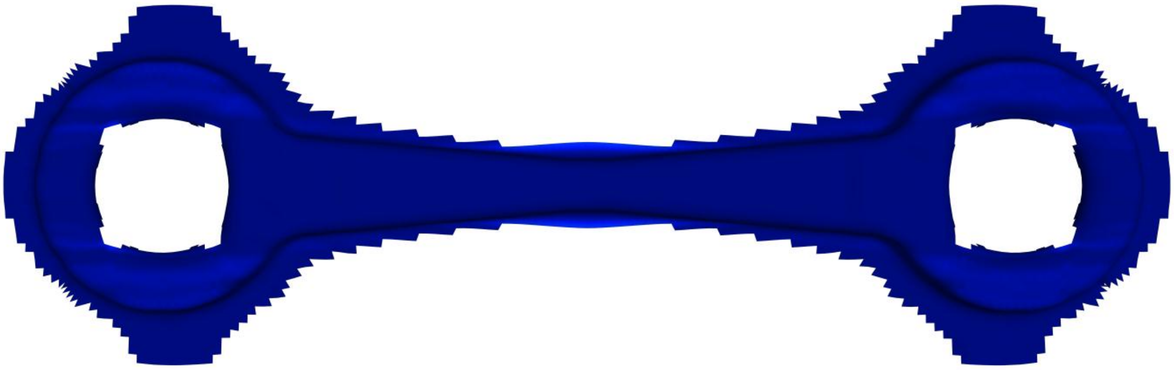


Figure 82 Fibre strain in a laminate using structured triangular mesh in AniForm.
Strain domain = [0, 0.1] (min = $-1.1*10^{-3}$, max = $6.1*10^{-3}$)

From Figure 80 and Figure 81 we notice a slight increase in maximum fibre strain at the structured mesh. This is odd, since a decrease was expected. The minimum did indeed increased as was expected. It is hard to tell whether this difference is caused by the absence of intra-ply shear locking or due to a change in the number of elements and topology.

More interesting is Figure 82, the value for the fibre strain is way lower as shown by the PAM-FORM results. The regions where the strain occurs are the same. Since the shear modulus used in AniForm is lower than used in PAM-FORM, the laminate deforms more easily by shear mechanisms. Therefore the fibre strain values are of less high magnitude. The fibre strain results as presented by PAM-FORM seem excessively high when it concerns polymers in melt, since it is already getting near the maximum strain limit of the fibres. Therefore a lower shear modulus as used in AniForm seems more suitable in this configuration.

A comparison between AniForm and PAM-FORM, where both software packages use a small shear modulus, would be preferable. However, we were not able to perform this simulation since this caused instability in PAM-FORM and caused the simulation to crash.

Three-layered structured mesh (AniForm)

Simulating the mesh using a separate mesh for each laminate is less time consuming for the user, since we can apply the calibrated material data onto the mesh. However more elements are used, therefore a larger computational time is necessary. The results of the three layered mesh simulation are shown in the figures below.

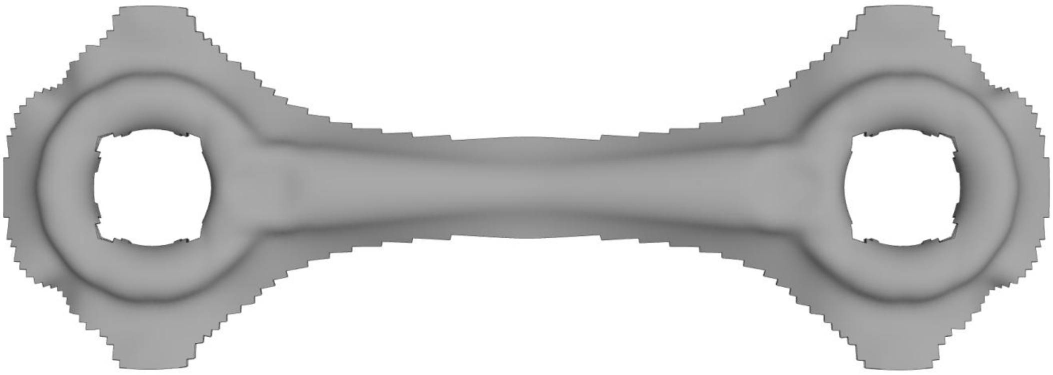


Figure 83 AniForm simulation results using a three-layered structured mesh at 7 mm mould spacing

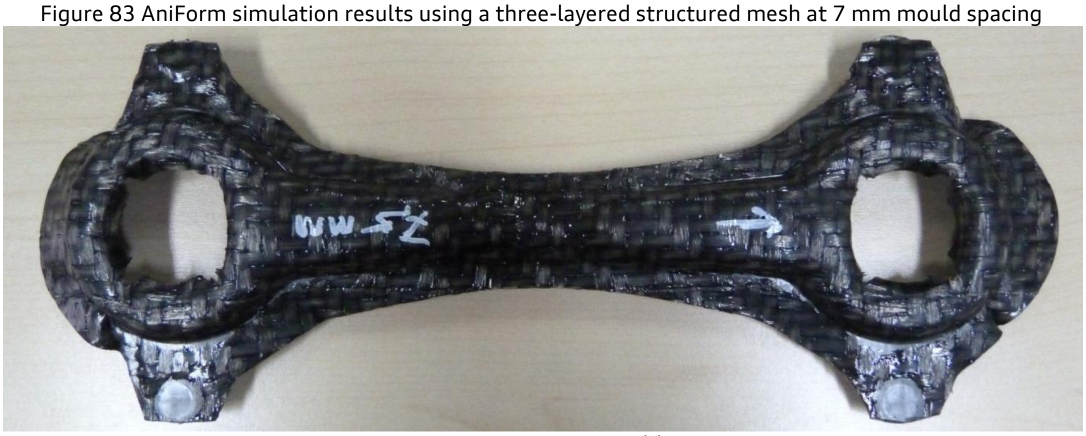


Figure 84 UPK at 7.5 mm mould spacing

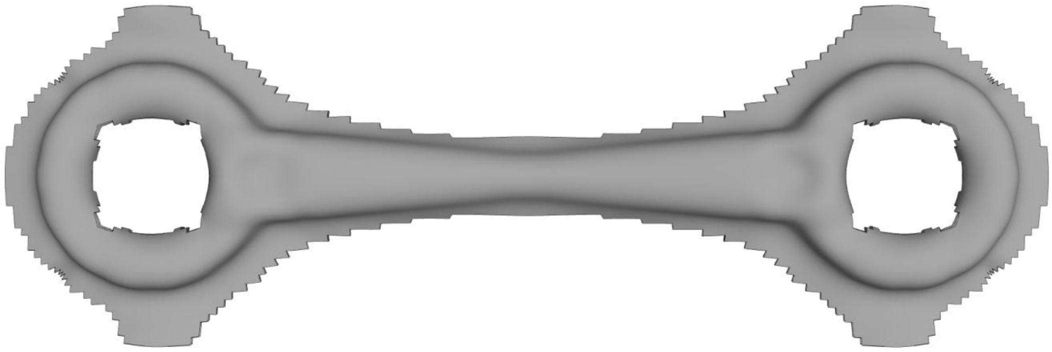


Figure 85 AniForm simulation results using a three-layered structured mesh at 4 mm mould spacing

Figure 86 UPK at 4 mm mould spacing

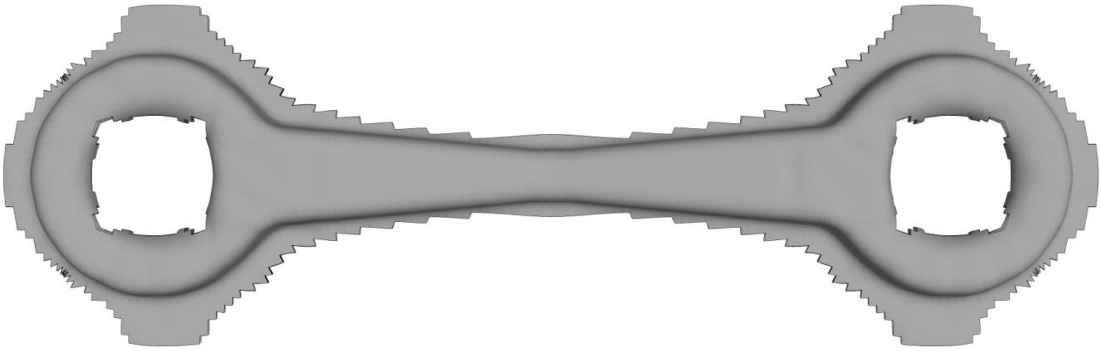


Figure 87 AniForm simulation results using a three-layered structured mesh at full mould closure


Figure 88 UPK at full mould closure

From the Figure 83 till Figure 88 we can notice that the simulation results are comparable to that of the one layer simulation. The occurrence of wrinkles and the outer contour show a great similarity with reality. The wrinkles in the outer corners, as displayed in reality, as present too in the three layer simulation. However they are very small, and do not buckle inwards as the wrinkles in reality do at full mould closure.

Similar to the one mesh layer simulation in AniForm, we increase the shear modulus to the value used in PAM-FORM. An increase in shear modulus can be caused by a decreasing temperature. In the paragraph where a one mesh layer was used, a non-uniform temperature distribution across the laminate is discussed. For this reason an increasing shear modulus simulation is of interest.

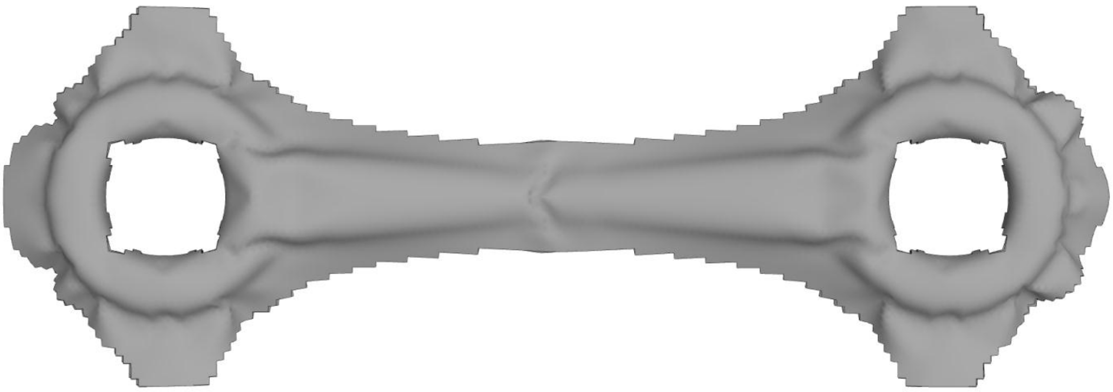


Figure 89 AniForm simulation results using a three-layered structured mesh at 7 mm mould spacing – higher modulus

Figure 90 UPK at 7.5 mm mould spacing

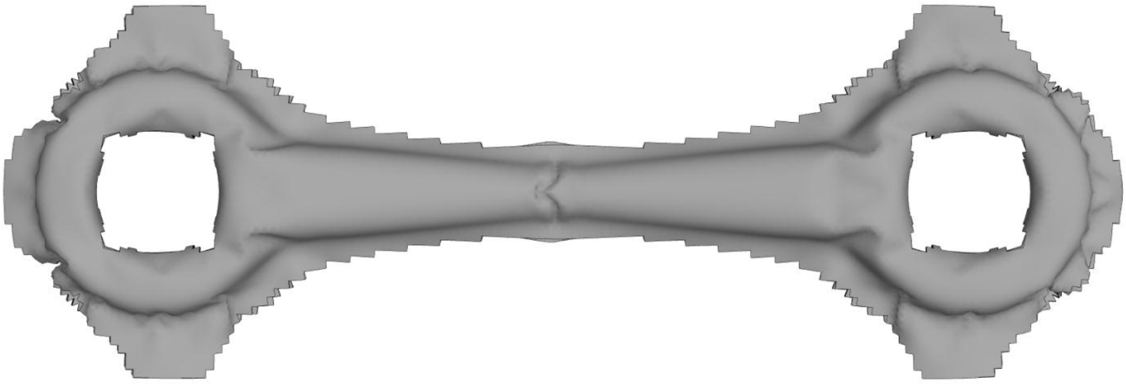


Figure 91 AniForm simulation results using a three-layered structured mesh at 4 mm mould spacing – higher modulus

Figure 92 UPK at 4 mm mould spacing

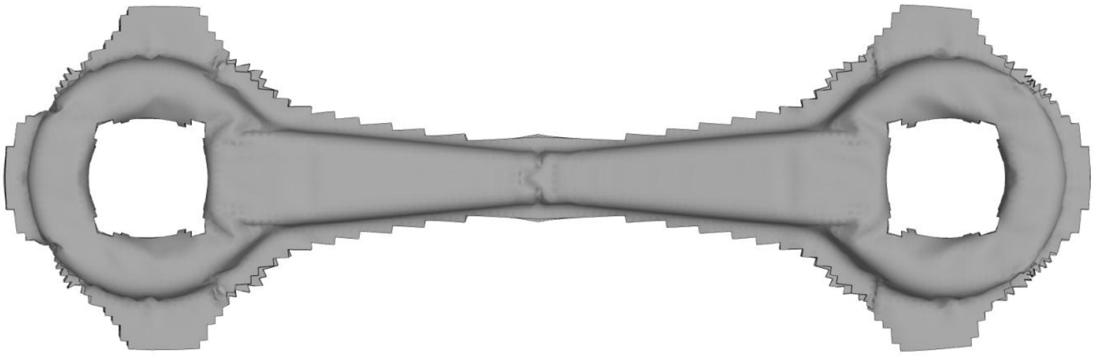


Figure 93 AniForm simulation results using a three-layered structured mesh at full mould closure – higher modulus

Figure 94 UPK at full mould closure

The total computational time of the lower shear modulus simulation is 11.5 hours. The computational time required for the simulation using a higher modulus was 15.0 hours. However multiple simulations were being solved at the time. Reducing the number of mesh layers is a promising method to reduce computational time as shown in the previous paragraphs.

Three-layered structured mesh (PAM-FORM)
When simulating a three layered laminate using a three layered mesh, we need to compensate for the bending stiffness as we did at the one layered mesh configuration. Doing so, the simulation shows the deformed shape as shown in Figure 95.

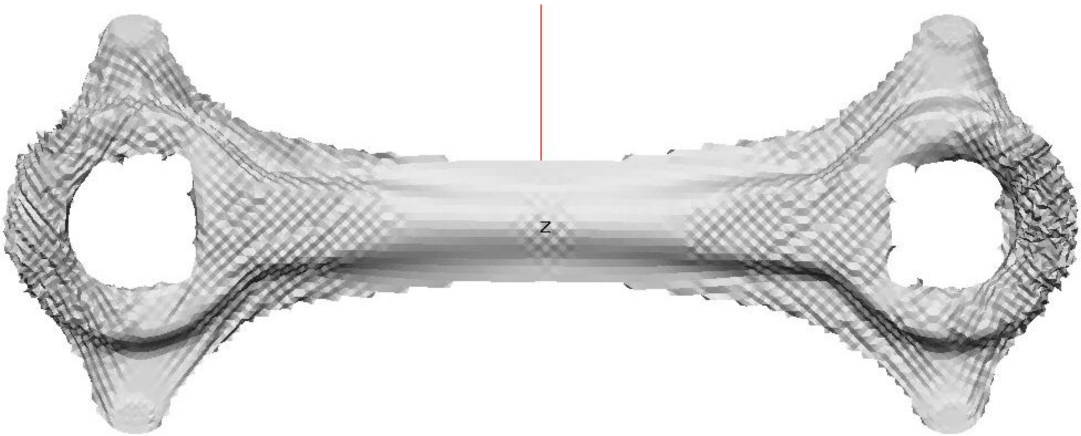


Figure 95 PAM-FORM simulation results using a three-layered structured mesh at 7.5 mm mould spacing

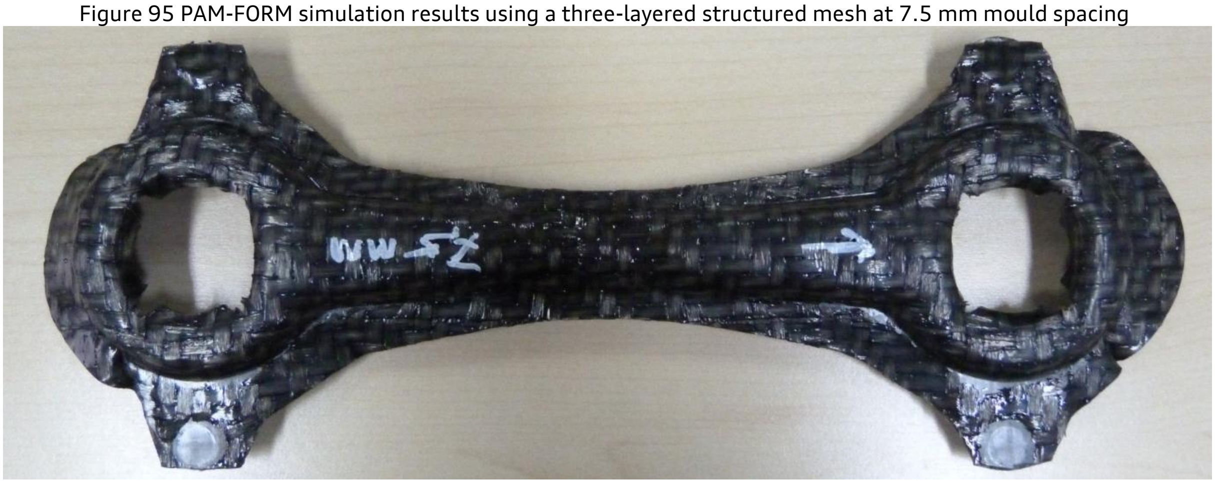


Figure 96 UPK at 7.5 mm mould spacing

This makes no sense when looking at the real results. The bending stiffness seems way to low over the entire part, especially when looking at the ends. The material buckles heavily, and causes the material be to pulled inwards. In the following steps during the simulation the solutions collapses. Therefore we will not continue using this material data set.

Additionally we will look at the material parameters as used by Audi. Applying these in the PAM-FORM simulation provides us with the following results:

Figure 97 PAM-FORM simulation results using a three-layered structured mesh at 7.5 mm mould spacing

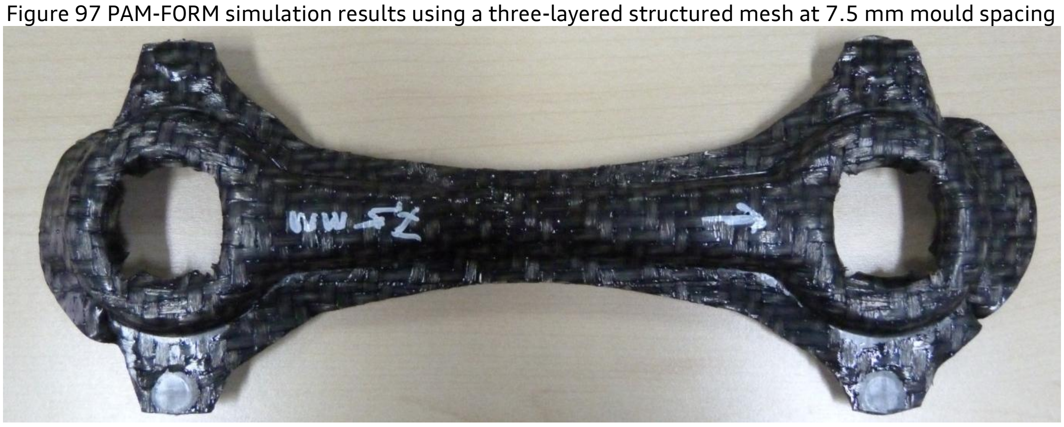


Figure 98 UPK at 7.5 mm mould spacing

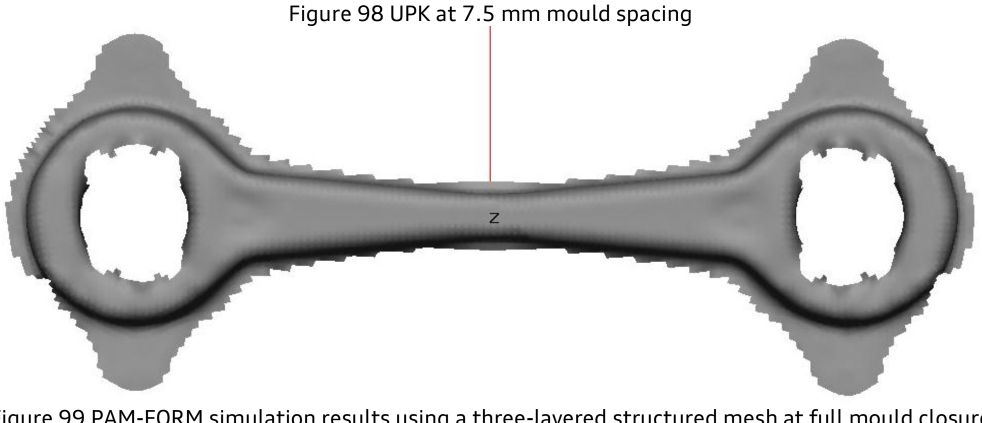


Figure 99 PAM-FORM simulation results using a three-layered structured mesh at full mould closure

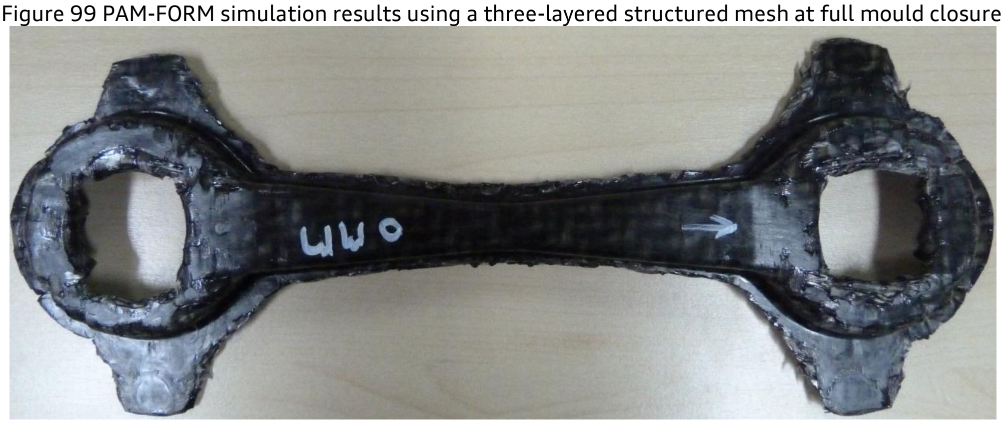


Figure 100 UPK at full mould closure

In comparison to the AniForm results, PAM-FORM shows large folds on the inside of the part. This can be caused by the high shear modulus (about 100 times higher), when compared to the AniForm simulation. The wrinkles on the left side are asymmetric whereas the simulation setup is symmetrical. It is unknown what caused this.

The outline of the laminate, at 7 mm mould spacing, diverges from reality. In reality, the middle part of the laminate it is broader than PAM-FORM shows. The outline at full mould closure is represented well.

The total computation time is 2.8 hours.

Three layered unstructured PAM-FORM

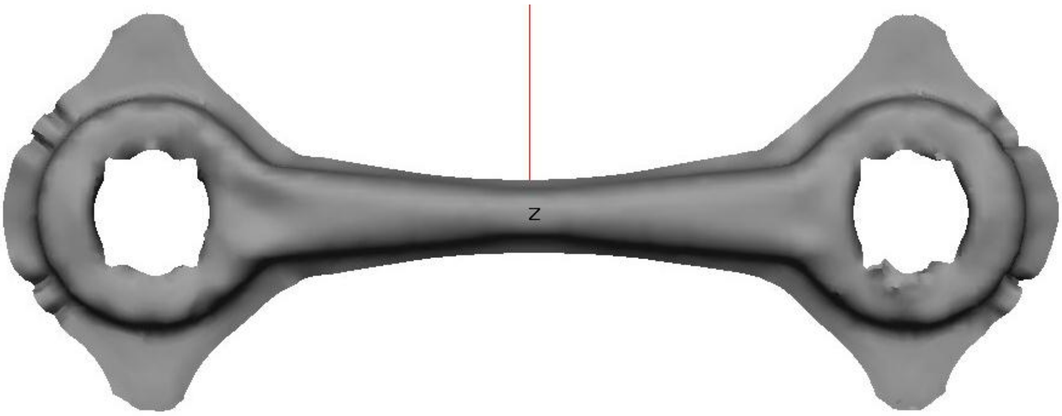


Figure 101 PAM-FORM simulation results using a three-layered unstructured mesh at 7.5 mm mould spacing

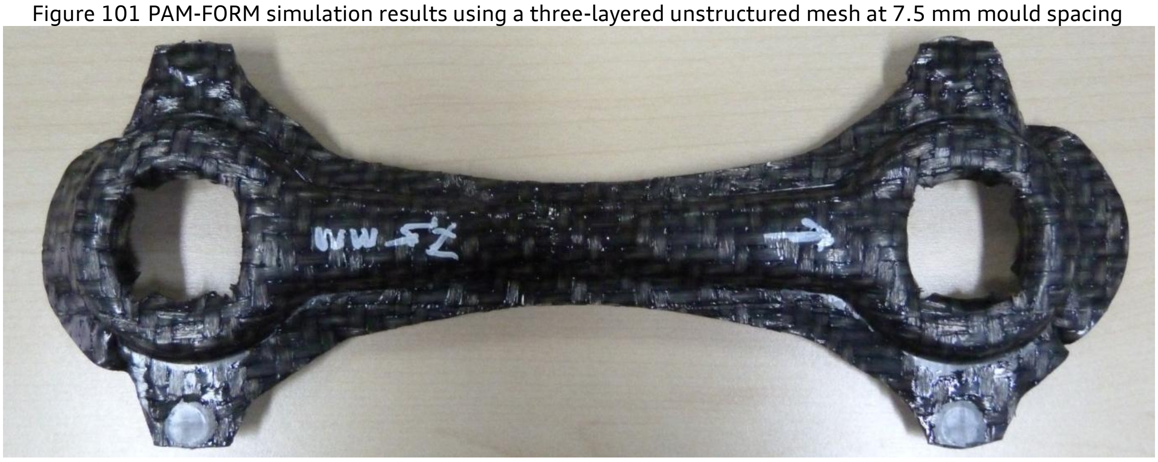


Figure 102 UPK at 7.5 mm mould spacing

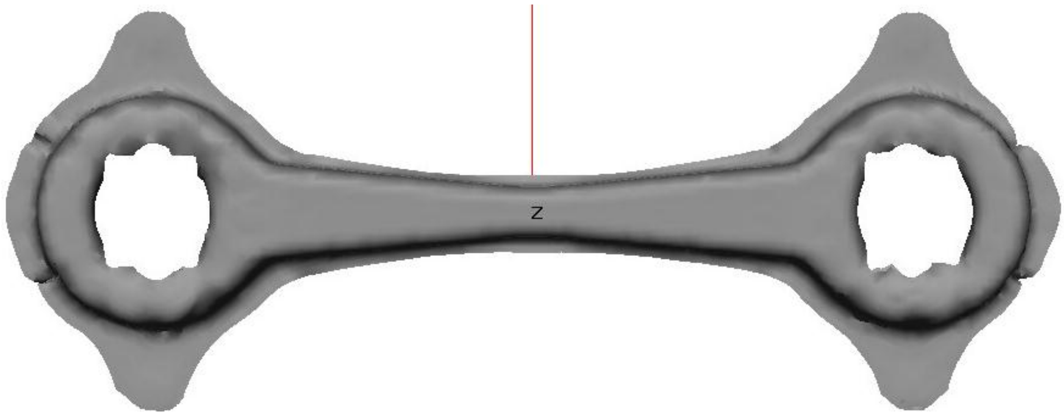


Figure 103 PAM-FORM simulation results using a three-layered unstructured mesh at full mould closure

Figure 104 UPK at full mould closure

When we compare the results shown in Figure 101 and Figure 103 with the results shown in Figure 97 and Figure 99, we obtain similar results. The influence of using a structured mesh is not of large influence when it concerns the outline of the laminate or the wrinkles. The unstructured mesh seems to represent the wrinkles more properly. This can be caused by the orientation of the elements at these areas.

The total computation time is 10 minutes.

3.2.6 Conclusion UPK

The PAM-FORM simulation, where three unstructured mesh layers combined with the Audi calibrated material card, is compared with the AniForm simulation using three structured mesh layers. Since this is way simulations that were performed in the past and possibly a new method respectively are compared. Most conclusions are based on the comparison between these two simulations using the Tepex dynalight material.

As described in the paragraph concerning one-layered structured mesh in AniForm, the results of the simulation are looking promising. However, the UPK part as produced is a combination between low and high shear moduli. The area at the outer sides (left and right) of the UPK, are represented well when using a high shear modulus. Whereas the area in the middle of the UPK is represented better when using a lower shear modulus. A temperature dependant material model will approximate reality more properly.

The outer contour of the UPK at 7.5 mm mould spacing is represented well by AniForm, where PAM-FORM shows better results at full mould closure. The wrinkles at 7.5 mm mould spacing are represented well in both software packages. The wrinkles at full mould closure are best represented in PAM-FORM.

In order to reduce the computational time of a simulation, it is advised to use a single mesh layer. The material properties should be adapted in such a way that they represent the full laminate.

3.3 Miscellaneous

During the internship, simulations on several other parts have been performed; many of them are not mentioned in this report since they were not in-depth or confidential. One worth mentioning is a part which is a internal research project for a car part based on carbon fibrous tapes. Goal of this simulation was to predict the contour of the laminate after pressing, and thereby check if the initial blank size was correct. Simulations have been performed in both PAM-FORM as AniForm.

4. FEM simulations of injection moulded parts

Injection moulding is a process that is commonly used in the automotive branch. In mass production almost every interior part of a car is produce by the injection moulding process. Therefore it is a crucial part in the supply chain of the automotive industry. In order to predict the outcome of the injection moulding process, we simulate the process using finite element menthod software packages.

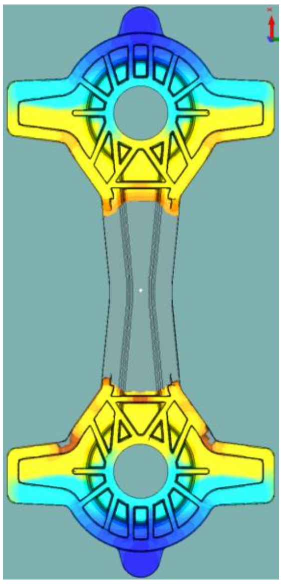
In this chapter the results of two filling studies will be presented. The “Universalprüfkörper” from the previous chapter is evaluated, however without glass fibre laminate as inlayer. Additionally a sandwichcore is evaluated. This sandwichcore is developed in a project at which multiple companies are involved. Further details cannot be given due to confidentiality.

We will evaluate several stages during the filling process. The injection mould process was interrupted during filling to obtain these specimens. Afterwards we simulate the part and compare the simulation results with reality. All simulation have been performed in Cadmould, and are part of a benchmark study within Audi.

4.1 Universalprüfkörper

The mould for the “Universalprüfkörper” has two injection points: one at the top and one at the bottom of the part. Both perpendicular to the parts neutral plane. The part was inject with nylon-6 resin. The parameters used in this process cannot be sketched due to the confidentiality of the data.

The “Universalprüfkörper” was evaluated at four different filling rates: 90%, 95%, 97.5% and 100%. The results of the filling study and the simulation results are presented in Figure 105.

Filling rate	**Cadmould simulation**	**Reality**
90%		

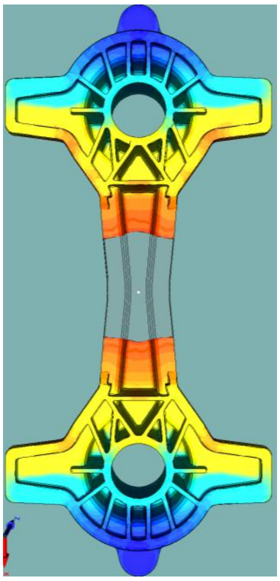
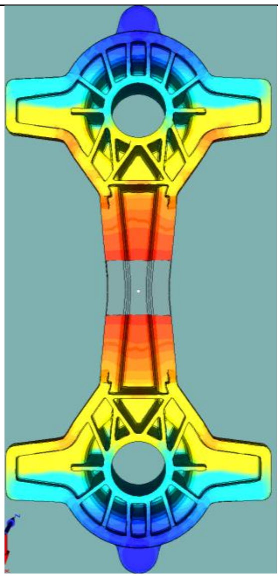
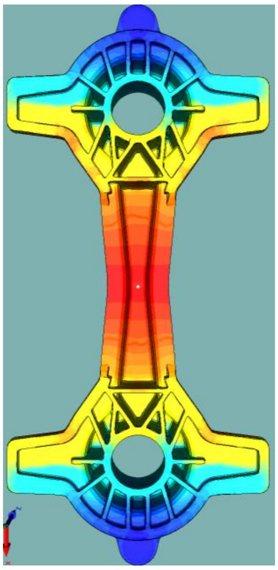
95%		
97.5%		
100%		

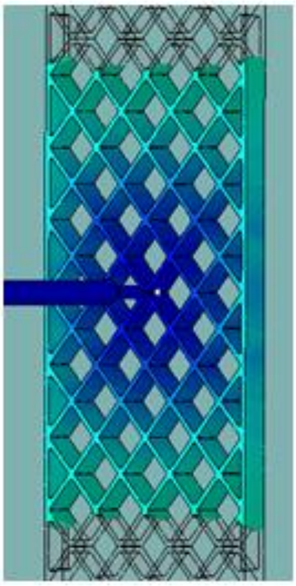
Figure 105 Fill study of the “Universalprüfkörper”

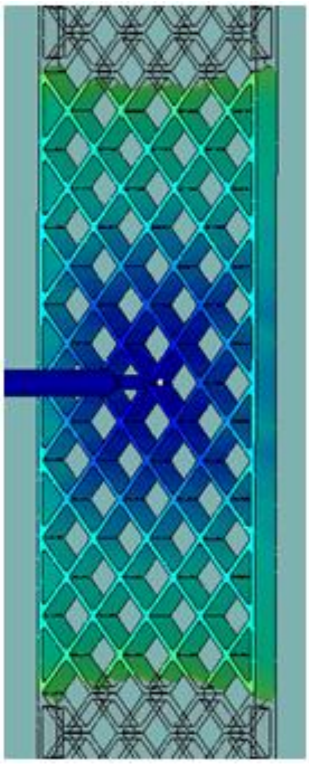
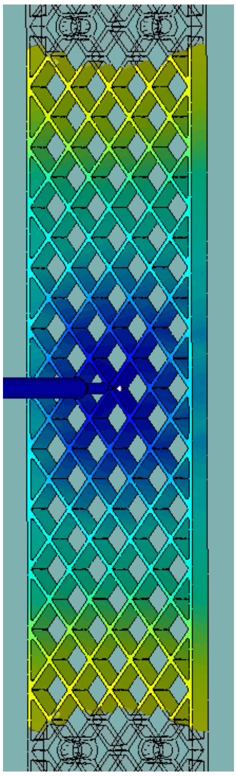
From the results presented in Figure 105, we can conclude that Cadmould is capable of capturing reality quite well. However, the time seems to have shifted. In reality the filling rate is higher in every stage. This can be caused by the inlet pressure which was probably higher in reality than it was in the simulation. Moreover we obtain that in reality the part is not equally filled from both gates. The bottom appears to have a higher filling rate than the top. It is unknown what caused this.

Additionally the sensitivity of the mould temperature was investigated. The mould temperature was slightly lower in reality than advised in the Cadmould material database. However the outcome of the simulation did not change noticeably.

4.2 Sandwichcore

The mould of the sandwichcore consists of two parts and one injection point in the middle of the geometry. The injected polymer is reinforced with short glass fibres.

Filling rate	**Cadmould simulation**	**Reality**
40%		 (37%)

50%		 (54%)
70%		 (66%)

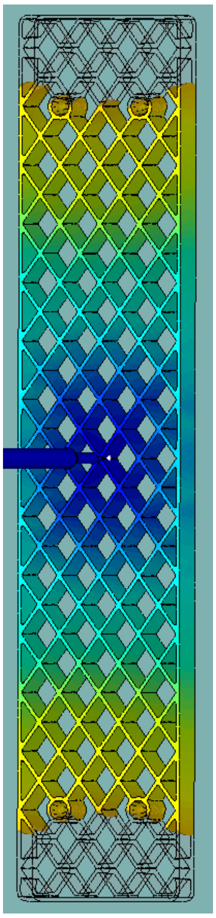
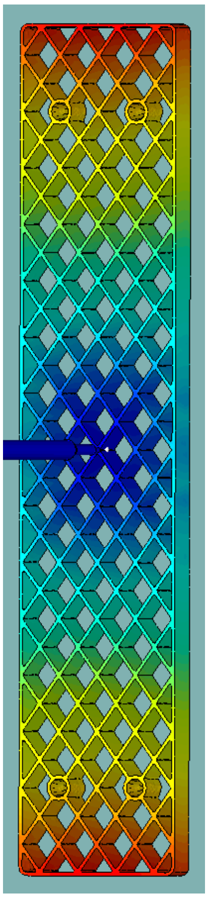
80%		 (83%)
100%		

Figure 106 Fill study of the sandwichcore

In Figure 106 the comparison between the Cadmould simulations and reality is presented. From the reality we notice that the flow front of the polymer has a higher velocity near the edges. This is not displayed so excessively in the simulations. The travelled distance of the flow front is in agreement with reality.

5. Constructional work

During the internship, several CAD geometries have been constructed. Some are applied in the laboratory; others are actual mould parts used to investigate a new production technique.

Two of these CAD geometries will be presented in this chapter.

5.1 Mounting for a ceramic element

Starting April, a research will be conducted on heat distribution across a laminate. This is especially of interest during the heating phase of the stamp forming process.

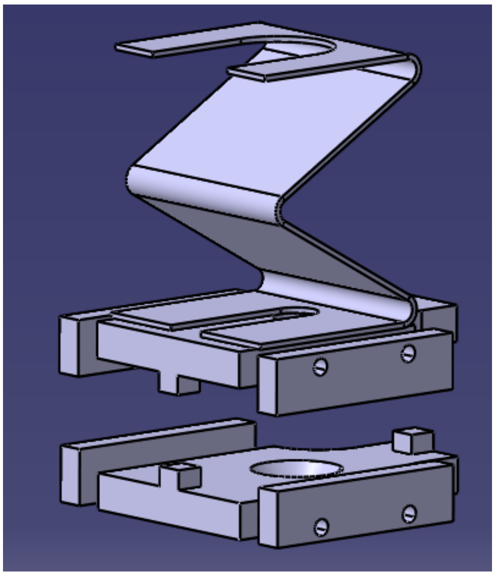


Figure 107 Design of a heating element mounting

The design of the mounting consists of only two unique parts, since the side walls are the same of the left and right side. The top and bottom mounting are the same as well. Only the thread which the mount is assembled to is different, therefore a adapted is required to make it work. A spring was introduced to fulfil this purpose. Secondly the spring is able to resolve misalignments as a result of assembling.

Figure 108 Heating element mounting as manufactured

The device will be used in research project at Audi.

5.2 Mould parts for an experimental production process

In the context of an internal project, a car part was developed to test a new production technique. To produce the required parts, two moulds need to be constructed. The starting point is the part geometry itself. Several things have to be kept in mind while constructing the mould: the laminate thickness, an extended product edge for cutting purposes, no sharp radii in the mould and enough space around the product to apply vacuum bagging.

Interesting about the mould is actually not the mould itself, but the process between the several project teams. Someone develops a part, the part is handed over to the simulation team who determine the layup. Parallel the mould for the part is constructed. When constructing the mould the part itself is a forbidden area for the mould designer. When the mould is finished it is evaluated by the composite forming department. Here it will be determined whether the mould will display the desired results. The forming simulation results are input for the mould designer, who has to adapt to mould if necessary.

During this project, the two moulds have been through the process as described above. The results are displayed in Figure 109 and Figure 110.

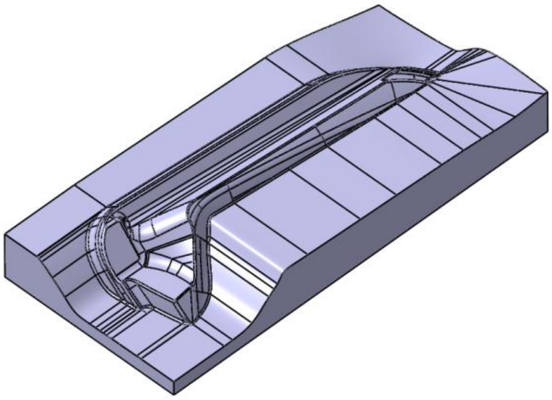


Figure 109 Mould 1 for experimental production process

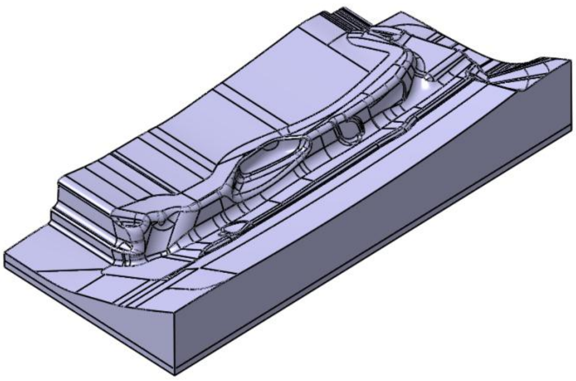


Figure 110 Mould 2 for experimental production process

6. References

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