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NLR-TP-2022-282 | November 2022

Composite process simulation comparative studies and integration in the design workflow

CUSTOMER: NLR

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EXECUTIVE SUMMARY

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Composite process simulation comparative studies and integration in the design workflow

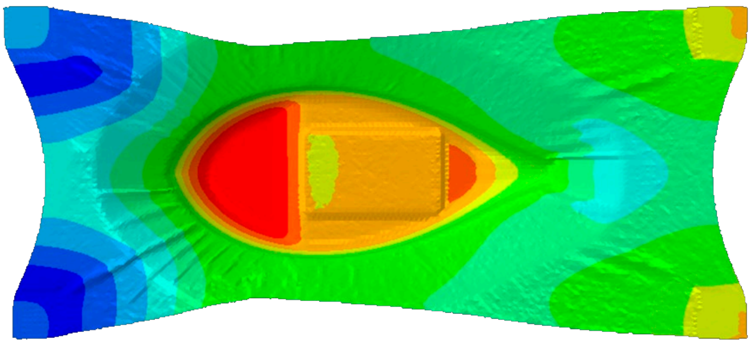

Figure 1: Process simulation result of the draping process of a composite thermoplastic laminate

Problem area

Composite material for lightweight structures has become the standard in aerospace. Still the manufacturing of accurate composite components does often provide challenges and trial and error is needed to optimize the process and to achieve first time right parts. Currently during the assembly steps, parts often do not align correctly and reshaping (inducing further residual stress) or shimming is needed. Also in case of repairs of composite structures the residual stress developed during the process can cause undesired distortions and reduce the service life. In recent years process simulation of composite manufacturing processes has gained more traction. This work supports the Dutch aerospace industry.

Description of work

In this report the work performed at Royal NLR in the field of process simulation for thermoplastic and thermoset composites is presented. For the approach of characterizing the manufacturing process for aerospace parts the following steps were taken.

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KNOWLEDGE AREA(S)
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Design workflow

On material and coupon level the important characterization is performed. This is then validated on the element and component level. Results of this validation is shown in the report.

Results and conclusions

The results shown in the report are part of a continuous development in the field of virtual manufacturing. It shows the capabilities of current tools to predict material behaviour and draping behaviour. This can only be achieved with gathering accurate material property and interaction data.

The ambition for future development is to use these tools more often to support the actual manufacturing and reduce trial and especially expensive errors. Ideally the whole manufacturing process from raw material to the final product is simulated and can be predicted including capturing and storing data.

Applicability

The work and methods presented in this report can be used for thermoplastic composite and processing in general.

GENERAL NOTE
This report is based on a presentation to be held at the ECCM, Lausanne, Switzerland, 2022.

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Summary

Composite material for lightweight structures has become the standard in aerospace. Still the manufacturing of accurate composite components does often provide challenges and trial and error is needed to optimize the process and to achieve first time right parts. Currently during the assembly steps, parts often do not align correctly and reshaping (inducing further residual stress) or shimming is needed. Also in case of repairs of composite structures the residual stress developed during the process can cause undesired distortions and reduce the service life. In recent years process simulation of composite manufacturing processes has gained more traction. In this paper the work performed at Royal NLR in the field of process simulation for thermoplastic and thermoset composites will be presented.

Contents

Abbreviations

ACRONYM	DESCRIPTION
ABAQUS	Finite Element Method software
AS4D-PEKK	Carbon fibre reinforced plastic
CFRTP	Carbon Fibre Reinforced Thermo Plastic
CUPID	Drone system
ESI PAM FORM	Finite Element Method for forming
MDSC	Modulated Differential Scanning Calorimetry
NLR	Royal NLR - Netherlands Aerospace Centre
S3R	Shell element 3 node
UD	Uni Directional

Abstract: *Composite material for lightweight structures has become the standard in aerospace. Still the manufacturing of accurate composite components does often provide challenges and trial and error is needed to optimize the process and to achieve first time right parts. Currently during the assembly steps, parts often do not align correctly and reshaping (inducing further residual stress) or shimming is needed. Also in case of repairs of composite structures the residual stress developed during the process can cause undesired distortions and reduce the service life. In recent years process simulation of composite manufacturing processes has gained more traction. In this paper the work performed at Royal NLR in the field of process simulation for thermoplastic and thermoset composites will be presented.*

Keywords: composites, process simulation, thermoplastic

1 Introduction

Current advanced computational tools enable apart from structural analyses also evaluation and analysis of the manufacturing process of high performance CFRP aerospace components. By combining manufacturing process parameters with thermo-mechanical-chemical material behaviour in the simulation, the manufacturing and the design processes are combined in the so-called “virtual manufacturing”, which can support the production of “first time right” parts [1]. In previous work by Royal NLR this has been addressed for composite braiding [2], fibre placement manufacturing of thermoplastic composite, see Figure 1 [3, 4] and thermoset curing [5].
In this paper, an overview of the broad experience developed in the field of virtual manufacturing is presented. Such experience ranges from using virtual manufacturing to support design and manufacturing of composite components, to the development of new virtual manufacturing models, both analytical and via finite element models. This knowledge has been developed via joint cooperation in several European projects.

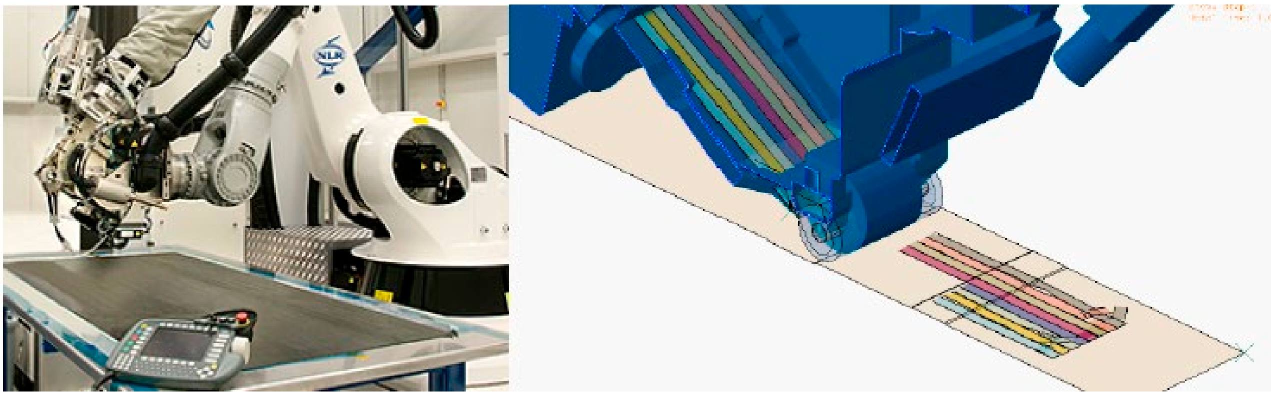


Figure 2: Fibre placement facility at NLR and virtual manufacturing tow head simulation. In the simulation the placement, wrinkling and cutting of tows is simulated

More projects are currently ongoing to build on the existing knowledge and to expand into making more manufacturing processes “virtual”. Several challenges and opportunities are still open in this field of research. One of the most intriguing concerns the determination of the material properties of the virtually manufactured components and of the process parameters required to achieve pre-determined material properties. A fundamental step to fully implement virtual manufacturing solutions in support of development and certification activities is to develop a framework for the validation of virtual manufacturing models and results, as currently no clear virtual manufacturing test standard is available.

An active research field for virtual manufacturing is in composite draping [6] which is also the focus of this paper. There has been extensive research and also commercial software offerings are available among which Aniform, SimuDrape, ESI PAM FORM. In research by Dorr [7] the different approaches are compared for a thermoplastic composite example case. This interesting overview shows the possibilities and challenges of these types of advanced analyses. One of the main challenges is accurate characterization of the material for processing conditions, i.e. at elevated temperature. While the mentioned examples are physics based analyses, in work by Maymard [8] one kinematic approach for draping of prepreg is presented. This method is faster and can thus be used in design approaches.

For the approach of characterising the manufacturing process for aerospace parts the following steps were taken, see Figure 3. On material and coupon level the characterisation is performed. This is then validated on the element and component level.

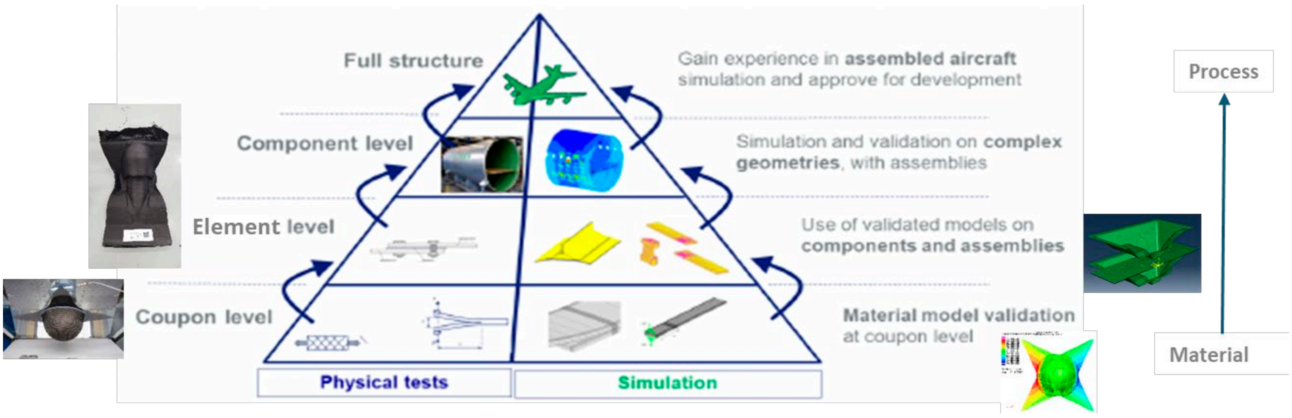


Figure 3 : Overview of the building block approach to characterise the manufacturing process. On material and coupon level the characterisation is performed. This is then validated on the element and component level

In the next section the setup for the analyses of draping of thermoplastic prepreg is shown.

2 Simulation of half sphere draping

The draping behaviour has initially been investigated using the standard draping model available in Abaqus and on a double curved half sphere case. Draping test result of a double curved half sphere is shown in Figure 4.

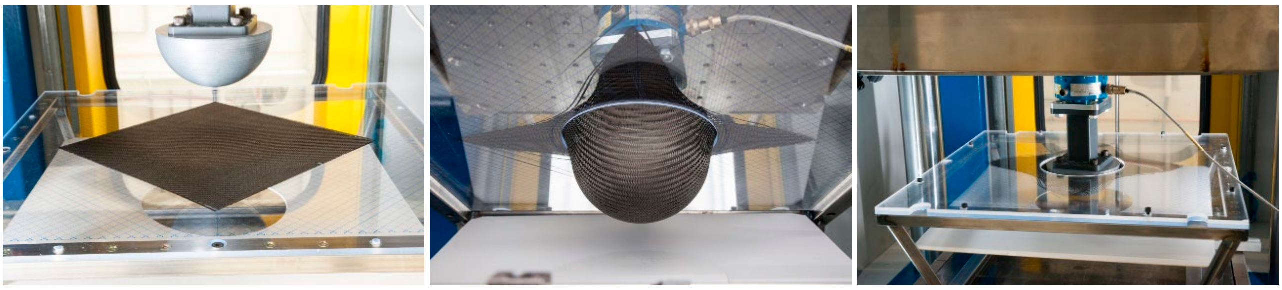


Figure 4: Draping of dry carbon fibre fabric into the double curved sphere shape. This is a common test shape to investigate the shear of the individual yarns of the fabric. At NLR the test was performed with the fabric between two transparent plastic sheets with a central hole and a 3D printed sphere mould was lowered through the transparent plates

For this the stiffness of the resin and the fibres have been adjusted for elevated temperature. Also the shear stiffness of the resin has been set low to simulation elevated temperature behaviour. The following inputs were chosen

- Rho_{ply} : 1.6E-6 kg/mm^3
- Warp direction: alfa_1 = 0 degrees, E1=10 GPa
- Weft direction: alfa_2 = 90 degrees, E2=10 GPa
- Shear coupling: G=1E-5 GPa
- Thickness 0.3 mm
- Friction sphere-blank: Coefficient 0.2
- Friction blankholder-blank: Coefficient 0.2
- Blank size: 300 x 300 mm
- Pressure on blank holder: 4E-5 GPa
- Imposed velocity sphere: 0.5 m/s
- Quarter model
- Element size: 1 mm

The results that are obtained are shown below. It appears that with large deformation it becomes more difficult to decouple the membrane stiffness of the material and the bending stiffness. During draping the laminate has a low bending stiffness but a high membrane stiffness in warp and weft directions.

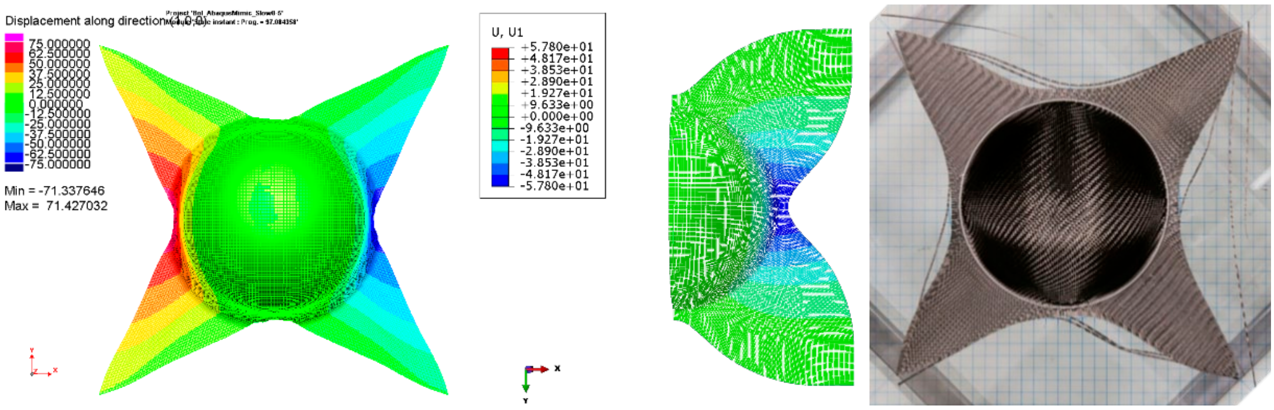


Figure 5 : Comparison of the predicted draping distortions with dry fabric and the tested half sphere. On the left the PAM FORM results and in the middle the standard Abaqus material results. Clear differences can be observed between the methods with more shear present in the actual test and PAM FORM model

From this it was concluded that the standard Abaqus elastic material model is not suitable to predict draping behaviour of dry fabric and probably prepregs. Therefore the focus was on the specific methods for predicting draping.

3 Simulation of CFRTP draping

In this section two demonstrators will be shown with complex shapes to determine the added value of virtual manufacturing simulations. Especially the focus lies on the added value of virtual manufacturing in the design process. For these demonstrators the material AS4D-PEKK was used. The characterisation of the material was done together with SimuTence and Fraunhofer institute, see Figure 6, including rheometer bending, friction and shear tests. Also Modulated Differential Scanning Calorimetry (MDSC) measurements have been done in-house. Before implementing the virtual manufacturing methods in the design process, first the method has to be validated.

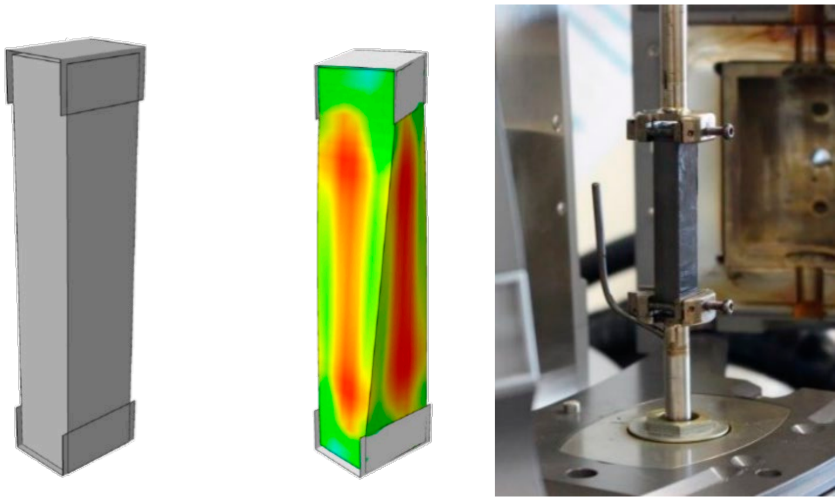


Figure 6: Torsion bar test configuration to determine shear rate effects with on the left the CAD model where the central part is the thermoplastic carbon reinforced material. In the middle the finite element verification of the test . On the right the test setup to apply shear rate effects

Complex draping simulations are performed in ABAQUS using the Simudrape plugin [9]. One beneficial application of virtual manufacturing in draping is for the development of the process and mould/stamp geometries. Criteria for the process development mainly include the circumvention of manufacturing defects such as wrinkles. However, the advanced draping simulations can also be used to determine the fibre orientation in the final part. These orientations can be used to determine the performance (using structural analyses) of the draped component after manufacturing. In this way, virtual manufacturing can be employed to ensure that the component is manufactured first time right and will behave as intended.

To develop the process by virtual manufacturing, fast iterations are preferable, as this could require many iterations. Therefore, isothermal simulations are performed, not taking into account any thermal effects occurring during the draping process. In the mechanical simulations, the material properties are taken at a constant temperature. In molten condition, the stiffness of the matrix material is assumed to be zero. However, because the material can rapidly cool down during the draping process, it is necessary to determine an effective matrix stiffness, see Figure 7.

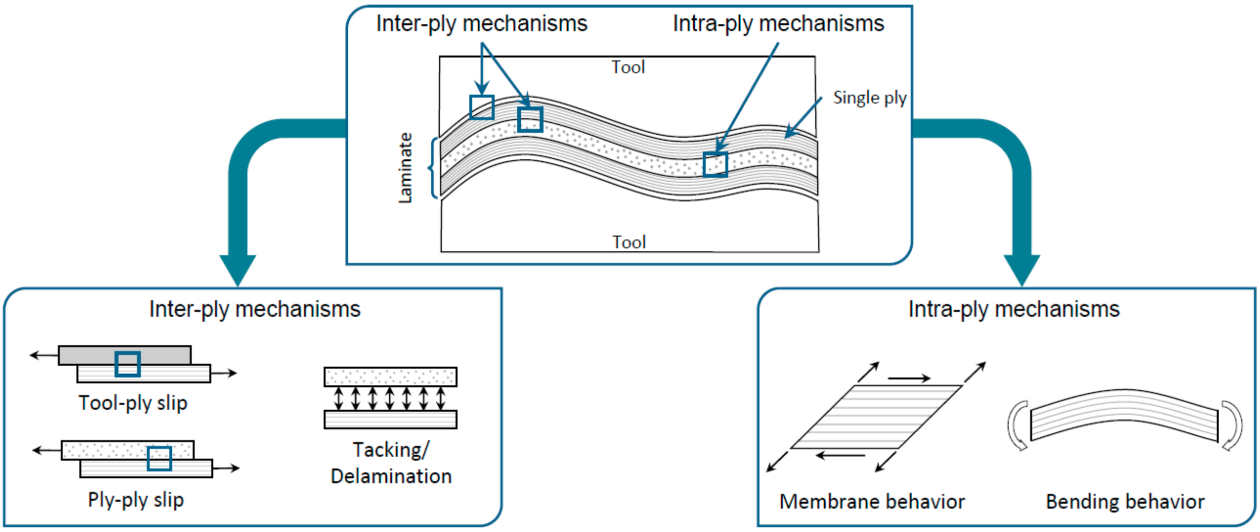
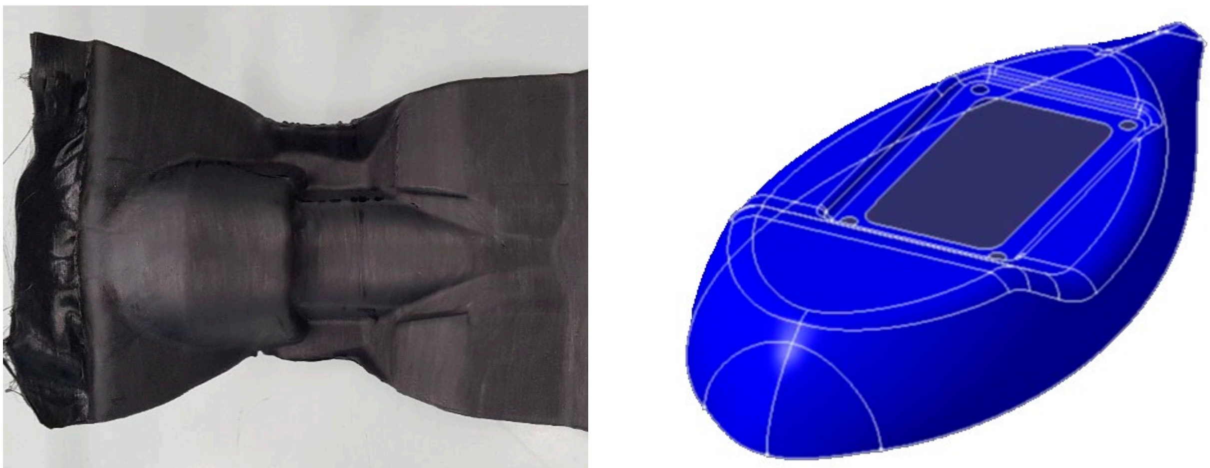


Figure 7: Overview of the interactions and mechanisms at play during the draping of thermoplastic material. It is very important to characterize these interactions and properties to achieve accurate predictions [9]

In this paper, the simulation approach is verified and calibrated using a generic CFRTP component. In the calibration, the effective value for the matrix stiffness during the draping process is determined. The calibrated draping simulations are subsequently used for the analysis and improvement of the draping process for a CFRTP component. Within this process development, different designs of mould geometry and the use of grippers are analysed by virtual manufacturing.

Figure 8 displays the generic CFRTP component used to validate and calibrate the mechanical simulations. This component is manufactured from $[90/45/0/-45/90]_s$ UD AS4D-PEKK blank of 200 x 400 mm, at a stamp velocity of 200 mm/s. The same blank and draping settings will be used to manufacture the CUPID component displayed on the right in Figure 8. In the draping simulations, de stamp and mould are assumed rigid, and the blanks are modelled individually with 3 mm triangular (S3R) elements.

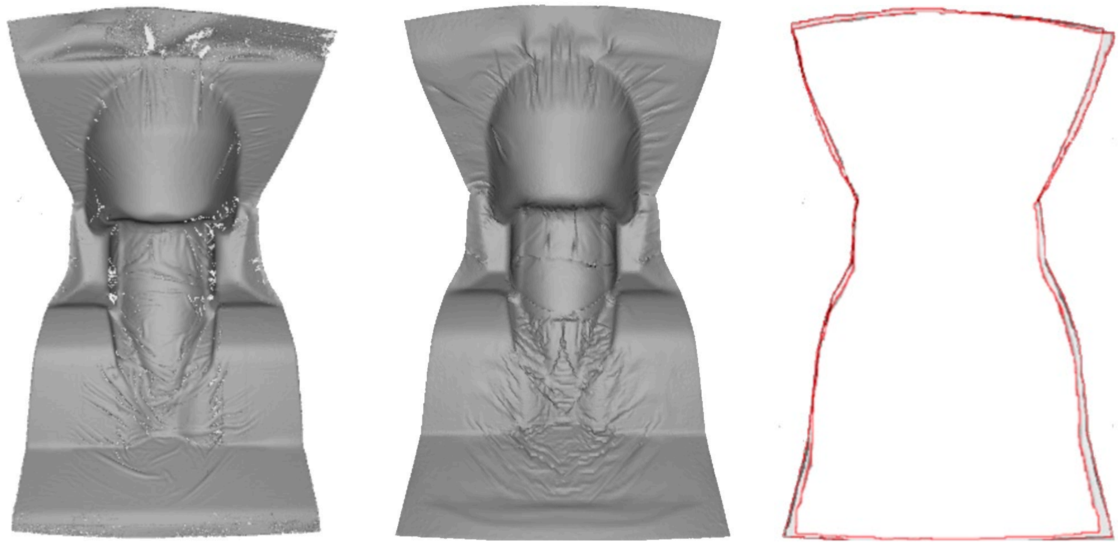


(a) **(b)**

Figure 8: Photo of the generic complex CFRTP components used to validate and calibrate the draping simulations

4 Comparison of CFRTP draping results

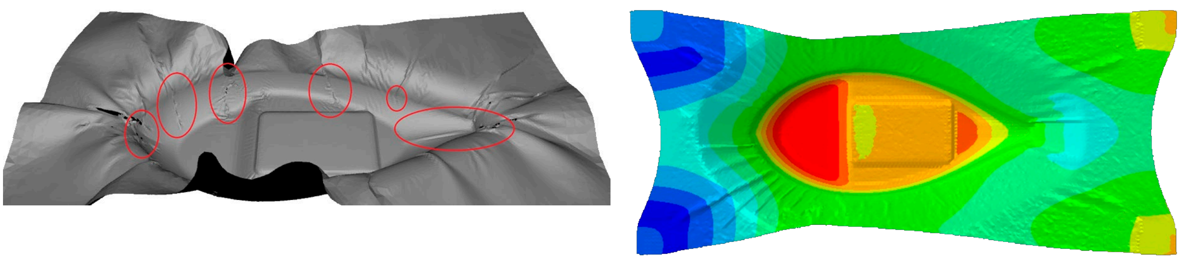
Figure 9 displays the results of the calibrated isothermal simulations in Abaqus with Simudrape plugin of the generic draping component. It is observed that with a low matrix stiffness of 50 MPa the contour and wrinkles in the final component can be accurately predicted. The predicted wrinkles displayed in Figure 9b clearly indicate critical areas also observed experimentally. The comparison of the contour in Figure 9c displays the numerically predicted and experimentally observed contours, illustrating very good correlation between the simulations and experiments.



(a) **(b)** **(c)**

Figure 9: Results of the isothermal simulations of the generic draping component, (a) is the experimental results as scanned, (b) the analyses result and (c) the comparison of the contour between the experiment and simulation

Figure 10a displays the result of a draping analysis of the CUPID component with the initial stamp and mould geometry. Many manufacturing defects are observed in the form of wrinkles. After multiple virtual iterations on gripper location and mould geometry, a component was obtained without any manufacturing defects as displayed in Figure 10b. A combination of grippers located on the corners and a mould geometry with a gradual transition into the final shape was found to result in a correctly manufactured component.



(a) **(b)**

Figure 10: Result of a draping analysis in Abaqus with Simudrape plugin of the CUPID component

It should be noted that the contour and wrinkle predictions are strongly dependent on the employed matrix stiffness. Further experimentation will be required to observe if the single value for the matrix stiffness is still valid when following different draping procedures, or when other components are manufactured. However, if this method remains predictive for these different situations, it is a strong tool for process development without costly and time consuming experimental work.

5 Results and future developments

The results shown in the previous section are part of a continuous development in the field of virtual manufacturing. It shows the capabilities of current tools to predict material behaviour and draping behaviour. This can only be achieved with gathering accurate material properties and calibration of the model.

The ambition for future development is to use these tools more often to support the actual manufacturing and reduce trial and especially expensive errors. Ideally the whole manufacturing process from raw material to the final product is simulated and can be predicted including capturing and storing data. The data can also be integrated in digital twin models to simulate the as-built product. Currently it is not feasible to include all manufacturing steps in simulations and for some areas also the added value is minimal. The focus of current and future developments lies on the manufacturing steps that are most critical and sensitive to process parameters. Examples are the draping analyses (thermo-mechanical), thermoplastic welding (thermo-mechanical-electromagnetic), thermoplastic material model including crystallisation kinetics, curing analyses (thermo-chemical-mechanical), composite braiding analyses (mechanical) and fibre placement simulation (thermo-mechanical).

6 Conclusion and discussion

In this paper the results have been presented of virtual manufacturing projects at Royal NLR. The aim is to gain insight in the manufacturing process of high performance CFRP aerospace components. With this insight the manufacturing process can be optimized to achieve first time right parts.

The draping simulations and comparison between software and experiments showed that material inputs are a current challenge. There are no standards yet to obtain these material inputs such as material stiffness as function of time and temperature for thermoplastics. Also to obtain the level of expertise required for use of the tools can take considerable time and some have quite a steep learning curve. Despite these challenges the current tools are very well capable to predict the global behaviour of CFRTP draping and fibre orientations. However the local effects such as wrinkling are more sensitive to the inputs and boundary conditions.

Other work on thermoplastic material model developments and welding is currently ongoing. The ambition is to combine the models to have a workflow to predict the material and part behaviour during the most critical steps of the manufacturing of aerospace components.

Acknowledgements

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