1 Introduction
With the increasing use of structural composites in the aerospace industry follows a need for higher production efficiency. Within this industry sector prepreg technology dominates, being the only material that today provides the excellent quality requested. Equipment for automated tape layup (ATL) enables efficient stacking of prepreg into different stacking sequences. However, the technique is limited to layup of flat to nearly flat structures, such as e.g. outer wing shell structures. More complex geometries can be efficiently produced using automated fibre placement equipment, however at lower production speed. An alternative solution is to use flatly pre-stacked prepreg to be formed into the desired geometry during a separate forming step or as a part of the autoclave process.

Forming of stacked prepreg requires that a set of forming mechanisms become active and work in a desired way in order to avoid wrinkle formation. It is generally considered that the most important forming modes for these already impregnated and structurally well integrated materials are interply and intraply shear in combination with out of plane bending [1].

Several studies have investigated the intraply shear properties of prepreg material, both in the form of woven fabrics and cross-plied unidirectional (UD) prepreg. Significant differences in intraply shear are reported in-between seemingly similar prepreg systems [2, 3]. Considering the interply shear, i.e. the prepreg-prepreg friction, published results mainly includes friction properties between weaves or UD systems where the fibres are parallel to each other and the pulling direction, see e.g. [4]. However, at the same time several works on both forming, wrinkle initiation and spring back phenomena underlines the importance of the stacking sequence [5,6,7,8]. The investigators note that the interply friction depends on the fibre directions of the two plies meeting at the sliding interface. It is further noted that when investigating wrinkle development during manufacturing of UD prepreg components, it is important to consider friction in-between prepreg and tool (prepreg-tool friction). By increasing the prepreg-tool friction coefficient, higher degree of interlaminar slippage is obtained inside the composite [8] which may reduce wrinkle development. It is however interesting to note that measurements on prepreg-prepreg friction and prepreg-tool friction are showing values of the same magnitude, indicating the importance of understanding this behaviour in order to obtain slippage at the desired positions.

Prepreg-prepreg friction tests are normally performed at relatively high contact pressures, simulating the forming behaviour during fully developed forming pressure. However, due to the continuous fibres forming is not a local phenomenon. If the multi-stack is formed over a radius, the continuous fibres require that interply slippage continues outside the radius in order to avoid wrinkling. At these areas the forming pressure may be significantly smaller or even zero.

The present work focuses on the forming possibilities offered by hot drape (HD) forming [9]. The technique uses a single rubber diaphragm that, at elevated temperatures, forces the underlying pre-stacked prepreg towards the tool. In previous work, HD forming of stacked UD prepreg onto a jogged spar has been studied both experimentally [10] and through simulations [11] showing the importance of stacking sequence for the forming outcome. It was experimentally shown that different stacking sequences, with the same number of layers in each fibre direction, forms with and without wrinkles, respectively. Forming simulations were performed
using continuum modelling implemented in commercial finite element (FE) code. The interply friction material model was calibrated based on friction tests with the fibres in parallel to the pulling direction. The simulations indicate that a majority of forming is performed during the first 50% of pressure build up [11].

The presented work aims to further investigate HD forming though increased understanding of the interply friction behaviour. Experimental friction measurements are performed where the UD prepreg layers have different relative fibre directions at the sliding interface. Experiments are also performed at low contact pressures to investigate the influence of interply friction during early forming. Some of the experimental results are implemented into friction models and used in simulations. The simulations aim to investigate the importance of having more detailed interply friction descriptions in order to accurately model HD forming of multi-stacked prepreg material.

2 Experiments

2.1 Materials

The experimental study considers interply (prepreg-prepreg) friction of UD carbon/epoxy prepreg M21-T700 from Hexcel. The material has a volume fraction of fibres equal to 57%.

2.2. Experimental setup

Friction tests was performed in an Instron 4505 testing device with a with a 5 kN load cell. The in-house developed friction rig [12], see Fig. 1, was mounted inside a heating chamber. Prepreg was applied to the surface of the quadratic side plates and to both sides of the middle plate. The middle plate enabled fixation of a variety of fibre angles, while the outer quadratic plates only enable fixing prepreg with fibres in the pulling direction. Contact pressure were applied using a pneumatic cylinder from Festo, FESTO AEN-63-20-I-P-A-TL.

2.3 Investigated parameters

The friction measurement tests are summarised in Table 1. As can be seen, tests were performed at different relative fibre angles. The numbers given represents the fibre directions of the two UD layers meeting at the slipping interface. The reason for choosing temperatures in-between 60°C and 85°C was that these temperatures have shown to provide good forming, thereby commonly used in the industry. Further, the epoxy resin viscosity changes rapidly in this temperature range. According to the material supplier, the matrix viscosity is 1500 Pa•s at 60°C, 300 Pa•s at 70°C and 90 Pa•s at 85°C.

Three different contact pressures were tested: 4 kPa, 10 kPa and 80 kPa, where the latter was chosen to enable comparison with earlier results [12]. The low pressure values were selected to obtain as low contact pressure as possible still achieving reliable and reproducible results. The pulling speed was investigated in earlier tests [12], showing little influence of speed on the friction coefficient for M21-T700 at high contact pressures. To limit the number of trials, pulling speed is therefore held constant at 0.1 mm/min throughout the study.

2.4 Interply friction measurements

The prepreg material was tested after approximately 24h in room temperature. Before each test, the plates in contact with the prepreg were cleaned using Acetone. New material was thereafter attached to the plates keeping the protective film on the outer surface. The prepreg was fixed to the plates by applying vacuum (~0.9 bar) for 5 minutes,. Following this, both outer plates and middle plate were fixed into the friction rig inside the heating chamber. At the same time, the protective films were removed. The test rig was heated for approximately 25 minutes, ensuring an even test temperature. The outer plates were kept at a distance from the middle plate during heating up in order to avoid influencing the test results.

As the set temperature was reached, the pneumatic cylinder was activated applying the set contact pressure. After approximately 30s at the set pressure, the upper part of the rig was pulled upwards with the set speed while recording the resulting reaction force.

The area of the two outer plates was 85*92 mm². A minimum of three tests per test point were performed and evaluated.

2.5 Evaluation of friction test data
A characteristic friction coefficient-displacement curve from one test is shown in Fig. 2. The friction coefficient was a recalculated from measured friction load, using

\[
\text{Friction coefficient} = \frac{\text{Load}}{2ap}
\]  

where \( p \) is the normal pressure applied to the surface area of the two side plates, \( 2a \).

The critical friction coefficient for sliding initiation was determined from the crossing of the black tangent lines with the bisection to the measuring curve (blue). The load where the bisection cross the experimental curve is the critical friction coefficient at sliding initiation. This value is used when comparing the results from the different sliding test.

2.6 Discussion on experimental results

The experimental results show significant difference in interply friction depending on the fibre angles at the sliding interface. As shown in Fig 3, at 80 kN normal pressure, the friction coefficient at the 0/90 interface is generally 25% lower than at the 0/45 interface. The 0/30 interface is very similar to the 0/45. Please note that the 0/0 friction coefficients shown in Fig 3 are used as reference and taken from previous tests on the same material system, presented in [12]. In that study the friction coefficient was determined from the friction load at 0.5 mm deformation. The 0/0 friction results are therefore 15-20 % higher than if evaluated in the same way as the herein presented study. This indicates that the interply friction for the 0/0 interfaces are similar to or lower than at the 0/90 interfaces at all temperatures considered.

Fig 3. shows that on general, the friction coefficients at high contact pressure are only slightly influenced by the test temperature although a significant difference in matrix viscosity. It is also interesting to note that the friction coefficient drops a little at 70°C. This is probably due to a combination of low viscosity at remained integrity of the prepreg surface. At higher temperatures, previous work has shown that the surface roughness increases [12] together with the friction coefficient. A minimum friction coefficient was found at viscosities around 250 mPas. Other studies have observed similar tendencies [6,7], where the fibre entanglement and lack of load bearing capacity of the matrix was then suggested as possible reasons.

Fig 4 shows the influence of contact pressure on the measured friction coefficient for interfaces at different relative fibre angle. The results clearly show that the friction coefficients are 2.5-5 times higher at the lowest contact pressure than at the highest contact pressure considered. For the 0/0 interface, the friction coefficient drops at 10 kPa, reaching the same value as at 80 kPa. This is in agreement with earlier measurements performed in pressure range of 53-120kPa [12], where the friction coefficient was constant. The results presented herein show that for all other relative fibre angles, the friction coefficient reduces continuously with increased contact pressure. The larger scatter in the test results at low pressures are due to lower frictional loads. Note again that the value from the 0/0 interface at 80kPa contact pressure is taken from the previous study.

Fig 5 shows the same data as in Fig 4 but recalculated showing the frictional load per tested surface area at the breakpoint defined by the friction coefficient, see Fig. 2. The results show that the frictional load per surface area for all considered interfaces seem to converge towards the same level, approximately 2kN/m², as the contact pressure approaches zero. This value can be compared to results of an experimental study on tack considering the same material system [13]. The tack, defined as the out-of-plane peel strength in-between two prepreg lamina with the same orientation, is reported to 6.7 kN/m² at 66°C. However, it is important to note that this value is reported to be both pressure dependent and time dependent, meaning that a longer contact time normally results in a higher tack. To obtain full tack at 30°C, 30s of contact at 40 kPa was required. It is expected that the recommended values on pressure and time reduces significantly at higher temperatures due to reduced viscosity. The contact time used herein is approximately 30s, wherefore full contact should have been established.

The test result presented indicate that in order to model forming of multi-layer, pre-stacked UD prepreg the friction model(s) needs to take both relative fibre angle, contact pressure, prepreg viscosity (tack) and deformation speed into account. Such models require numerous test data to be
accurately calibrated. In the following, the influence of refined friction modelling will be investigated. Since the contact pressure has been shown to have the largest influence on the friction coefficient, the refined model is focusing on describing the friction coefficients at a larger range of contact pressures.

3 Numerical simulations

3.1 Modelled geometry and forming process

HD forming of a spar geometry with recess area is considered in modelling, see Fig 6. The spar has the following geometry: length 480mm, web width 70mm in straight areas, flange length 55 mm, recess length 2*125 mm + 50mm, recess depth 6.25 mm and inner radii 2 mm.

The HD forming setup considered in modelling includes support walls, spar tool, rubber diaphragm and bottom plate, as shown in Fig 6. Isothermal forming at 70°C is modelled. The pre-stacked prepreg material is assumed flatly placed in-between mould and vacuum tight rubber diaphragm at the start. The support walls are placed 195 mm from the spar centre and they are 20 mm higher than the spar in order to ensure that the rubber is always in tension during forming, see e.g. [10] for further details on the process.

3.2 Materials

The M21-T700 prepreg material, the same as used in the friction experiments, are considered in modelling. The charge to be formed consists of flatly stacked UD prepreg, stacking sequence [-45 0 45 0 90]. Ply thickness is set to 0.32 m

The diaphragm considered is a 1mm thick silicon rubber certified for aerospace application, Mosites 1453-D.

3.3 Model set up

For HD modelling, the AniForm [14] software is used. AniForm includes a nonlinear FE solver developed for large deformations. Further, it enables tracking fibre orientations during forming of soft composite materials. AniForm includes continuum elements where in-plane and out-of-plane properties are modelled in a decoupled way to enable separate material models in the same element. Below follows brief descriptions of the material models used. All numbers used in modelling are presented in Table 2-4.

3.3.1 Modelling of the elastic rubber

During HD forming the rubber deforms and compresses towards the tool as the air is removed and vacuum is established under the rubber. The rubber transfers tensile force to the soft lamina due to its elongation and pressure in the normal direction, thereby deforming and compacting the prepreg stack.

In AniForm, the rubber is modelled by the hyperelastic Mooney-Rivlin material model. The coefficients are calibrated from tensile tests using least square fitting in MATLAB [15], see [11] for further details.

Due to symmetry reasons and long calculation times, only part of the rubber is considered in modelling, see Fig 6. The cut along the centre of the beam excludes simulating forming of the straight side of the beam. Further, the rubber length is cut to cover almost the entire tool length, but not all the way to the stiff frame holding the rubber in position. The rubber translations are considered locked in all degrees of freedom at the support wall edges.

3.3.2 In plane properties

The constitutive models used to describe the fibre properties are linearly elastic and based on Hooke’s law. The fibre direction is defined by a local coordinate system and is for each step mapped onto the deformed state. The fibre stiffness is down scaled for numerical reasons; to use the true fibre stiffness would cause problems due to the large difference between fibre stiffness and the cross fibre stiffness.

The matrix is modelled by a combination of a viscous and an iso-elastic material model, a so called Voigt-Kelvin model. The viscosity and the Young’s modulus, E, are calibrated from bias extension (in-plane shear) test; for details about the tests see [3] and for calibration of shear properties see [16].

Two different friction models were used in this work, see Fig 7. The interply prepreg-prepreg properties were first calibrated towards the 0/0 friction measurements presented in [12] using a
penalty friction model hereinafter referred to as Viscous/Coulomb. This model combines viscous friction and Coulomb friction, i.e. the friction load increases linearly with contact pressure with an offset given by the viscous friction. This model should give correct results for mainly UD laminates and if assuming that forming mainly takes place in areas at high contact pressures from the rubber diaphragm. Due to its linearity, the model doesn’t enable predicting friction forces at low contact pressures and other fibre angels.

In order to achieve better predictions at lower contact pressures the frictional data presented herein were calibrated towards the penalty polymer friction model in Aniform, a non-linear model including a possibility to vary the friction coefficient non-linearly over the pressures span. This model is hereinafter referred to as the Polymer/Coulomb model. In these first simulations, only the 0/45 friction data was used when calibrating the model. Figure shows comparison of experimental friction measurements and friction model predictions at different contact pressures for 0/45 interply slippage.

3.3.3 Out-of-plane properties

The out-of-plane bending stiffness was modelled with orthotropic elastic material model which was calibrated against bending experiments, see [11].

3.3.4 Model mesh

The pre-stacked lamina and vacuum rubber were modelled using 2.5D coupled elements, where each layer consisted of triangular mesh elements. Maximum side length of each element was 2 mm, where the rubber mesh was refined along the radius of the tool. The aluminium tool was considered stiff compare to rubber and prepreg lamina and therefore modelled by ridged elements.

3.4. Discussions of simulation result

During forming the pre-stack is forced to deform to adapt to the shape of the tool. Due to the recess area, this doesn’t only require bending around the tool radius, but also shearing of the un-cured lamina in order to move excessive material from the outer part of the recess towards the centre. Further, since the flange with recess is longer than the flat web, the lamina will undergo tension in the spar axis direction. Due to the tackiness and the interply friction in-between the different prepreg layers in the pre-stacked lamina, the deformation occurs without splitting. The effect of these different deformation modes (further described in [10]) need to be captured in the simulations.

Figures 8 and 9 shows the simulated, local fibre stresses in each layer of the lamina after HD forming. For improved visibility, only the recess side of the flange is shown. The light grey lines show the recess area, the chamfers and the flat bottom. As can be seen, Fig 8 related to the Polymer/Coulomb friction model shows significantly more distinct result with larger differences in-between areas in compression and in tension than the result obtained when using the Viscous/Coulomb model, Fig 9. The general trends are however similar showing

- mainly tensile stresses close to and in ±45 degree angle to the radius in the layers with ±45 degree fibre orientation (Layer 1 and 3)
- low tensile stresses in Layer 5, with fibres perpendicular to the radius (90 degree fibre orientation)
- a combination of tensile and compressive stresses when moving down the recess in Layers 2 and 4, i.e. with fibres in the 0-direction.

Further considering Layers 2 and 4, it seems like the material in the beginning of the recess, toward the radius, is neutral. However, further down there is a slightly curved band of compressive stresses, possibly caused by the big area under tension underneath. If the area under tension is resisting deformation, the lamina will not slide enough downwards the recess area as. The excessive material above the material under tension will then be forced into compression. This is definitely more clear from the results based on the Polymer/Coulomb model, but can also be seen from the Viscous/Coulomb model if changing the scales. It is however interesting to note that the position of the compressive band ends up at different locations depending on friction model.

Looking at the same layers (2 and 4) but instead considering the local shear, a high degree of shear in alternating directions can be seen in the upper part of the chamfer and further down the web, see Fig. 10
and 11. Since the fibres are directed along the spar axis the alternating shear is directed perpendicular to the fibre direction. Again, this is more distinct and covers a larger area in the simulations based on the Polymer/Coulomb model (Fig 10) than in the simulation based on the Viscous/Coulomb model (Fig 11).

None of the simulations show signs of global out-of-plane wrinkling. However, wrinkling is often described as a local instability phenomena occurring as a result of combined shear and in-plane fibre compression [17]. For the stacking sequence considered herein, [-45/0/45/0/90], experimental studies have shown that HD forming does not come without out-of-plane wrinkle formation [10]. The wrinkle has the appearance of a smiling mouth, as shown in Fig 12. The curved line of axial fibre compression along the flange length in Layers 2 and 4, shown in Fig 8 and 9, could possibly be a sign of areas prone to wrinkle development. This is further supported by the large amount of alternating shear, occurring in the same region and ending at the same position as the compressive band.

So is the resemblance between the compressive band and the wrinkle shown in Fig 12 just a coincident? Considering the simulation outcome on transverse fibre stresses in Layer 2, the simulation doesn’t provide further signs of wrinkling (see Fig 13, Polymer/Coulomb model). However, further inspections of earlier simulations performed on both wrinkling and non-wrinkling specimens [11] based on the Viscous/Coulomb friction model supports the thought. Further investigations are however needed to understand when a compressive area results in a wrinkle, the compressive forces required and if there is a size dependency in the wrinkle development.

The improved friction model used herein, the Polymer/Coulomb model, provides a much more detailed description of the interply friction at lower contact pressures. Further, it enables capturing non-linear phenomena related to increased softness and roughness of the heated prepreg plies. The improved model has provided more detailed simulation outcome which has opened up for increased understanding of the interply slippage during forming. In these simulations, the model has been calibrated towards 0/45 interply friction measurements, which provides the highest friction coefficient. In future work, friction models for different relative fibre angles will be used to further improve the modelling. However, since the resulting interply sliding direction is not easy to foresee for forming of more complex geometries, this requires further work and development of modelling methods.

4 Conclusions

The presented work aimed to provide further insight into hot drape forming of stacked UD material by studying the interply friction. New friction measurements were performed with different relative fibre angles at the sliding interface (0/0, 0/45, 0/30 and 0/90) and at lower contact pressures, 4 kPa, 10 kPa and 80 kPa. Based on the findings an improved friction model was calibrated, which was used in forming simulations. The simulations considered forming of a [-45/0/45/0/90], stack onto a joggled spar. Comparison was performed towards results based on a friction model derived from previous test at high contact pressures (53-120 kPa).

The experimental friction test showed large difference in interply friction coefficient depending on relative fibre angle at the interface. The 0/45 interfaces generally showed the highest interply friction, approximately 25% higher than at the 0/90 interfaces. The 0/30 interfaces showed friction coefficients similar to the 0/45 interface, while the 0/0 interface showed friction values similar to or lower than the 0/90 interface. Further, it was shown that for all relative fibre angles considered, the friction coefficient reduced with a factor of 2.5-5 at the highest contact pressure (80kPa) compared to at the lowest (4kPa).

The simulations showed that a band of compressive stresses occurs across the recess area of the considered spar during HD forming. Underneath the compressive band there was an area experiencing tension. The compressive band coincides with out-of-plane wrinkle development obtained during experimental forming of the same geometry and using the same stacking sequence. The simulated local shear in the area above the compressive band, predict high degree of alternating shear in the direction perpendicular to the fibres. Further investigations are needed to further explore the
relation between local fibre compression, shear and out-of-plan wrinkle formation.

Acknowledgements
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References
[8] Lightfoot, Wisnom, Potter

Table 1. Test matrix friction tests

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Table 2. In-plane model parameters

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Table 3. Out-of-plane model parameters

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Table 4. Interply friction model parameters

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Fig 1. Sketch of test rig. (a) pneumatic cylinder (b) attachment to Instron; (c) pneumatic cylinder creating pressure between (d) and (e); (d) quadratic side plates; (e) prepreg samples; (f) fixed middle plate (picture to the right); (g) clamping plate.

Fig 2. Experimental friction coefficient–displacement curve

Fig 3. Friction coefficient as function of temperature for different relative fibre angles. Contact pressure 80 kPa.

Fig 4. Influence of contact pressure on the interply friction coefficient for sample in different relative fibre angles.

Fig 5. Influence of contact pressure on the interply friction load (normalised by surface area) for sample in different relative fibre angles.
Fig 6. Modelled spar geometry (left) and HD forming setup (right).

Fig 7. Schematic of interply friction models used. Lines only for visual help.

Fig 8. Local fibre stresses from simulation based on the Polymer/Coulomb friction model. Stacking sequence, from Layer 1, [-45,0,45,0,90].

Fig 9. Local fibre stresses from simulation based on the Viscous/Coulomb friction model. Stacking sequence, from Layer 1, [-45,0,45,0,90].

Fig 10. Local fibre shear from simulation based on the Polymer/Coulomb friction model. Layers 2 and 4, 0° fibre angle.

Fig 11. Local fibre shear from simulation based on the Viscous/Coulomb friction model. Layers 2 and 4, 0° fibre angle.

Fig 12. Out-of-plane wrinkle on HD formed spar with [-45,0,45,0,90] s stacking.
Fig. 13 Local transverse fibre stress in Layer 2 (0° fibre angle). Simulation based on the Polymer/Coulomb friction model.