On Interply friction in Prepreg Forming Simulations

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1 Introduction

The usage of composite materials in automotive body structures has the potential of reducing weight and thereby improving energy efficiency of the vehicles. Two key factors that limit their usage are long cure time for the material and the lack of simulation support. The recent development of snap-cure or rapid-cure prepregs can address the former problem. For the latter, LS-DYNA simulations can support the design of composite parts and production process which can improve both their structural properties and manufacturability, avoiding the economic and environmental costs of trial and error used today to obtain defect free parts. This paper concerns the simulation of the forming of parts using unidirectional (UD) carbon fiber prepreg.

Compression molding of carbon fiber reinforced snap-cure prepregs have the potential of substantially reducing cycle times and manufacturing costs while providing the enhanced mechanical performance of the traditional prepreg hand lay-up process. However, the high level of automation in the process poses the risk of design and lay-up driven defects that may have a negative impact the quality and performance of the part. The objective of the simulations is to be able to improve the process, predict defects such as wrinkles and the resulting fiber angles that influence the part performance. The parts consist of number of layers of unidirectional (UD) prepreg material stacked on top of each other in a sequence where each layer can have different fiber direction to optimize process and product. The interaction between the layers will play a big role for the process and it will influence the wrinkle formation as well as the fiber rotations. Efforts have been made previously to model the friction in detail, see the manual [1] for the keyword *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_COMPOSITE where the friction is defined in terms of the Hershey number and a Stribeck curve model is used to predict the change of the coefficient of friction with respect to different parameters. However, it has not been possible to account for the difference in friction depending on the relative fiber angle in the layers in contact and the sliding direction. This difference in friction depending on direction is believed to be very important for the draping and sliding behavior in a compression molding process as well as for instance vacuum forming of prepreg composites. Previous research has indicated that the frictional load can vary by as much as one third for varying fiber angles [2]. It is also known that the consolidation pressure has a large effect on the inter-ply friction [3][4]. To improve the capability of LS-DYNA to predict defects and properties in the forming process, direction dependence was implemented in the orthotropic friction for the Mortar contact, see the manual [1]. The contact uses the fiber direction of the materials in the two layers in contact and lets the user input 4 friction values taken from tests of layers with different fiber directions sliding against each other in different directions. The 4 friction values can furthermore be replaced by tables to account for the dependencies of velocity and pressure. This paper explains the implementation, it's correlation to physical tests and trials on a virtual demonstrator.

2 Orthotropic Friction in Contact

An orthotropic friction model is available in the Mortar contact (*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR_ORTHO_FRICTION) that is here used to model the difference in friction depending on the fiber orientation in the prepreg plies in contact and the relative sliding direction, see Fig.1:. The amount of data needed for input is a tradeoff between accuracy and the extent of testing needed to feed the model with data. The input is the following four coefficients of friction, see Fig.2:.

FS1_S = coefficient of friction for $\boldsymbol{v}$ in direction $\boldsymbol{s}_{\parallel}$, when $\boldsymbol{s}_{\parallel}$ is aligned with $\boldsymbol{m}_{\parallel}$
FS1_M = coefficient of friction for $\boldsymbol{v}$ in direction $\boldsymbol{s}_{\parallel}$, when $\boldsymbol{s}_{\parallel}$ is aligned with $\boldsymbol{m}_{\perp}$
FS2_S = coefficient of friction for $\boldsymbol{v}$ in direction $\boldsymbol{s}_{\perp}$, when $\boldsymbol{s}_{\parallel}$ is aligned with $\boldsymbol{m}_{\parallel}$
FS2_M = coefficient of friction for $\boldsymbol{v}$ in direction $\boldsymbol{s}_{\perp}$, when $\boldsymbol{s}_{\parallel}$ is aligned with $\boldsymbol{m}_{\perp}$,

Each of these four friction values may be replaced by a table reference to achieve a dependency on pressure and velocity. Each table consists of curves where in each curve the coefficient of friction is a function of the pressure at a particular velocity. Values for intermediate velocities and pressures are determined by interpolation and which is also the case for intermediate sliding directions and fiber angles, see the manual [1].

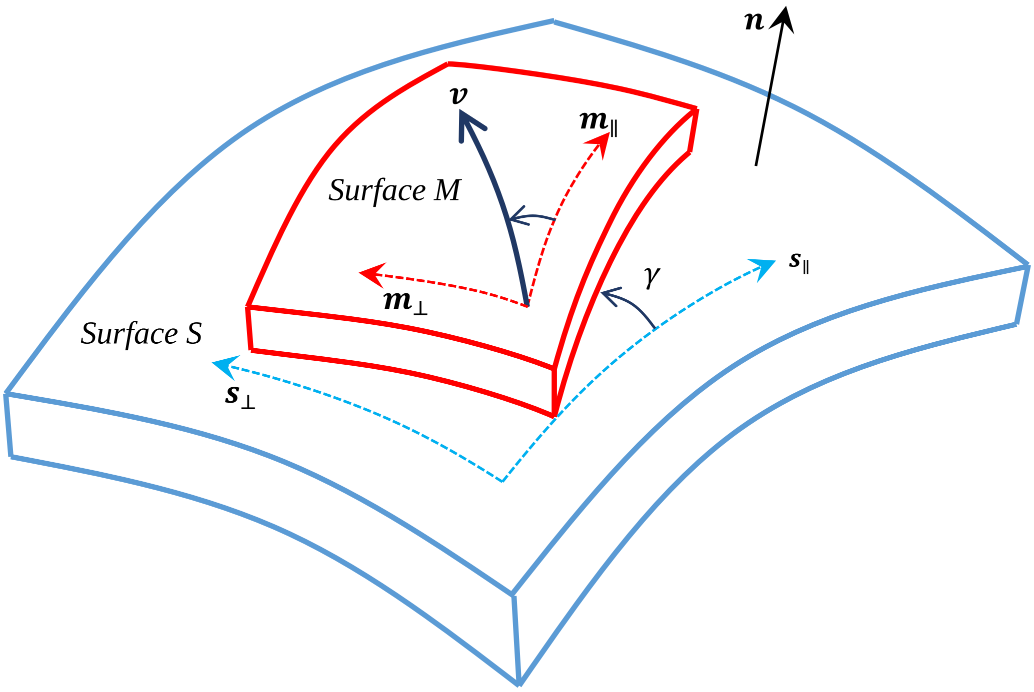

Fig.1: The prepreg ply surface M with main fibers in direction $\boldsymbol{m}_\parallel$ slides on prepreg ply surface S with its fibers in direction $\boldsymbol{s}_\parallel$. The contact pressure is p and the sliding velocity of surface M relative to S is in the direction $\boldsymbol{v}$. This results in a frictional traction $\boldsymbol{t}$ on surface S directed approximately in the same direction as $\boldsymbol{v}$. The corresponding traction on surface M is in the opposite direction and of the same magnitude as $\boldsymbol{t}$. Figure taken from the manual [1].

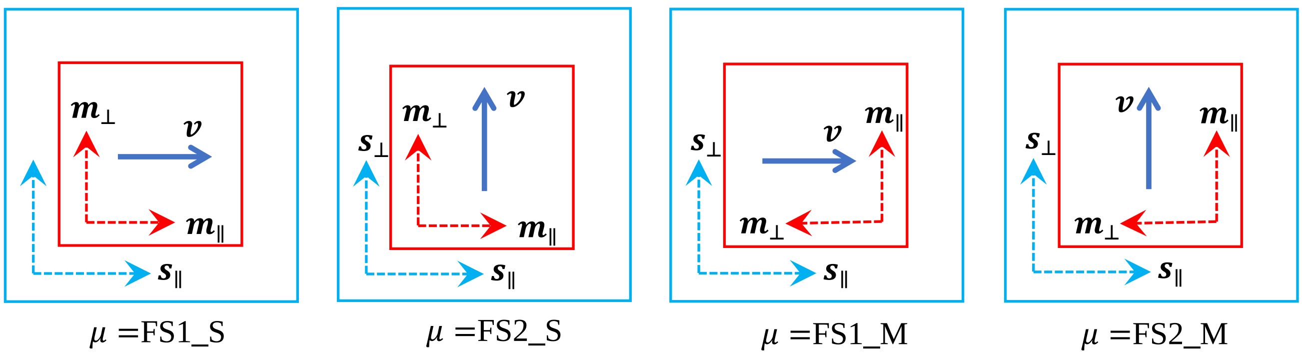

Fig.2: Four friction coefficients are the input for the orthotropic contact corresponding to the situations: 1_S where fiber directions of both plies coincide and so does the sliding direction, 2_S where fiber directions of both plies coincide and the sliding direction is transverse to these, 1_M where fiber directions are orthogonal, and the sliding is in the ply S fiber direction, 2_M where fiber directions are orthogonal, and the sliding is in the ply M fiber direction. Figure taken from the manual [1].

3 Inter-Ply Friction Tests

Inter-ply friction tests were performed at KTH Royal Institute of Technology in Sweden, the friction rig used for these tests consists of a fixed center plate and two floating side plates upon which the prepreg material is mounted, this rig is then placed in a tensile testing machine. The temperatures of the side and floating plates are controlled by a PID temperature control system and a pneumatic cylinder is used to control the normal pressure at the contact interface. The test setup has been used previously to measure inter-ply friction in [5] and [2].

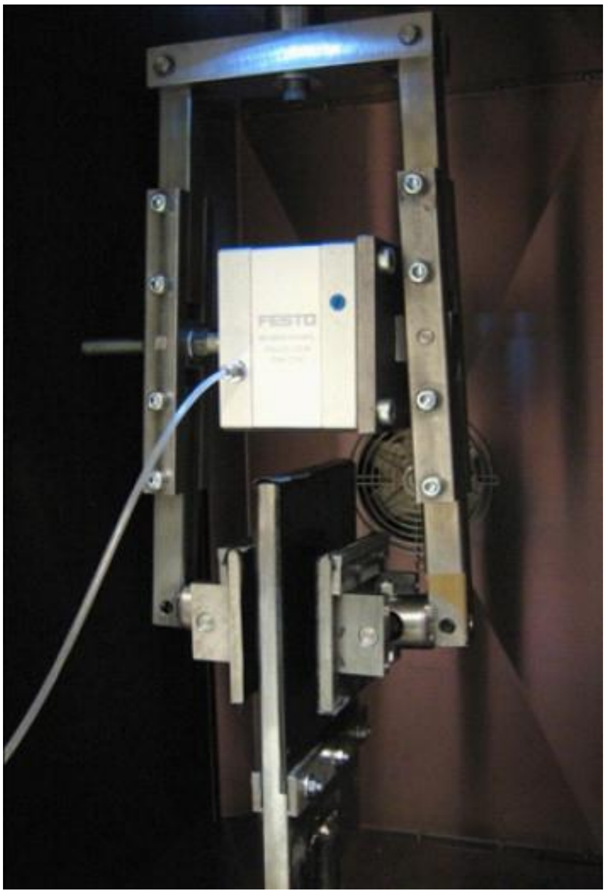

Fig.3: Friction Rig used for testing [5]

The material used for testing was automotive grade UD prepreg material. The tests were performed at a constant temperature that was recommended for forming by the manufacturer. Results are presented as normalized coefficient of friction (that is, the maximum coefficient of friction for each case is normalized to one and all other coefficients are scaled with respect to the maximum). The variables for the test are temperature (constant), normal pressure, fiber angle orientation at interface and sliding speed.

3.1 Pressure Dependency

Fig.4 shows the influence of normal pressure on the coefficient of friction, tests were performed at standard consolidation pressure (referred to as CP in Fig.4) and half the standard consolidation pressure (referred to as CP/2 in Fig.4), the temperature, sliding speed and fiber orientation at interface was kept constant.

Results show a large dependence of the coefficient of friction on the normal pressure. In this case, the material seems to follow standard Coulomb model of friction, where the frictional force is directly proportional to the normal force. However, this might not be the case for all materials and pressure ranges.

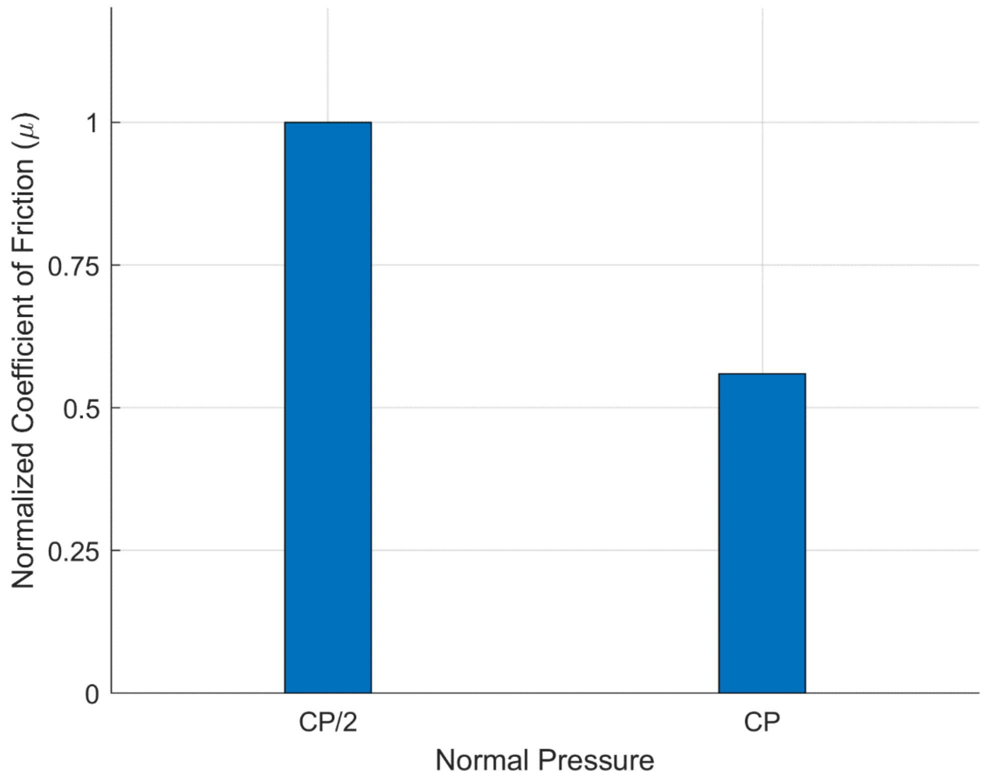

Fig.4: Variation of coefficient of friction with respect to normal pressure, temperature, normal pressure and fiber orientation kept constant.

3.2 Orientation Dependency

Fig.5 illustrates the change in coefficient of friction for different sliding interfaces, the temperature, pressure and sliding speed were kept constant. These results are for standard sliding speed and normal pressure and will vary as the sliding speed and normal pressure vary.

Tests must be performed in the relevant range of sliding speed and normal pressure and used as an input for the contact card.

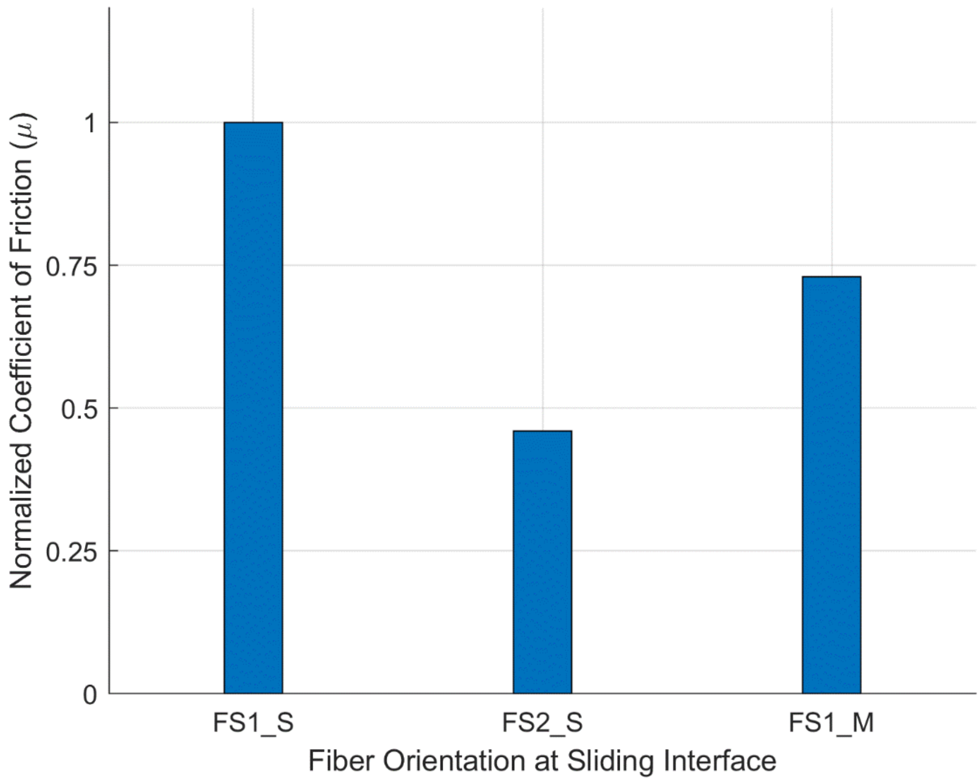

Fig.5: Variation of coefficient of friction with respect to fiber orientation at sliding interface at fixed sliding speed and normal pressure

4 Interpolation in orthotropic friction contact and comparison against physical test

A simple test model is used to verify the orthotropic friction implementation and see how the implementation handles interpolation between the input values. The verification is performed in two steps; first the interpolation is investigated where the sliding and fiber angles are varied, then the orthotropic friction model is calibrated against the intra-ply tests and a comparison is made between simulation and physical tests.

4.1 Interpolation test

The test model consists of shell elements with a small part moving on top of a larger bottom part. A pressure is applied on the upper smaller part. In the first test the fibers in the two layers are parallel and the sliding angle is varied from 0 degrees up to 90 degrees. This scenario corresponds to going from FS1_S to FS2_S in the contact keyword setup. The friction coefficients are set to 0.1 for FS1_S and 0.4 for FS2_S. Fig.6 shows the results from this first interpolation test. It is shown that the interpolation is not linear but more elliptical.

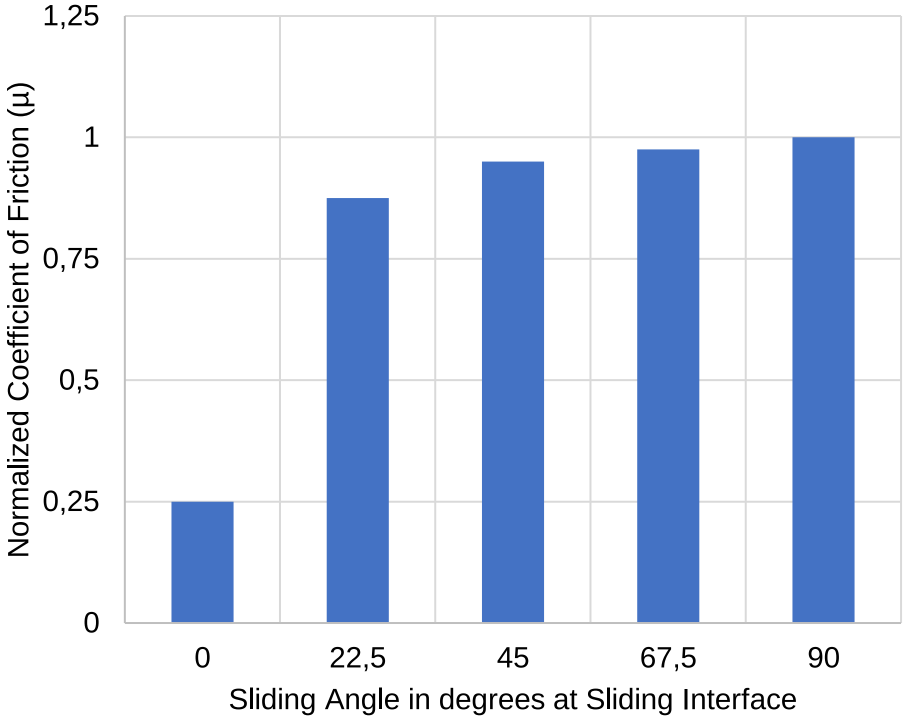

Fig.6: Variation of coefficient of friction with respect to sliding angle with fixed fiber orientation.

In the second test the sliding angle is constant while the relative fiber angle is varied from 0 degrees up to 90 degrees. This scenario corresponds to going from FS1_S to FS1_M in the contact keyword setup. The friction coefficients are set to 0.1 for FS1_S and 0.4 for FS1_M Fig. 7 shows the results from this second interpolation test. A more linear interpolation is now seen in this scenario.

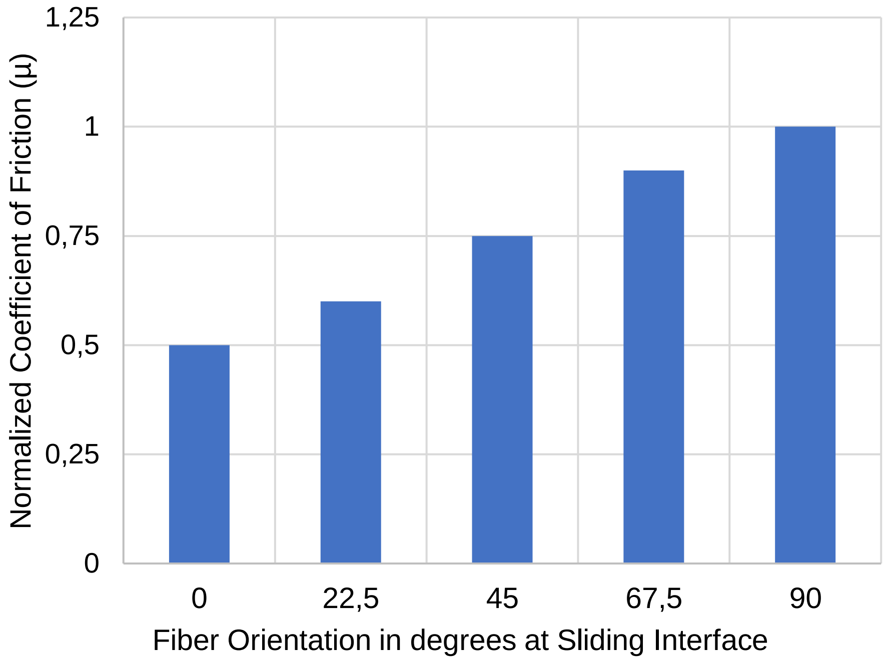

Fig.7: Variation of coefficient of friction with respect to fiber orientation with fixed sliding direction.

4.2 Comparison with physical test

The frictional coefficients from the intra-ply tests are used to calibrate the orthotropic friction model. The same simple test model is used in these comparison tests as in the previous interpolation tests. This test model does not include all details of the physical test setup, but the model is still sufficient to test the orthotropic contact implementation. Tables are used as input with the two different test pressures and the three different sliding velocities. From the physical tests, the fiber and sliding orientations FS1_S, FS2_S and FS1_M are obtained. For the current scenario and material, it is assumed that FS2_M is equal to FS1_M so the input for these is the same in the contact keyword.

Except from FS1_S, FS2_S and FS1_M there are also two other scenarios tested. These will be called (45/0) and (45/90), where the fiber orientation is 45 degrees for both cases, but the sliding direction is different. Fig. 8 shows a graphical summary of all the cases tested. These five cases are then simulated with the different test pressures and sliding velocities. Table 1 shows a comparison of the normalized coefficient of friction between the physical test and the simulation model for a specific pressure and velocity. The (45/0) and the (45/90) are the only cases that are not directly inputted in the orthotropic contact keyword and it is for those cases some differences can be seen between the simulated and the tested friction coefficient.

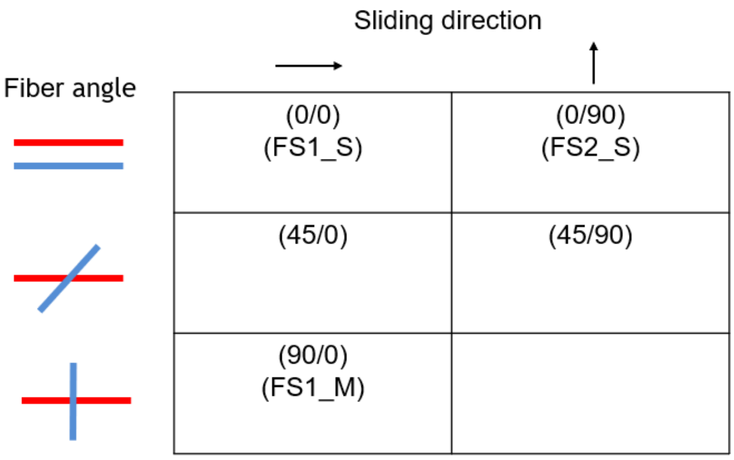

Fig.8: Overview for the tested combinations of fiber orientations and sliding direction.

Sliding interface	Physical test	Simulation
(0/0)	1	1
(0/90)	0.47	0.47
(45/0)	0.72	0.87
(45/90)	0.63	0.61
(90/0)	0.74	0.74

Table 1: Comparison between simulation and physical test of the normalized coefficient of friction for all tested cases.

5 Numerical simulations on virtual demonstrator

5.1 Process description and demonstrator geometry

In order to evaluate the effect of the newly implemented orthotropic friction in contact as described in Section 2, a demonstrator geometry of a joggled beam undergoing hot drape forming is used. Hot drape forming (HDF) is a process where the male half of the tool is rigid, and the forming is done by a polymer diaphragm. The forming forces are created by vacuum between the membrane and the male die. A schematic of HDF can be seen in Figure 6 [6].

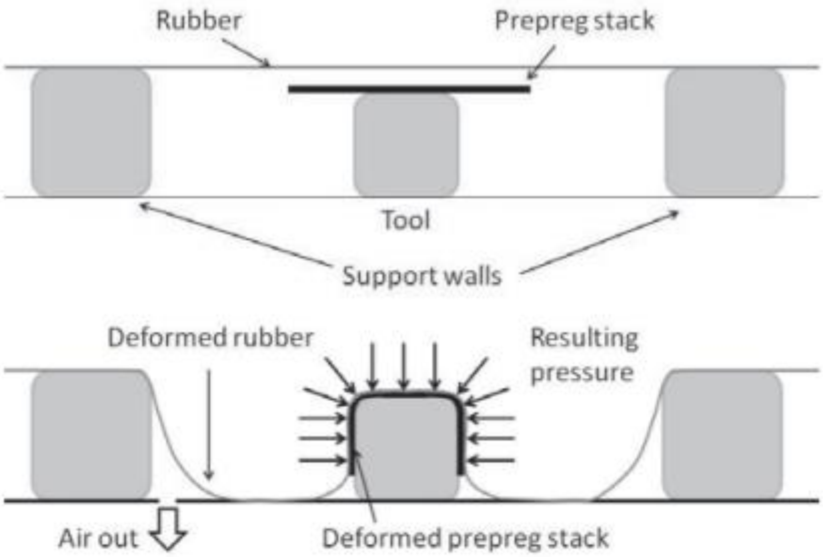

Fig. 6 Schematic of Hot drape forming of a prepreg stack

The process of HDF is chosen for this study as it is a quasi-static process and does not require tuning of parameters such as die setup and blank holders which have a large effect on the defects. HDF forming is preferred as it is easier to perform and evaluate defects at different stages than conventional die-die compression molding.
The geometry of the joggled beam (see Fig.7:) is similar to the one used by Hallander et al [7] to study the effects of inter-ply friction. However, in this case, the geometry is modified by deepening the joggle. The modification is made to create a geometry aggressive enough to induce defects. The joggled region is known to induce defects that are sensitive the stacking sequence and inter-ply friction. The geometry of the demonstrator is shown in Figure 7.

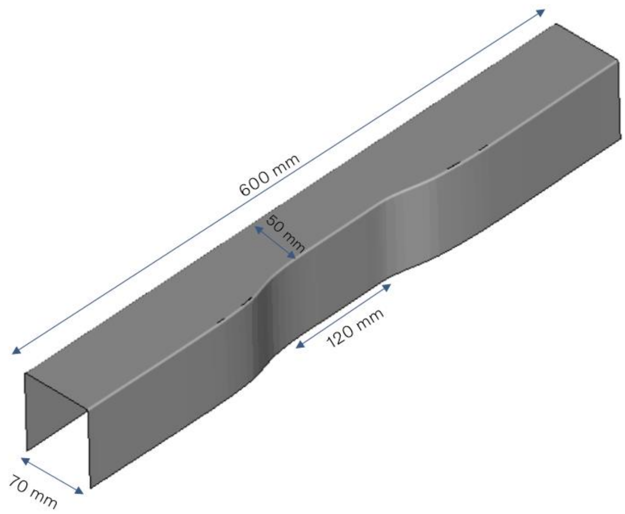

Fig.7 Geometry of virtual demonstrator

5.2 Modelling technique and results

The composite prepregs in their uncured state are modelled using *MAT_REINFORCED_THERMOPLASTIC (MAT 249). This material formulation captures the in-plane properties of the material. Each layer in the composite stack is used modelled as separate layer of shell elements. The membrane/diaphragm used to form is modelled using *MAT_RUBBER_MOONEY_RIVLIN. The simulation is isothermal, and the material properties are obtained for the optimum forming temperature of the resin system. The contact between the membrane and prepregs and rigid tool uses *CONTACT_FORMING_ONE_WAY_SURFACE_TO_SURFACE.

The purpose of this section is to compare the outcome of using the aforementioned orthotropic friction to other available methods. Hence, the same model is run with 3 different contact formulations, namely

1) *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE
2) *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE with pressure dependency
3) *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR_ORTHO_FRICTION → pressure and direction dependency included

The first trial is run with inter ply friction defined using a fixed co-efficient of friction that is independent of pressure and direction. The second trial uses pressure dependent friction. The coefficient of friction is defined as a function of pressure and relative velocity between the two interfaces using *DEFINE_TABLE.

Lastly, the third trial uses pressure and direction dependency of friction using the orthotropic contact implementation explained in Section 1. In the image below, the forming induced wrinkling on the joggled beam is shown towards the end of the forming process. When a conventional contact is used, now out of plane wrinkling can be seen in the region of interest. However, when pressure dependency of inter-ply friction is included, formation of an out of plane defect (wrinkle) is predicted. Using the latest implementation of pressure and direction dependent contact, it also predicts a wrinkle in the same position however it is of a smaller size. It can be concluded that, the different contact formulations used produced different results and defects of different severities.

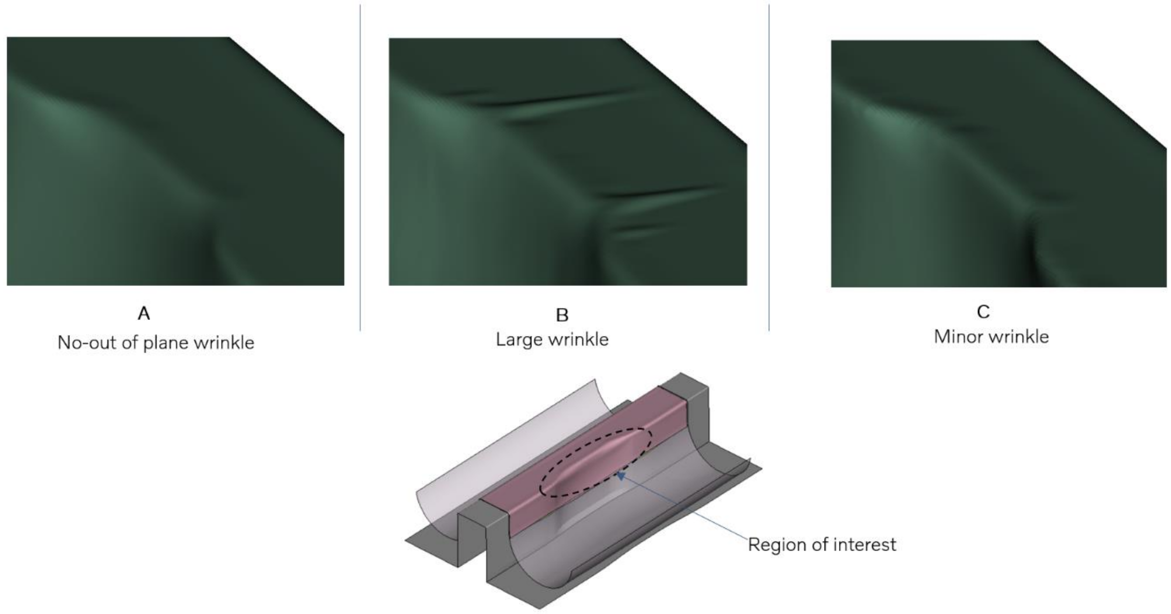

Fig.9 Defects in joggled area using A) Conventional friction B) Pressure dependent friction C) Orthotropic friction

The difference in the severity of the defects in different modelling techniques could be attributed to the counteraction of different forming mechanisms. The accuracy of this prediction requires physical verification. Another metric for quantifying the effect of the different friction models is the sliding interface energy in the model. This refers to the work done by the contacts present in the model. As can be seen in Fig. 10, the orthotropic friction results in a 44% increase in work done by the frictional forces in comparison to the conventional modelling technique. The contact which only accounts for pressure dependency results in a 69% increase in the work done by the frictional forces.

6 Conclusion

A contact with orthotropic friction is implemented in LS-Dyna. The model is evaluated against physical tests (characterization tests) and shows good correlation. A virtual demonstrator setup is evaluated, and different contact formulations are compared with the latest implementation which shows visible difference in the results. The next steps in the development of this contact formulation is to correlate with physical forming trials.

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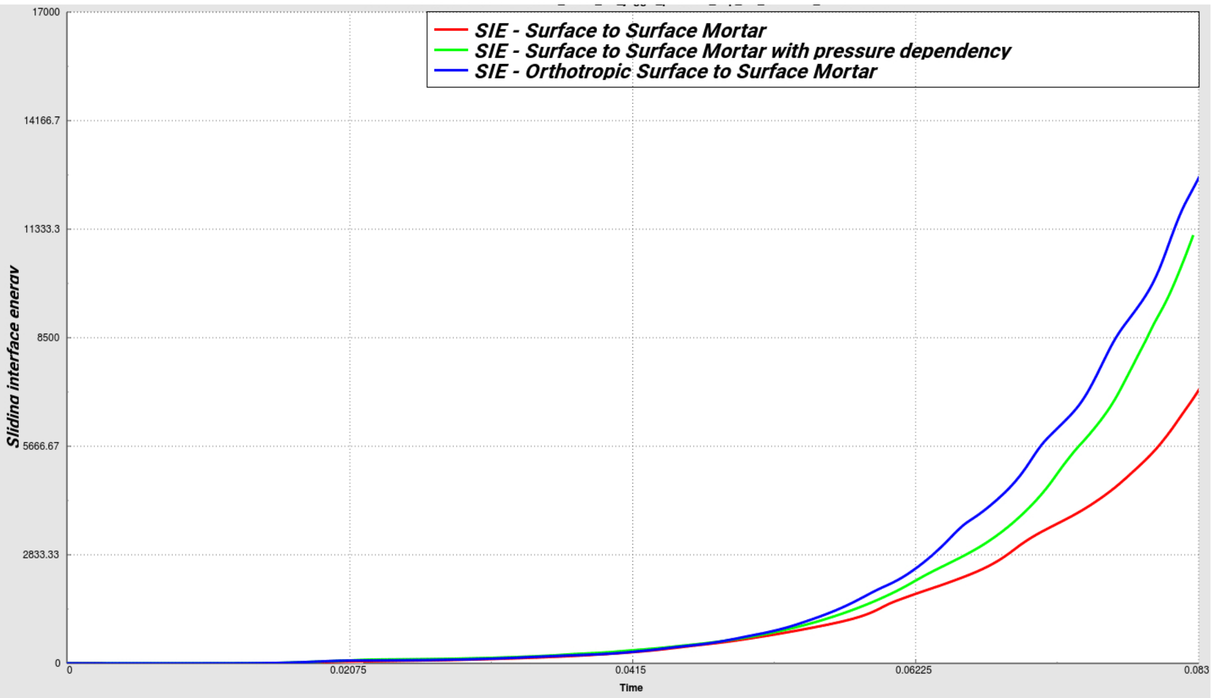

Fig.10 Difference in the sliding interface energy between different contacts

7 Literature

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