Key Engineering Materials
ISSN: 1662-9795, Vol. 926, pp 1343-1349
doi:10.4028/p-8xg60i

Submitted: 2021-12-08
Revised: 2022-01-12
Accepted: 2022-02-18
Online: 2022-07-22

Frictional and Cohesion Behavior of Natural Tows in Order to Assess the Tow Sliding During Composite Forming

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Keywords: Composite forming, tow sliding, yarn friction, forming defects.

Abstract. The tow sliding defect cause of the apparition of gaps in the reinforcement during woven reinforcement preforming is due to tows failing to accommodate the shape and sliding instead of holding together. The main reason for the defect formation can be attributed to increased pressure or tensions in some tows. Several parameters such as the reinforcement material, weave and tows orientation can significantly impact the sliding of tows and the apparition of the defect. In order to assess the tow sliding, it is important to understand the frictional behavior of the tows as units and the effect of the cohesion of the reinforcement as a whole. In this study, the frictional behavior of the tows was compared to their sliding behavior inside the reinforcement as whole in different conditions using two different methods.

Introduction

During Resin Transfer molding (RTM), some defected can appear during the preforming phase. These defects can range from aesthetic to mechanically altering [1]. One of the defects that requires more in-depth look into is the tow sliding defect (also known as reinforcement gaping). Observed by Ouagne et al. [2] on different locations of the preform using a complex geometry die, it was proposed that the pressure of blanc holders was responsible for the apparition of the defect (cf, Fig. 1). Allaoui et al. [3] observed tow sliding as well during the forming of multilayer interlocks. They found that the sliding was influenced by the effect of inter-fabric friction only when the displacement of the tows is larger than the width of the unit cell of the weave pattern. Nezami et al. [4] tested several parameters to understand the fabric/tool friction, inter-fabric friction and used a segmented blank holder in order to mitigate the appearance of preforming defects such as the tow sliding. Labanieh et al. [5] explored the effect of the blank holders and die pressure on the forming of the sliding defect near the edges of the blank holders due to high local pressures and loss of cohesion. Gatouillat et al. [6] and Iwata and al. [7] used meso-scale based models to simulate woven fabric forming and observed the formation of gaps in the preforms due to tow sliding.

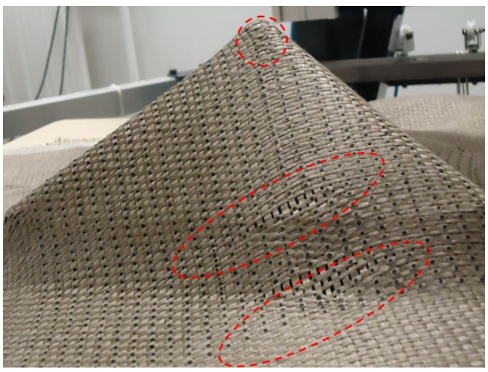


Fig. 1: Tow sliding (gaping) defect on different locations of a natural fiber woven reinforcement on a complex geometry.

To allow for accurate simulations and for the modeling of the sliding (gaping) defect, further investigations are required to characterize the meso-behavior of the tows during preforming of the reinforcement. Different approaches were used in order to study the inter-tow behavior. Some studies have focused on the friction coefficient between two tows via a tribological approach [8]. Other focused on the cohesion aspect of the tows in the reinforcement as a whole via tow pullout methods [4,9-10]. In this study, we propose to study the effect of weave on the cohesion of flax based woven reinforcement. To do so, we started by establishing a baseline while studying the inter-tow friction coefficient at different friction angles. Two pullout methods are then compared; a more classical in-plane pullout (IPP) akin to most of the literature and a novel out-of-plane pullout (OPP).

Material and Setups

Material. Two similar in composition flax-based tows were selected for the following study. The tows are extracted from either a twill 2 × 2 weave (cf, Fig. 2(a)) or plain weave (cf, Fig. 2(b)) that were made from the same initial yarn by the “Depestele” group. The tows are desized and similar in dimensions with a thickness of 0.4 mm ± 0.1 and width of 2.6 mm ± 0.2.

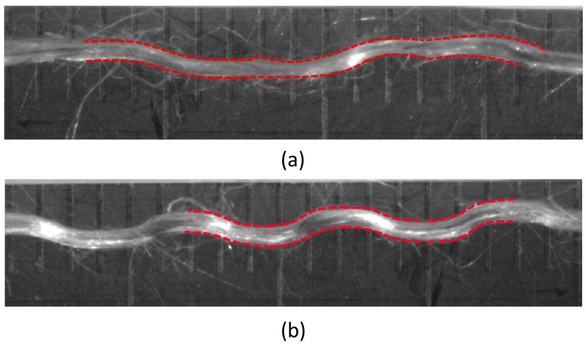


Fig. 2: Desized flax tows from (a) 2 × 2 twill and (b) plain weave.

Setups

Friction coefficient assessment. For assessing the friction coefficient of both tows, two specifically designed sample holders were designed. The holders allow for a specific tension to be applied on each tow and chose the angle at which the two tows will be scrubbed. The two holders are affixed to the “UMT Tribolab” from “Bruker” with the lower part fixed on the moving plate and the upper part fixed on the 5 N load cell (cf, Fig. 3). The tows are tensioned under 1.2 N and pressed onto one another with a normal load of 0.8 N. the sliding zone is 2 mm with a cycle frequency of 0.5 Hz. Three samples on the four shear angles of 0°, 15°, 30° and 45° (from the orthogonal reference position) were tested.

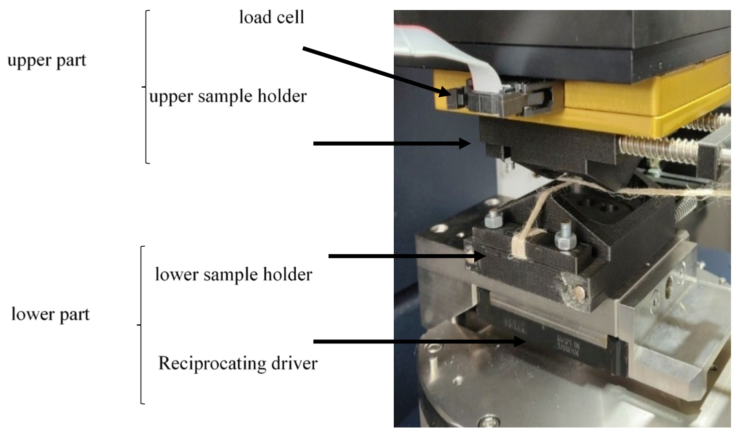


Fig. 3: Friction setup on tribometer UMT Tribolab.

In-plane pullout (IPP) assessment. In order to assess the cohesion of the fabric, the IPP test was done using the testing frame (cf, Fig. 4). The sample was cut so one tow was pulled through the width of 10 transversal tows. The transversal tows are put under a tension of 1 N/tow via the one of the lateral jaws that is linked to a compression cell of 200 N. The pullout is done via the jaw of the “Instron 400 II” traction machine with a load cell of 500 N. The pullout rate is 1 mm/min. Three tests were conducted.

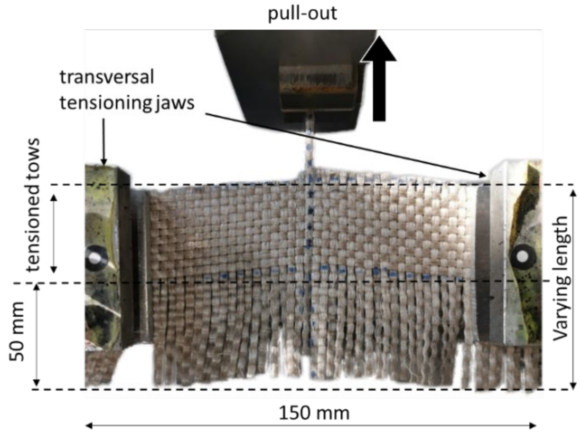


Fig. 4: IPP setup.

Out-of-plane pullout (OPP) assessment. The OPP was done by pulling an untensioned tow from the center of 10 × 10 cm reinforcement for a total of around 37 × 37 tows, held into place by a shear frame (cf, Fig. 5). Similar to the IPP, each of the tows is put under 1 N tension using weights. The pulled tow is extracted via a hook from the center of the reinforcement with the same load cell of 500 N and same pullout rate of 1 mm/min. Unlike the IPP, three tests were conducted with different shear angles (0°, 15°, 30° and 45°).

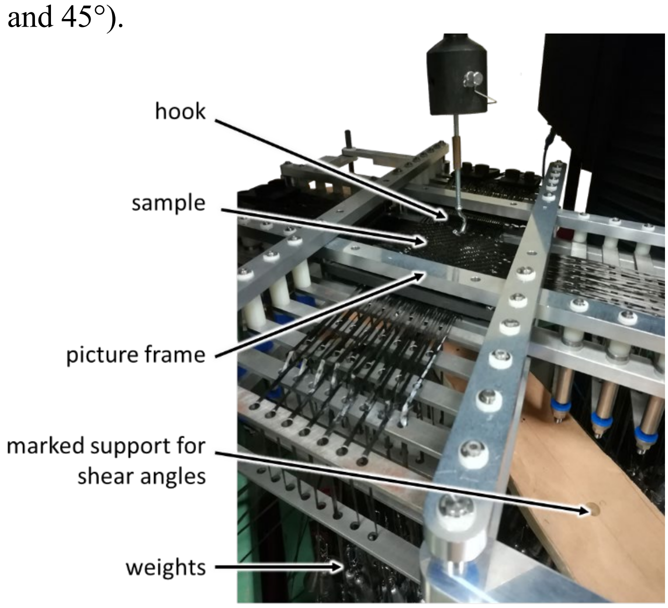
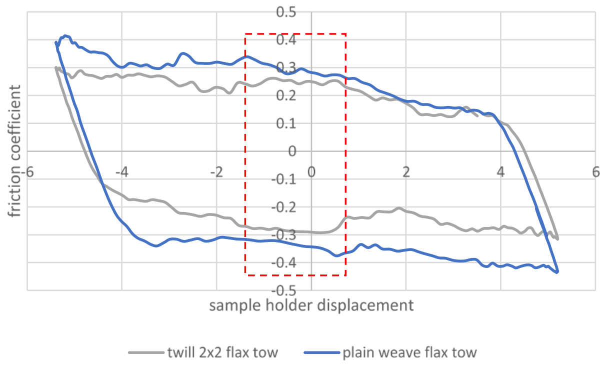


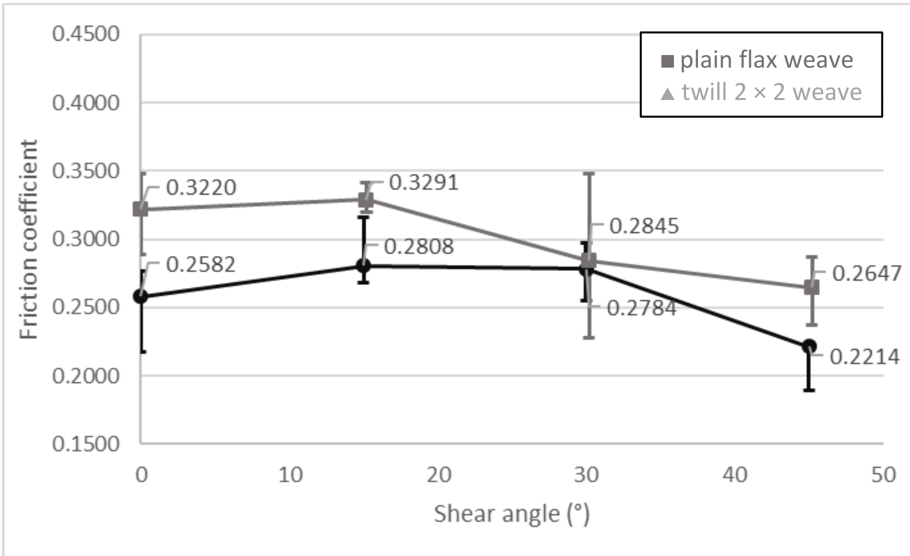
Fig. 5: OPP setup.

Results and Discussion

The friction tests carried on the tribometer yield displacement vs friction coefficient graph as demonstrated in Fig. 6(a). The final friction coefficient displayed in Fig. 6(b) is the average of the flat central zones of the graphs (dashed red square) in order to alleviate the effect of the borders of the sample holders or the effect of the direction change. The final friction coefficient was also averaged between the results of the 10th and 20th cycle to eliminate the setup effect or any wear that might appear due to prolonged friction.



(a)



(b)

Fig. 6: (a) Holder displacement vs friction coefficient, (b) Average friction coefficient for the considered tows (the error bars represent max and min values).

The resulting friction coefficient for neither tow seems to follow a trend as they seem to increase with the shear angle and then decrease. It is of note that for synthetic fibers, contrary to Coulomb model, the friction coefficient is expected to increase with the added surface area granted by the increased shear angle as the frictional behavior is mainly governed by adhesion [8]. This is probably due to the increased randomness of the free surface end of fibers which explains the big difference between the max and min of the registered friction coefficient. As presented in Fig. 7, the plain weave seems to promote more surface fibers that favors the entanglement and thus the increase of friction coefficient (the largest difference at 0°: 0.25 for twill compared to 0.32 for plain). This explains why the friction coefficient is higher across the board for the plain weave. The increase in the friction coefficient due to the increase of the angle can still affect the results, but in this case, seems to be overshadowed by the effect of the randomness of surface fibers.

After investigating the friction coefficient, we explored the behavior of the tow relative to the reinforcement; i.e., the cohesion of the reinforcement. During both IPP and OPP, the recorded pullout loads follow the pattern illustrated in Fig.8. In these graphs, the non-linear loading that corresponds to tensioning and rearrangement of the pulled tow and the decreasing state at the end that corresponds to the free tow will not be considered. Only the periodic state in which the tow is sliding through the reinforcement while still fully constrained will be considered and averaged. In this periodic state, we observe a pattern that is related to the residual imprint of the tow (cf, Fig. 2) with different peaks of the pullout load being due to the different steps of advancement of the pulled out tow in a representative unit cell.

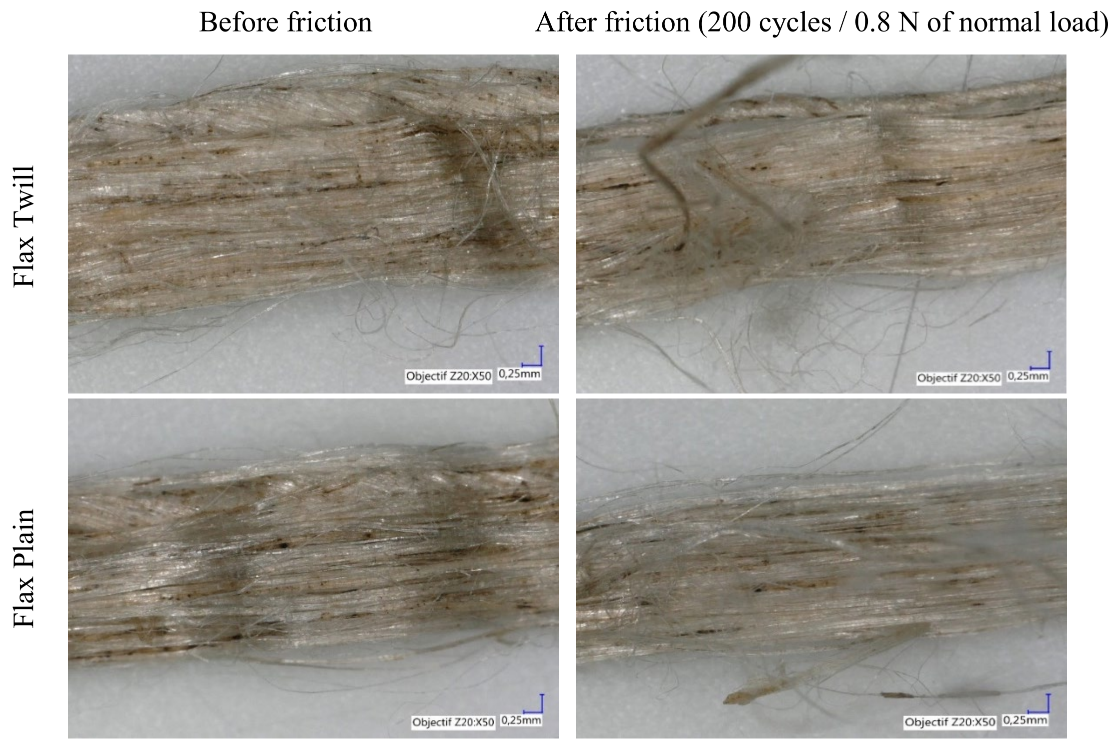


Fig. 7: Aspect of tows before and after friction

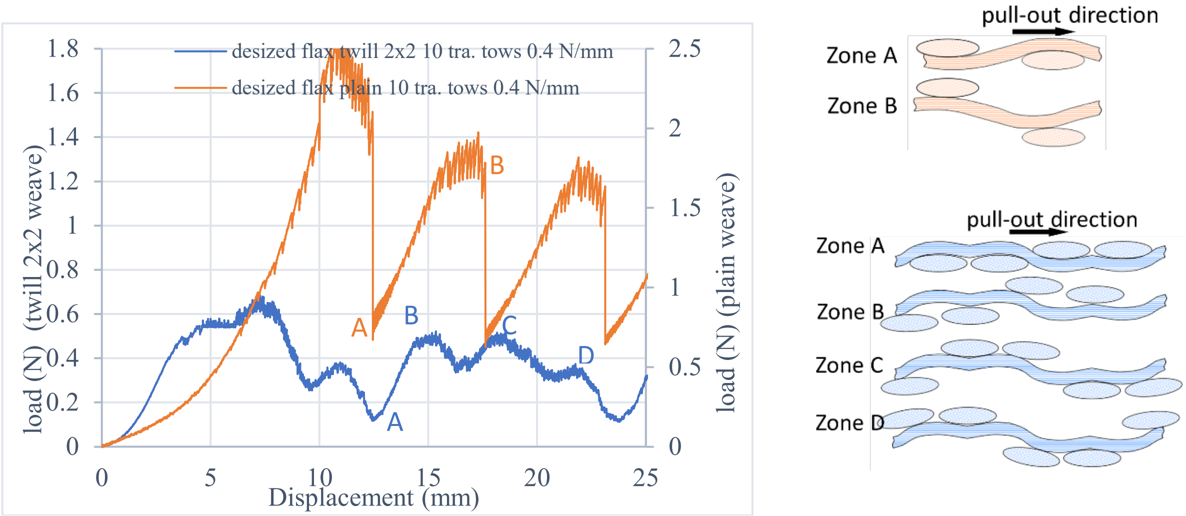


Fig. 8: Typical pullout loads (in-plane and out of plane) for flax twill 2 × 2 and plain weaves

As presented in Fig. 9, the average IPP load goes from 0.36 N for the twill to 1.34 N for plain weave (+272%). This increase is due partly to the increase of the friction coefficient as discussed previously and substantially to the increase in crossover points that the pulled tow needs to overcome. In this case there is twice as many crossover points in the plain weave than the twill. Combining the two phenomena increases the cohesion of the reinforcement more than the double.

As for the OPP loads represented in Fig. 10, it is harder to compare to the IPP quantitatively since the tow is dawn vertically from reinforcement and the pull out motion isn't strictly the same. Nonetheless the increase in the first shear angle of 0° that is akin to the unsheared IPP, sees a comparable increase of 330% from the 3.40 N required to pullout the twill tow to the 11.28 N required to pull the flax tow. The added value of this test is the control of the shear angle. In this case it is interesting to observe the sudden increase of the pull out load followed by a relative stabilization of the plain weave while the twill goes for a more subdued increase until the 45° mark where the increase is more notable. This is due to the lateral loads on the pulled tow which appear as the fabric reaches a locking stage in shearing. The shear locking happens earlier for plain weave making the lateral tows squeeze the pulled tow harder and increasing the reinforcement cohesion. This happens up to a certain point where the shear locking blocks the actual shearing of the reinforcement and thus limiting its actual effect on the pull out load value. The shear locking doesn't happen until the 45° angle for the twill thus the sudden increase in the pullout load.

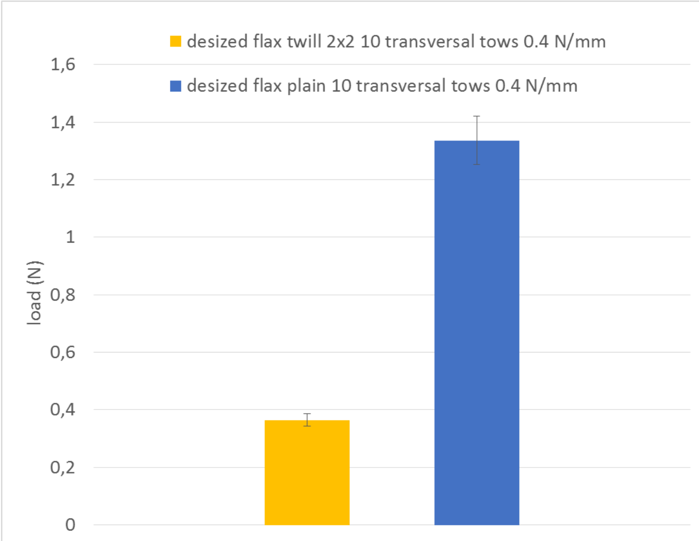


Fig. 9: Average IPP loads for twill 2 × 2 and plain weaves (error bars represent min and max loads)

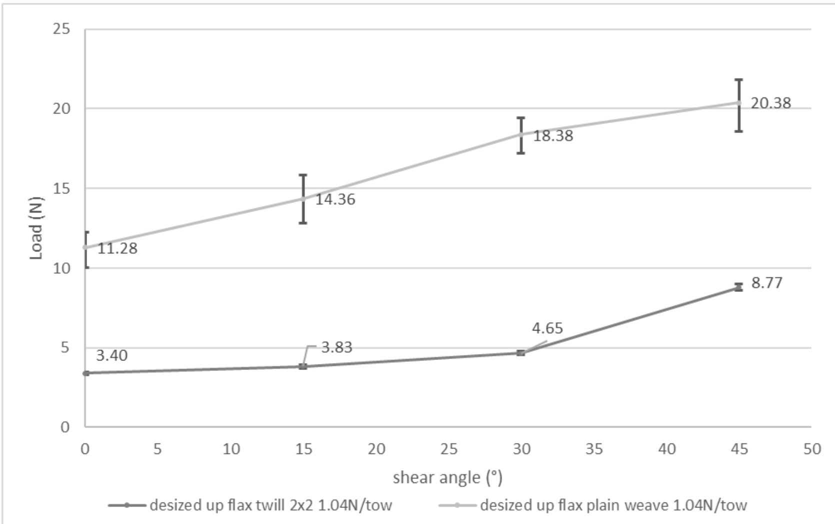


Fig. 10: Average OPP loads for twill 2 × 2 and plain weaves (error bars represent min and max loads)

Conclusion

In this paper we investigate the effect of architecture and shear angle on the cohesion of a fabric which is assumed to be highly correlated to the pull out load. In plane and out of the plane pull out where performed together with a detailed friction study. The conclusions are that the friction coefficient for natural tows isn't affected much by the angle between the tows and that the pull out load increase is related to the shear locking stage of a fabric. The cohesion of a fabric can be improved by using fabrics with more entanglement and more resistant behavior in shearing. Those two arguments could lead to prefer plain fabrics over twill or satin if cohesion become an issue during the forming.

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