


# Layup effects on core movement in sandwich panels

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**ABSTRACT**

Core movement is a major concern in autoclave processing of composite sandwich panels. Progress has been made in improving resistance to core movement by increasing frictional resistance of material systems. However, a complete understanding of the physics of the problem is still lacking. Hence, methods to mitigate core movement are largely empirically based.

The focus of this research is to understand core movement from a processing perspective. Specifically, how different layups affects core movement. The problem is investigated using in-situ data collection. Both onset and the progression of core movement are accurately captured, including individual ply movement.

**KEYWORDS:** *Core movement, Ply movement, Sandwich panel, In-situ*

## 1 INTRODUCTION

During autoclave processing of sandwich panels, external pressure can result in collapse of the core. This manifests itself as inward deformation in the core's weak, lateral direction, pulling plies with it. This is known as core movement or core crush. Crushed panels are irreparable and must be scrapped, making it a costly defect (Hsiao et al., 2006). Processing methods are typically altered to prevent core movement (Brayden & Darrow, 1989; Hsiao et al., 2006; Pelton et al., 1999); however, these are often empirically based. Much of the research on core movement focusses on the material aspect of the phenomenon, particularly from a frictional resistance standpoint (Hsiao et al., 2006; Martin et al., 1996; Pelton et al., 1999). There has been some work done in investigating processing conditions in relation to core movement (Alteneder et al., 1993; Brayden & Darrow, 1989; Renn et al., 1995), however these studies are limited. The mechanisms involved in core movement initiation and progression are still not well understood. Basic mechanical models have been proposed to describe the problem (Brayden & Darrow, 1989; Hsiao et al., 2006), though such models have yet to be validated.

The aim of this research is to better understand the effect various layups have in relation to core movement. In-situ data capture is used to identify the initiation and progression of core movement, allowing for a detailed look into the phenomenon as it develops.

### 1.1 Honeycomb Mechanics

Nomex honeycomb is a common core material in composite sandwich panels. It is manufactured by expanding sheets of glued ribbons. This gives directionality to the structure as shown in Figure 1. The in-plane dimensions are denoted by the $X_1$-$X_2$ plane, and are more commonly referred to as the non-ribbon (W) and ribbon (L) direction, respectively (Gibson & Ashby, 1988; Zhang & Ashby, 1992). The ribbon direction follows the direction of the glue lines, while the non-ribbon direction is perpendicular in-plane to this.

In-plane compression of honeycomb results in three distinct phases. That is, I - bending, II - collapse, and III – densification (Ashby & Medalist, 1983; Chen & Pugno, 2012; Gibson & Ashby, 1988; Papka & Kyriakides, 1998; Papka & Kyriakides, 1994). Bending represents the linear, elastic portion of the stress-strain curve. Collapse occurs thereafter, due to failure of the cell walls through buckling or plastic deformation. During this phase stress is constant as strain increases significantly, resulting in a plateau region. Densification begins as the cell walls start to touch each other, marked by a rapid increase in stress.

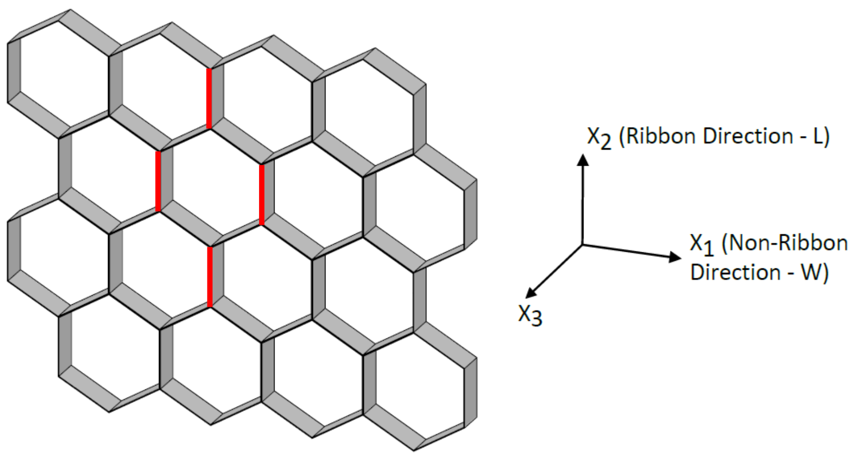


Figure 1: Regular hexagonal honeycomb. Red lines represent glue lines in the ribbon direction.

## 1.2 Inter-ply friction

Inter-ply friction is a combination of hydrodynamic friction arising from the viscous resin layer through to coloumb friction as a result of fiber-fiber contact. The dominant friction mode changes during cure (Erland et al., 2015; Larberg & Åkermo, 2011) as the resin infiltrates the ply tows (Springer, 1982) or is squeezed out under pressure. When the resin film is of molecular thickness, the system is said to be under boundary lubrication and coloumb friction dominates. When the shear force exceeds the inter-ply friction, relative movement of plies occurs.

## 1.3 Core movement

Core movement occurs when the lateral forces acting on the panel exceed the resistive forces of the panel. These resistive forces are a combination of the core stiffness, entrapped gas, and friction (inter-ply friction and friction between bag and tool-side surfaces) (Brayden & Darrow, 1989; Hsiao et al., 2006; Martin et al., 1996). Figure 2 provides a simplified diagram of the forces involved. $F_{stiffness}$ refers to the material stiffness of the core along with in-core pressure which has be known to contribute extensively to resisting core movement (Alteneder et al., 1993; Brayden & Darrow, 1989).

Hsiao et al (2006), postulate that in order for core movement to occur, slippage must occur across both a bag and tool-side surface. This is dictated by the interfaces of least friction, for which three are outlined. Namely, between plies ($F_{prepreg\text{-}prepreg}$), between the tool and first ply ($F_{prepreg\text{-}tool}$), and between the bag and top ply ($F_{prepreg\text{-}bag}$). Friction between the bag and top ply is ignored as it is assumed this represents the highest friction and therefore bag-side slippage will preferentially occur between prepreg plies. Hence, the condition for core movement is:

$$F_{prepreg-prepreg} + F_{prepreg-Tool} + F_{stiffness} < P_{Horizontal} \cdot A \quad (1)$$

Where $P_{Horizontal}$ refers to the horizontal component of pressure and A refers to the area of the panel over which the pressure acts.

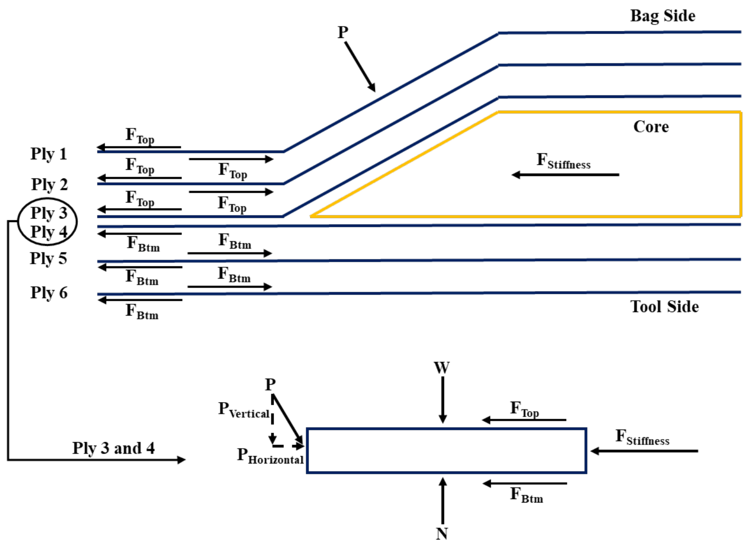


Figure 2: FBD of sandwich panel

## 2 METHODOLOGY

### 2.1 Experiments

Experiments were conducted to test the effect various layups have on core movement. Namely, use of tie downs, core machining stabilization (CMS), and use of a 45° core. Panels were built following the standard layup outlined in Figure 3 with individual modifications. A control panel was also built that followed the standard layup with no modifications. In each experiment, heating was applied until 120°C was reached after which pressure was increased in a stepwise manner to ensure slow pressurization. Pressure was applied in sets of 103 kPa with a one minute hold between applications. Once the pressure reached 621 kPa gauge it was held for 3 hours while the panel cured. Parts were initially held under full vacuum. At 103 kPa gauge the bag was vented to atmosphere to prevent early onset of core movement.

### 2.2 Materials and sensors

Regular Nomex honeycomb with a cell density of 48.06 kg/m$^3$ and cell size of 3.175 mm was used as the core. The core height was 25.4 mm with a chamfer angle of 20° in all tests but one. Plain weave carbon prepreg consisting of Cycom 970 resin with T300 3k fibers was used as the face-sheets. This system is qualified to BMS 8-256. It is a low flow, toughened, high-temperature cure (177°C) material. Metlbond 1515-4 was used as film adhesive to bond the core and face-sheets. Surface Master 905 was applied directly to the tool as a surfacing film. The tool was 12.7 mm thick A36 steel with stainless steel grit strips along the perimeter for restraining plies.

Two linear variable displacement transducers (LVDTs) were positioned against the panel to track deformation. One to two pressure sensors were surgically placed inside the core during layup to track in-core pressure fluctuations. An autoclavable camera was implemented to film the core movement process in-situ. Both pressure sensors and camera were developed by Convergent Manufacturing Technologies Inc.

### 2.3 Layup

Figure 3 details the standard layup used. Four tool-side plies (plies 1-4) and four bag-side plies (plies 9-12) were placed under and over the core respectively. In addition, four filler plies (plies 5-8) were placed around the core to allow for a smooth edge-band transition. Plies 5 and 6 butt against the core while ply 7 and 8 extend 6.35 mm and 12.7 mm, respectively, up the core. Ply 1 was held under vacuum for five minutes after being laid down to prevent shifting during layup. Film adhesive was laid down between the core and skins. Polytetrafluoroethylene (PTFE) release film was placed over the part, followed by breather cloth and vacuum bag material. Pleats were made in the vacuum bag along the edge-band to prevent bridging.

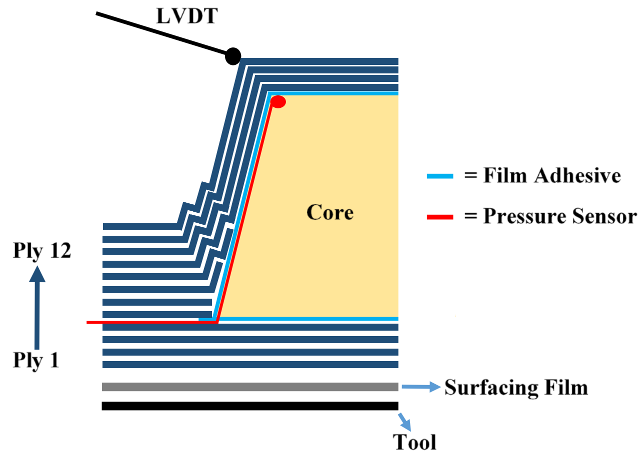


Figure 3: Panel layup

Two tests incorporated the use of tie down plies, wherein plies 4 and 9 were restrained using grit strips. In the first test (full tie downs) all four edges of these plies were restrained. In the second test (half tie downs), only one L and one W edge were retrained. The full tie down test exhibited no notable movement allowing for the breather deformation to be extracted.

The CMS test involved pre-curing a 76.2 mm wide picture frame of film adhesive along the tool-side of the core. This stabilized core was then implemented in the standard layup procedure.

The last experiment involved the use of a core with a 45° chamfer angle instead of 20°.

### 2.4 Data capture

Sensor data was synchronized with the video camera results to allow for an accurate depiction of when core movement occurs. Two points of failure were identified, namely onset and collapse. These correspond to elastic bending and collapse of the honeycomb structure. Onset is defined as the point where deformation in the LVDTs deviate from that of the breather cloth. This is confirmed in the video footage as the first point of noticeable movement. Collapse refers to the point where, beyond which, deformation is continuous, and significant. This typically presents itself as an obvious inflection point in the LVDT data and is again confirmed by video footage. Figure 4 provides an example.

RAVEN models (Web-1) were used to determine the resin viscosity at the time of onset and collapse for the three processing temperatures.

Following cure, panels were scanned using a coordinate measure machine (CMM) to obtain the surface topography. They were then sectioned through-thickness along the L and W direction using a vertical bandsaw with a diamond blade cutter. Cut samples were polished allowing for individual plies to be observed. The position of each ply was recorded using a Keyence digital microscope so that ply movement could be determined.

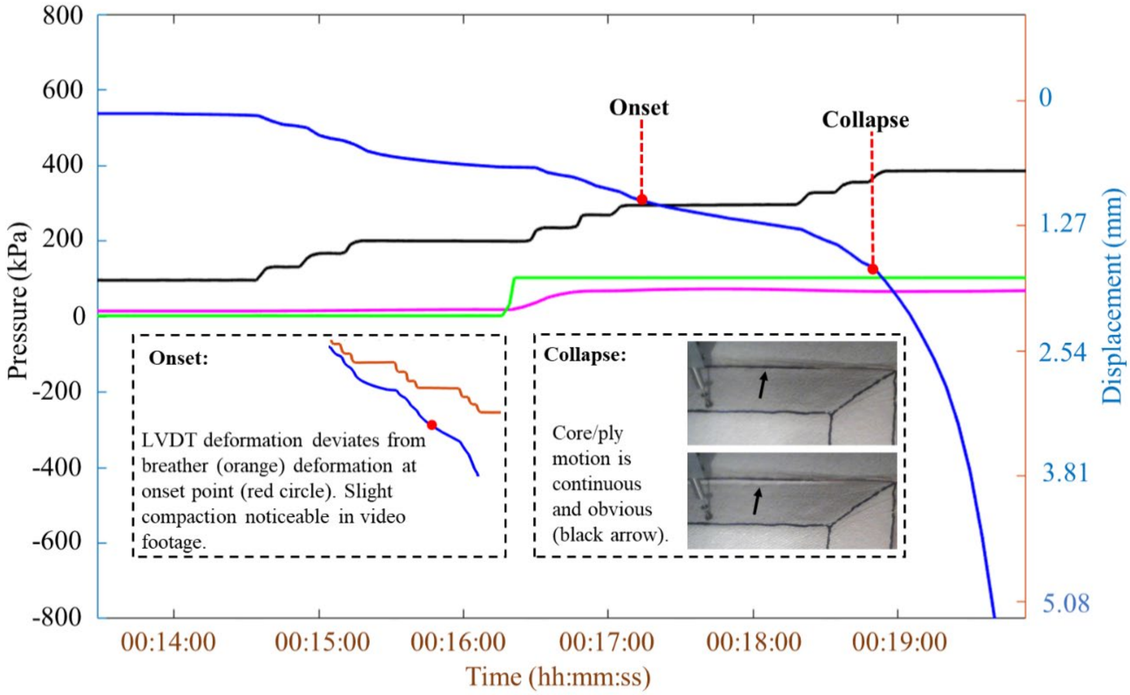


Figure 4: In-situ data capture showcasing core movement

# 3 RESULTS AND DISCUSSION

## 3.1 Resistance to core movement

Net pressure is defined as the external pressure acting on the panels minus the vacuum pressure within the bag. Figure 5 displays the net pressure at onset and collapse for each of the experiments. The full tie down test displayed no core movement.

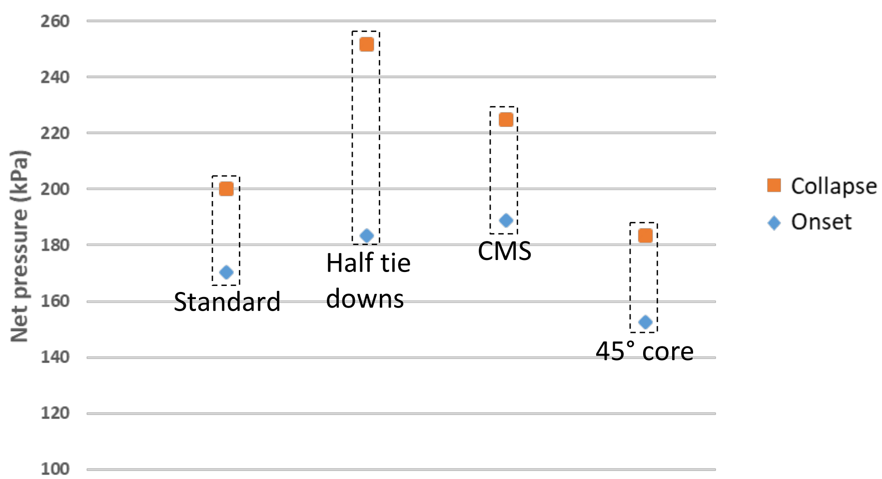


Figure 5: Net pressure at onset and collapse for various layup features. Note that results for the half tie downs represents those of the unrestrained edges.

The range of pressure between onset and collapse can be thought of as a critical zone, wherein core movement initiates within this region. Beyond this zone drastic core movement is likely. Under the standard layup, the critical zone ranges from 170 kPa to 200 kPa.

Restraining the first complete plies above and beneath the core (i.e. ply 9 and 4) virtually eliminates core movement. Small distortions in the cellular pattern were seen upon sectioning the panel, however this was not externally visible. Not surprisingly, restraining only two edges (i.e. half tie downs) of the plies allows for movement along the unrestrained edges while, at the same time, restricting movement along the restrained edges. Interestingly, the resistance to movement increases along the unrestrained edges in comparison with the standard layup, indicating that core movement in the L and W direction are somewhat coupled. The critical zone also increases in size, providing a buffer between onset and collapse.

CMS slightly increases the resistance to core movement with onset and collapse occurring at 189 and 225 kPa respectively. The critical zone remains similar in size however. It was observed from video footage that crush initiates beyond the stabilized zone which extends past the chamfer radius. For all other samples crush initiates around the radius of the core. CMS, therefore, prevents crush from occurring along the stabilized zone while providing resistance to crush in the unstabilized zone. A fully stabilized core would likely prevent crush, however, a larger stabilized area could result in a poor bond between the core and underlying plies. This brings about the idea that an optimum area of stabilization exists where core movement can be prevented in both stabilized and unstabilized regions, whilst still providing a good bond with the neighbouring ply.

As would be expected, a steeper chamfer angle increases the chance for core movement. Again, the size of critical zone does not change however. Interestingly, in the 45° core test, collapse occurs immediately following venting of the vacuum bag. In this instant, the net pressure is actually reduced to 129 kPa. The pressure prior to venting was 183 kPa and had been held for one minute. It is likely that the higher pressure-state prior to venting was responsible for core movement and is therefore the value used in Figure 5. This suggests a time dependent response as the core was likely on the verge of collapse and reducing the net pressure did not delay failure.

### 3.2 Ply Movement

Ply movement profiles were generated for each of the four samples to understand core movement from a mechanical perspective. Movement profiles in the W direction are presented in Figure 6. A profile for the full tie down case is not given, as no visible movement occurred. Patterns in the L direction are similar.

Half tie downs show similar results to the standard layup despite a greater resistance to crush as previously mentioned. For the CMS sample, the bag-side plies seem to move slightly more than the tool-side plies. This could be due to a weaker bond between ply and core along the tool-side due to stabilization. The extent of movement is also less; likely due to a smaller susceptible area to core movement. The 45° core sample displays the most movement. Considerable relative movement is also observed between plies, with the plies immediately surrounding the core (plies 4-9) experiencing the largest displacement. Recall Figure 3. Hydrodynamic friction increases with velocity. Therefore, it is possible that plies 4-9 initially slipped across the ply 9/10 and 3/4 interfaces. As these plies slid, the hydrodynamic friction acting on the neighbouring plies would have increased; thus dragging further plies inward resulting in a cascading effect. Plies 5-8 are filler plies and do not extend fully over the core. The gap between the core and plies 5/6 is due to deformation of the core relative to the plies. Such relative deformation was not observed in any of the other samples.

In all cases, ply 1 remains stationary indicating a higher degree of friction along the tool-side surface. This is in opposition to the assumptions supporting Equation 1.

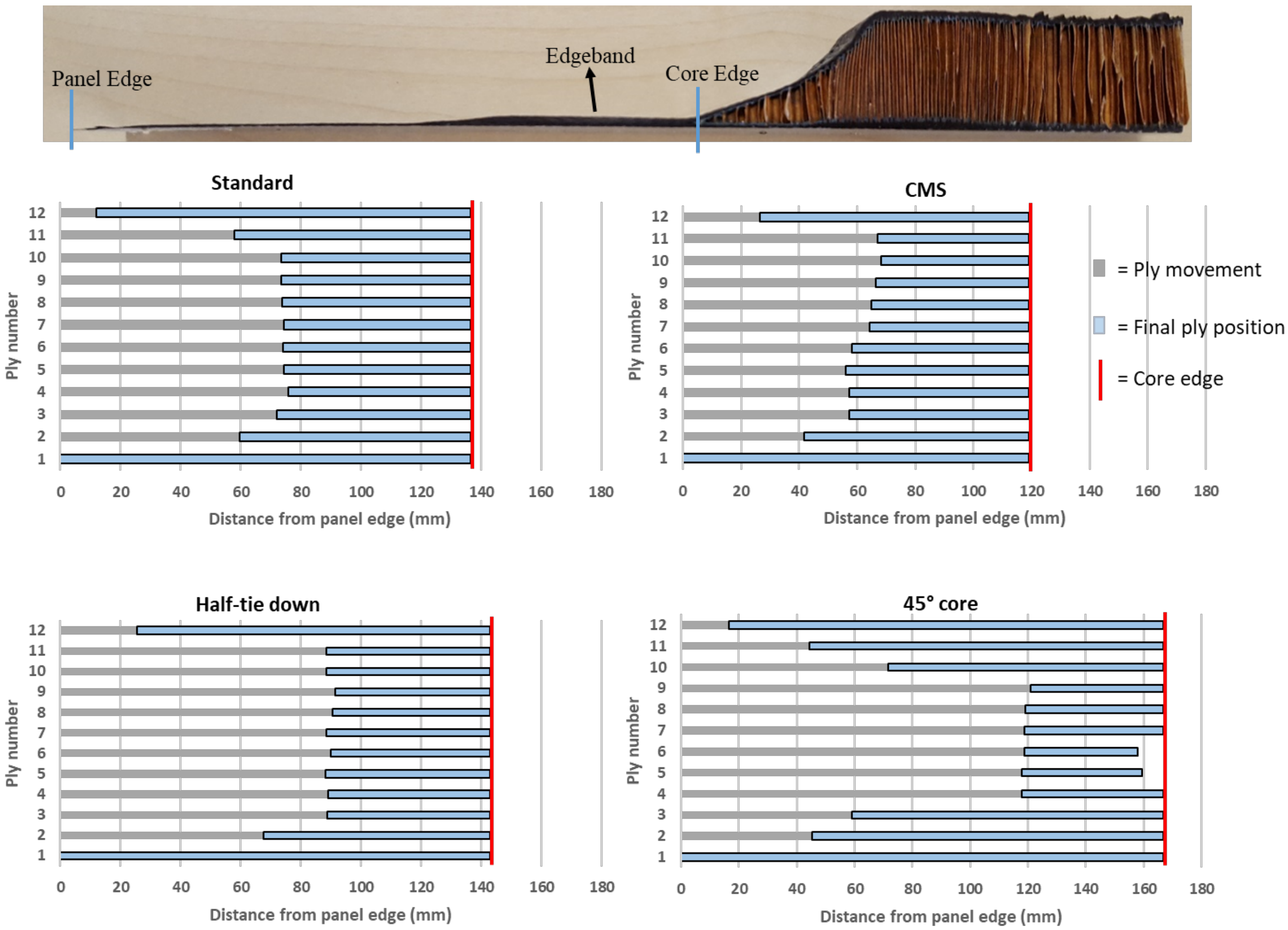


Figure 6: Top photo displays a through-thickness cut of a part that experienced core movement. Bottom photo is the individual ply movement for each sample in the non-ribbon direction. Note that prior to core movement, the core edge was at 50.8 mm.

## 4 CONCLUSION

In-situ data capture allows for an accurate depiction of core movement in real-time. Whereas typically the autoclave is treated as a black box, this method of data capture allows for process-induced deformation of composite materials to be better understood.

Altering features of the layup can influence a sandwich panel's resistance to core movement as well as the nature in which core movement initiates and progresses. Methods such as tie down plies and core machining stabilization are effective at mitigating core movement to varying degrees. For core with a 20° chamfer angle, single tie down plies are an adequate solution. Even restraining just two edges of the panel increases the panel's resistance to crush as a whole; however, it will not eliminate it. CMS, on the other hand, is not a standalone solution, offering a minimal increase to resistive capabilities.

Changing to a steeper chamfer angle results in earlier onset and a higher degree of crush. Moreover, a larger degree of relative movement is seen among plies as well as between the core and plies. It is suspected that the high degree of relative motion observed between plies is due to a largely hydrodynamic friction regime.

The prepreg-tool interaction offered greater frictional resistance than the prepreg-bag interaction. This is opposite to current mechanical models, suggesting that the use of tool-side surfacing film and bag-side release film is not captured in such models. This is an important consideration as these features are often implemented in sandwich panel processing.

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