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Core Crush Problem in Manufacturing of Composite Sandwich Structures: Mechanisms and Solutions

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Manufacturing of composite honeycomb sandwich structures is significantly impacted by poor production yields caused by the core crush problem that occurs during the autoclave curing process. It is a major manufacturing defect that leads to costly part rejects because the defects are nonrepairable. This failure mechanism also constrains aircraft engineers, limiting the design range of core density and core thickness in attempts to mitigate core crush. Recent studies that have led to basic understanding of core crush mechanism are discussed. It was found that the prepreg frictional resistance is the key factor in controlling core crush. Research in the scientific community has mainly focused on resin effects in core crush. However, studies conducted show that core crush can also be significantly reduced by controlling construction of the fiber tow shape and the fabric architecture. Rounder fiber tow or more open fabric produces rougher prepreg surface, which results in a higher prepreg frictional resistance, reducing the effects of core crush. Experimental results indicate that a developed core crush resistant prepreg increases the prepreg frictional resistance and effectively reduces core crush, without changing the resin system.

Nomenclature

F_{btm} = frictional force between bottom skin prepreg ply and tool plate
F_{P-B} = frictional force between prepreg and bagging material
F_{P-P} = frictional force between prepreg and prepreg
F_{P-T} = frictional force between prepreg and tool plate
$F_{stiffness}$ = combined stiffness of core and uncured prepreg plies
F_{top} = frictional force between top skin prepreg ply and bagging material
$P^{net}_{horizontal}$ = horizontal mechanical driving force for core crush

Introduction

COMPOSITE honeycomb sandwich structures are widely used in the aerospace industry as panel parts in various aerospace structural applications such as ribs, flaps, spars, and rudders. They are typically formed from a layup of prepreg skin plies sandwiching over a honeycomb core. The panel edge closeouts are often designed with honeycomb edges chamfered to a constant tapering angle (Fig. 1). Despite the aerospace industry's long production experience in manufacturing such structures, the manufacturing process still suffers from a significant reject ratio due to a particular type of manufacturing defect, core crush, as known in the industry. Core crush is caused by the collapse of the honeycomb core in its weak lateral directions during autoclave curing of the sandwich structure, especially when the core density is low (Fig. 2). It is among the costliest manufacturing problems in composite fabrication. The crush of the panel is generally so extensive that it is beyond repair. Figures 3a and 3b show an example of a core-crush composite honeycomb sandwich panel from the side view and top view, respectively.

Core crush occurs during the autoclave curing process when the honeycomb sandwich structure is subjected to pressure and heat well before the thermosetting resin in the prepreg skins is cured. The pressure difference between the autoclave pressure and the vacuum in the core provides the mechanical driving force for core crush. Whereas the honeycomb core is usually strong enough to resist such a pressure difference by itself in its thickness direction, it contributes relatively little in its lateral direction to counter the pressure-induced resultant force component in that direction. The resisting forces developed to prevent the core from lateral collapse are internal core pressure, the lateral compressive stiffness of the skin/core combination, and the prepreg frictional resistance.[1,2] When core crush occurs, slippage is initiated and the prepreg plies move inward with the core. The elevated temperature during curing facilitates the slippage of prepreg plies by lowering the resin viscosity and providing the lubricating effect.[3]

Several techniques have been developed in the past to restrain the core from collapsing inward. For example, Corbett and Smith[4] used tie-down plies in contact with the core to prevent core crush in sandwich structures. These tie-down plies were extended beyond the trim line of the finished product and secured to the layup mandrel with tape. Hopkins and Hartz[5] found that Corbett and Smith's tie-down method did not eliminate core crush because the tie-down plies could occasionally pull away from the tape. They later developed an improved tie-down method. These approaches impact the manufacturing process, increasing labor, production time, and material cost and, therefore, may not be the most desirable solution.

Core crush is a complex phenomenon, where every component and manufacturing operation such as the following can contribute to the failure mechanism: raw material selection (fiber, resin), fabric/prepreg processing (tow forming, weaving, impregnation, postimpregnation, and part manufacturing (curing cycle, vacuum level, layup, bag/tool surface). Previous studies on the root cause of core crush have mainly focused on the resin effects.[6,7] The leading conclusion from these studies indicated that resin strongly controls core crush. At the similar degree of impregnation, a highly rubberized low-flow epoxy prepreg consistently showed greater core crush resistance than a standard high-flow epoxy prepreg. However, our studies[8,9] have demonstrated that core crush can also be dramatically

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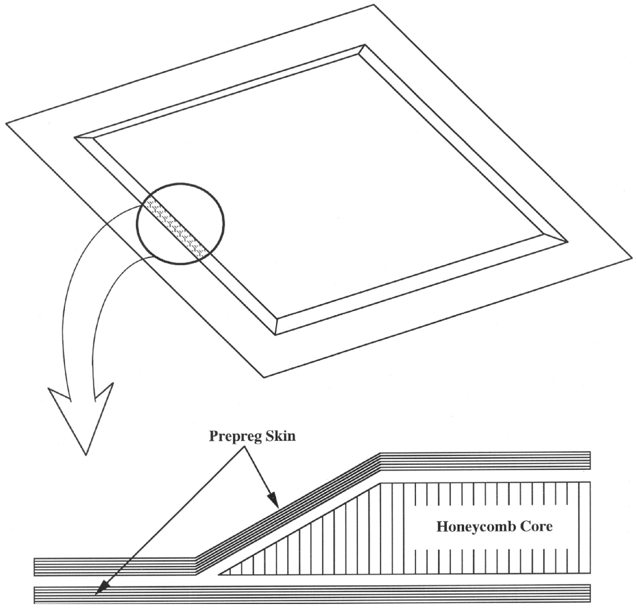

Fig. 1 Typical composite honeycomb sandwich structure with chamfered edge.

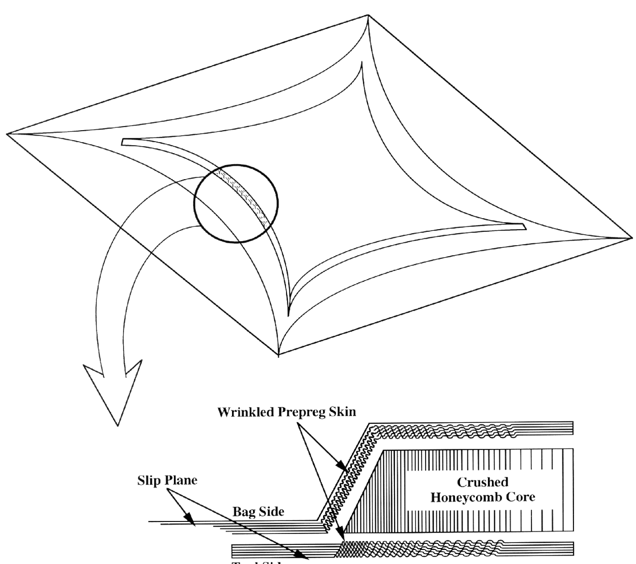

Fig. 2 Typical composite honeycomb sandwich structure after core crush.

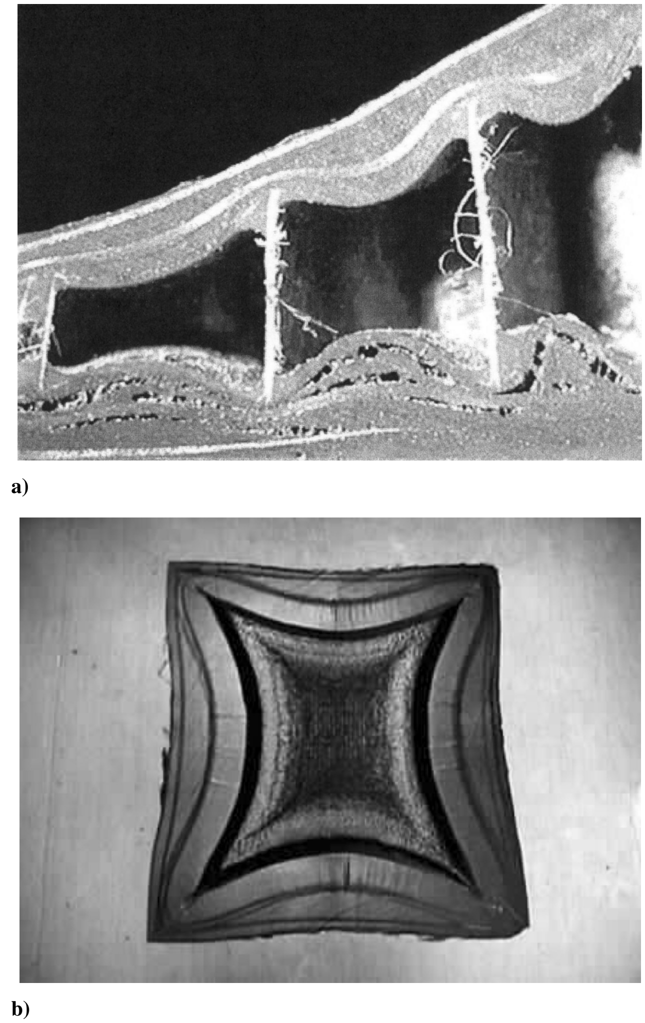

Fig. 3 Core crush sandwich panel: a) prepreg wrinkles at chamfer location (side view) and b) symmetric crush mode (top view).

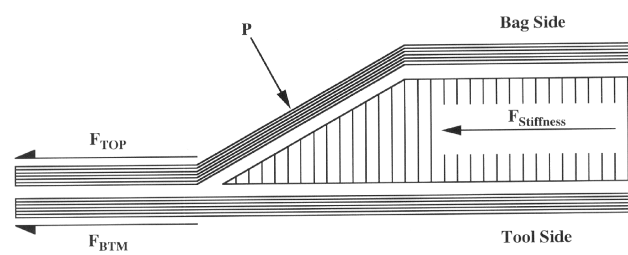

Fig. 4 Free-body diagram of the sandwich structure as a whole.

reduced by controlling construction of the fiber tow shape and fabric architecture.

In this study, the mechanisms controlling the entire core crush sequence were first clarified at the individual ply level, which differs from the more macroscopic level descriptions reported by others. Based on this understanding, conceptual approaches were then formulated to solve the core crush problem by manipulating the fiber tow configuration and fabric architecture, without changing the resin system in prepregs. A series of prepregs with various fiber tow and fabric constructions were prepared and tested for their core crush behavior. A strong correlation between the fiber/fabric architectures and test results validated the conceptual approaches in developing prepregs to resist core crush effectively.

Core Crush Mechanisms

Core crush occurs during the autoclave curing when the honeycomb sandwich structure is subjected to pressure and heat. As the autoclave is pressurized, a compacting pressure P perpendicular to the structure's surface is applied to the bag covering the structure. This compacting pressure counteracted by the internal pressure (usually vacuum) in the core results in a horizontal force component $P^{\text{net}}_{\text{horizontal}}$ providing the mechanical driving force for core crush. For the structure considered as a whole (shown schematically in Fig. 4), this horizontal force is opposed by three independent forces: 1) the frictional force F_{top} developed by the top skin prepreg ply against the bagging material, 2) the frictional force F_{btm} developed by the bottom skin prepreg ply against the tool plate, and 3) the combined stiffness $F_{\text{stiffness}}$ of the core and the uncured prepreg plies. However, such a consideration may be oversimplified and does not sufficiently describe the underlying core crush mechanisms.

This is a problem dealing with the equilibrium of a structure made of a honeycomb core and several connected prepreg plies. Because the frictional resistance between various interfaces of these connected plies is different, for example, prepreg-to-bag,

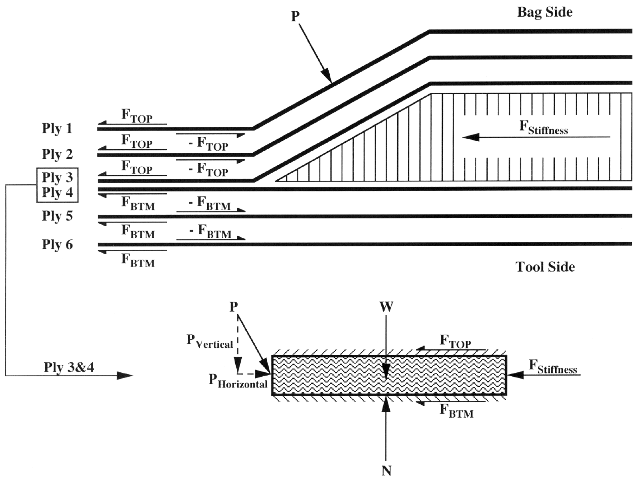

Fig. 5 Free-body diagram for component ply of sandwich structure.

prepreg-to-prepreg, prepreg-to-tool, this problem calls for the determination not only of the external forces acting on the structure but also the internal forces that hold together the various plies of the structure. In this case, the internal forces, such as the frictional force developed by the prepreg plies against each other, did not appear in the preceding equilibrium diagram of the structure. To account for all such interaction forces at the individual ply level, Fig. 5 shows the free-body diagram for each component ply of the structure (originally shown in Fig. 4) after it is disassembled schematically. To simplify the diagram, only six prepreg plies are included in Fig. 5 to represent the actual case. When the notation in Fig. 5 is used, the core crush mechanisms and sequences are described as follows:

1) When the autoclave pressure is applied, the honeycomb core tries to crush and drag its two adjacent prepreg plies (plies 3 and 4) with it. These two plies are treated as one free body as they move together with the crushed core. The movement of plies 3 and 4 is resisted by the frictional forces developed between plies 2 and 3, F_{top}, and between plies 4 and 5, F_{btm}.

2) At the interface between plies 4 and 5, to reach the force equilibrium, a reaction force $-F_{\text{btm}}$ that is equal and opposite to the friction force within the same interface develops. This reaction force tries to drag the next neighboring ply, ply 5, inward by shear and again a frictional force F_{btm} develops between plies 5 and 6 in response to that. Similar scenario occurs on the prepreg plies of top skin with the friction/reaction forces of $F_{\text{top}}/-F_{\text{top}}$ instead.

3) The crushing force applied to the honeycomb core, therefore, reaches the outermost plies (plies 1 and 6) through a series of internal shear force interactions and transfers across the prepreg skin plies. Before the onset of core crush, these outermost plies are held in place by the stationary bag and tool via friction forces.

4) Once the internal driving force $-F_{\text{top}}$ and $-F_{\text{btm}}$ exceeds the frictional resistance of the weakest interface on the top and bottom skin, respectively, the honeycomb core is basically ready to begin the crush process. However, because there are three types of interface for these prepreg plies (prepreg-to-bag, prepreg-to-prepreg, and prepreg-to-tool), their frictional resistance (F_{P-B}, F_{P-P}, and F_{P-T}) could be quite different. Therefore, it is critical to determine the order of F_{P-B}, F_{P-P}, and F_{P-T} so the slip planes on the top and bottom skin during core crush can be accurately identified. Indeed, friction tests conducted using the test method of Martin et al.[2] gave the order of F_{P-B}, F_{P-P} and F_{P-T} as

$$F_{P-B} > F_{P-P} > F_{P-T}$$

Therefore, as the honeycomb core crushes, slip will more likely occur between the prepreg and prepreg interface on the top skin and between the prepreg and tool plate interface on the bottom skin (Fig. 2). In fact, this is exactly what has been observed in numerous core crush test panels through visual inspection and microscopy. One important implication here is that, unlike what is plotted in Fig. 4, during core crush the critical frictional resistance for the top skin is F_{P-P} instead of F_{P-B}.

5) Based on the preceding discussion, core crush can be prevented when the combined resisting forces exceed the horizontal component of the net crushing force:

$$F_{P-P} + F_{P-T} + F_{\text{stiffness}} \geq P^{\text{net}}_{\text{horizontal}} \cdot h$$

At the very early stage of curing with the temperature low and the resin still viscous, this relationship holds true with the left-hand side of the expression much larger than the right-hand side. However, all of these resisting forces continue to change throughout the cure process. As the resin softens due to heating and starts to act like a lubricant, both the frictional resistance, F_{P-B}, F_{P-P}, and F_{P-T}, and skin/core stiffness resistance $F_{\text{stiffness}}$ decrease significantly. At certain temperature before the bottom-out of resin viscosity, when these combined resisting forces drop below the crushing force component $P^{\text{net}}_{\text{horizontal}}$, core crush will take place.

As already discussed, the crushing force applied to the honeycomb core is transmitted to the outermost plies through shear forces. During this process, those two prepreg plies next to the core are the most key elements because they are the ones that react to the core movement and trigger the subsequent mechanisms. If these two specific plies were tied-down and not allowed to move, the core crush sequence 1–5 will be disrupted and core crush is unlikely to occur.

As shown in Fig. 3b, the core crush mode is always symmetric instead of other modes (such as biased crush mode). During the autoclave curing, all four panel chamfered edges are subjected to the pushing force resulting from the compacting pressure. The center point of each panel edge is mainly subjected to the pressure loading perpendicular to that edge, whereas it is less affected by the pressure loading coming from the other direction. As a result, the honeycomb cells around the center points could be easily collapsed/buckled in one direction and pushed far inward. On the other hand, the four corner points of each panel are subjected to biaxial pressure loadings. The honeycomb cells around the corner are more difficult to collapse/buckle bilaterally and, thus, cannot be pushed too far from their original positions.

Conceptual Approaches to Improve Core Crush Resistance

Because the prepreg frictional resistance dictates honeycomb core crush, a core crush resistant prepreg can be developed by increasing its frictional resistance. Based on the principles of friction, higher frictional resistance can be achieved by increasing the undulation or roughness of the contact surface, reducing the amount of lubricant on the dry surface, or selecting a different lubricant system. For fabric-based prepreg materials, these factors translate into rougher dry fabric surface, less resin on prepreg surface, and a resin system with different rheology/cure behavior, respectively.

Based on these understandings, it can be deduced that rounder fiber tows as shown in Fig. 6 result in a rougher dry fabric surface (higher undulation degree) and, thus, yield higher prepreg frictional

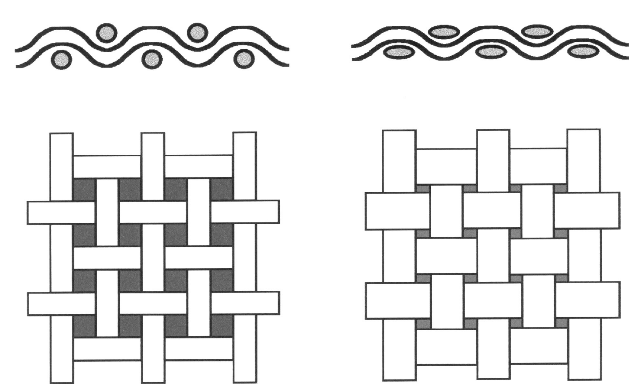

Fig. 6 Round vs flat shape tow and their respective openness degrees.

resistance to better resist core crush. In addition, rounder fiber tows create a more open fabric architecture that promotes mechanical interlocking or nesting between prepreg plies (as will be shown later) to further increase prepreg frictional resistance. Another surprising advantage of the rounder tows is that they allow better impregnation in fiber bundles during prepregging, thus leaving less resin on the prepreg surface. This leads to lower surface lubrication and, thus, greater fabric contact to the benefit of the prepreg frictional resistance.

Various methods can be used to manipulate or modify the fiber tow shape and, therefore, the fabric architecture of a prepreg to the desired levels. Examples of such methods include, but are not limited to, sizing the tows before weaving, tow twisting, tow twisting and untwisting, varying the cross-sectional shapes of the individual filaments in the tows, or employing various other modifications of the tow forming, weaving, prepregging, or postimpregnation process.

One way to modify the fiber tow shape is to twist or twist/untwist the tow mechanically to a desired extent. A twisted tow means a tow that is twisted during the carbon fiber manufacturing process with the degree of twisting, that is, the number of turns per unit length, varying with the tow shape desired. This twisting process can occur either before or after the carbonization of the precursor filaments. Typically, twisted tows have a rounder tow shape following weaving. An untwisted tow can be achieved by untwisting an already twisted tow by winding the twisted fiber filament bundle or tow in the opposite direction to a desired degree. For example, precursor filaments can be carbonized after twisting and then untwisting thereafter. Such twisting and untwisting can be optimally performed at different stages of the carbon fiber manufacturing process involving the precursor forming and the subsequent carbonization.

Another method of reaching a desired tow cross-sectional shape is by chemically sizing the tow. Sizing refers to a process that includes coating or impregnating a tow after carbonization with a suitable sizing agent (usually diluted in solvent or water) to fix or substantially fix the fiber tow shape. Various drying methods to remove the solvent or water can be used after the sizing agent is applied, including, for example, drum drying, air drying, and air blowing. Such drying methods may also affect the cross-sectional shape of a fiber tow.

Cross-sectional configurations of the individual fibers or filaments in the tow can also affect the filament entanglement and, thus, the tow shape. For example, individual filaments with a kidney- or pea-shaped cross section have been found generally to form a bulkier tow following weaving and impregnation as compared to an otherwise identical tow with filaments having a round cross section.

Experimental

A. Materials

In this study, various techniques such as twisting, twisting–untwisting, and sizing were employed to manipulate or modify the fiber tow shape to the desired levels. The carbon fiber tows studied were all of the 3K type, where 3K means 3000 filaments in each tow strand. After tow forming and sizing, different drying methods such as drum drying, air drying, and air blowing were used for evaluation. Plain weave fabrics made from these 3K carbon fiber tows were impregnated by the solution method. Fiber areal weight of all fabrics studied was in the range between 180 and 205 g/m^2. The resin system used in this study was a rubber-modified epoxy with relatively low flow.

B. Characterization of Fiber Tow and Prepreg Architecture

As the fiber tow gets rounder, the prepreg generally becomes more open, thicker, and less tacky (less resin on surface). Three parameters were found to be a good indicator for predicting core crush and can be used to define prepreg requirements: average fiber tow aspect ratio in prepreg, prepreg openness, and prepreg thickness. These parameters well represent the prepreg architecture and, thus, strongly correlate with the prepreg frictional resistance and core crush. When maintained within certain ranges, they can allow sufficient frictional resistance developed between prepreg plies to restrain them from slipping during autoclave curing and thereby eliminate or minimize core crush.

The three parameters mentioned were evaluated using the test methods developed previously.[8,9] This way, prepregs can be screened to determine their tendency to cause core crush during manufacture. For each prepreg material, several pieces of prepreg were randomly chosen from different locations and several measurements were taken for each piece. The average of these measurements gave the reported values for each material.

Method of Measuring Prepreg Openness

A piece of prepreg was laid flat under a microscope with transmitted light passing through the prepreg from under. An image, showing the prepreg and its openness as black and white, respectively, was viewed by a video camera, which transmitted the image to the image grabber of a computer. The image was then converted into a rectangular array of integers, corresponding to the digitized gray level of each pixel. An image analysis program (Optimas 6.2) was used to process this digital image information and represent it in the form of a gray-level histogram. In this case, two distinct groups, corresponding to the prepreg and openness, were found in the histograms. These two groups were easily separated by a simple thresholding process. The prepreg openness was, thus, obtained as the percentage ratio between the number of pixels corresponding to the group associated with openness and the total number of pixels in the image.

Method of Measuring Prepreg Thickness

Prepreg thickness was measured by a thickness gauge. The apparatus contained a thickness gauge with a 6.45 cm^2 (1-in.^{2}) presser foot and a 2.27-kg (5-lb) dead weight on it. This was equivalent to approximately 34.47-kPa (5-psi) pressure applied to the specimen when a measurement was taken.

Method of Measuring Fiber Tow Width and Thickness in Prepreg

The width of a fiber tow strand was determined by the light-transmission method as described earlier for determining prepreg openness, except that high magnification was used in this case to increase the measurement resolution. Fiber tow was magnified in such a way that its width covered most part of the image. Fiber tow width was measured by simply drawing a line to cover the entire fiber tow width and the Optimas 6.2 program automatically calculated the length of this line based on the saved calibration data.

Similarly, to measure the fiber tow thickness, a piece of prepreg was carefully cut with a surgical scissor along the centerline of fiber tows. The thickness was then measured in a way similar to that for measuring the width of a fiber tow strand.

C. Core Crush Discriminator Panels

For evaluation of core crush degree, test panels as shown in Fig. 7 were produced. A core crush discriminator panel consists of 711 × 610 mm (28 × 24 in.) composite skins and a 610 × 508 mm (24 × 20 in.) 48 kg/m^3 (3 lb/ft^3) Nomex core (Hexcel HRH-10 or equivalent) with a 20-deg chamfer angle. The type, direction, and dimension of the prepreg plies and the honeycomb core are specified in Ref. 10. For curing, the panel was first placed in a vacuum bag. The vacuum bag and the panel were then placed in an autoclave. The bag was evacuated by a vacuum pump and cured under pressure at an elevated temperature. The detailed curing cycle may be found in Refs. 8 and 9.

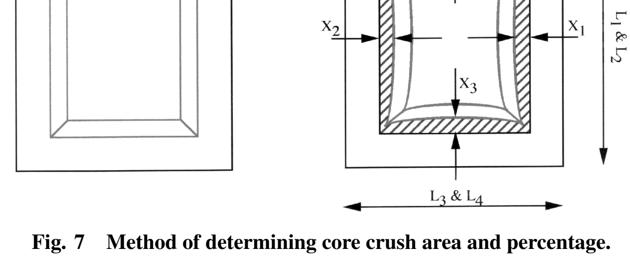

Fig. 7 Method of determining core crush area and percentage.


Fig. 8a Rounder shape tow (left) vs flat shape tow (right).

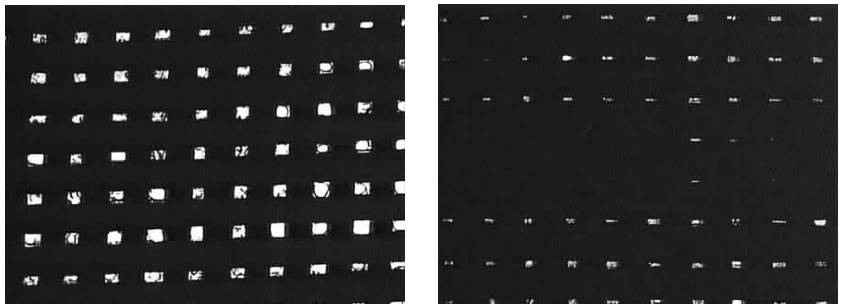
Fig. 8b Fabric openness degree in prepreg.

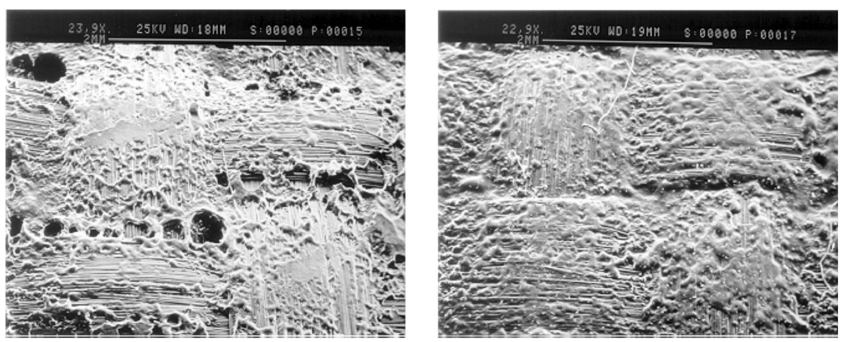

Fig. 8c Surface resin on prepreg surface.

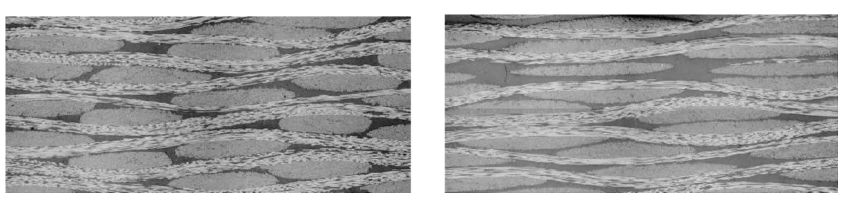
Fig. 8d Microstructure in cured panels.

The dimensions of the cured core crush panel were measured as shown in Fig. 7. ***X*** is the displacement at the center of the core side from its original position. ***L*** represents the original length of the core side. The crushed area A was calculated according to the formula

$$A = \sum_{n=1}^{4} \frac{2}{3} \cdot X_n \cdot L_n$$

The degree of core crush in percentage was determined by the following formula:

$$\text{percent core crush} = 100 \times \text{A}/480$$

Results and Discussion

A. Fiber Tow Shape in Prepreg vs Prepreg Openness

The photomicrographs in Fig. 8 show the different tow and fabric architectures of a rounder tow vs a flat tow. A rounder tow with its cross-sectional view shown on the left side of Fig. 8a has larger thickness and smaller width than a flat tow, resulting in a rougher surface topography and thus higher frictional resistance. Rounder fiber tows also result in more open fabric architecture (Fig. 8b) to promote more mechanical interlocking or nesting between prepreg plies and further increase prepreg frictional resistance. Such a mechanical interlocking effect can be observed in the cross-sectional view of a test panel (without core crush) shown in Fig. 9, where the opened areas between the tows of one ply, indicated by arrows, locked and trapped the tow crossover (peak/valley) points of its neighboring plies and vice versa.

The trend of increasing tow thickness with reduced tow width (increased openness) is sufficient, but not always necessary to increase prepreg frictional resistance. Through tow shape manipulation by some special techniques, it is possible to create the tow shape that is sufficiently wide and yet sufficiently thick to favor high friction with reduced openness. This would give an additional degree of freedom in designing fabrics to meet requirements in the design and fabrication of composite honeycomb sandwich structures.

B. Fiber Tow Shape in Prepreg vs Prepreg Surface Resin

The scanning electron microscope photomicrographs in Fig. 8c show different amounts of resin covering the prepreg surface for fabrics with rounder tows vs flat tows. The resin in the rounder tow case is forced more into the fabric opened areas, as well as the fiber bundles, leaving less resin on the prepreg surface. Dryer prepreg surface in this case results in lower resin lubrication effect and allows for greater fiber contact between adjacent prepreg plies to increase friction. In contrast, flat tows cause reduced degree of fabric openness and more resin retained on the prepreg surface. This in turn leads to a more pronounced lubrication effect due to excess surface resin to promote slipping between plies during autoclave

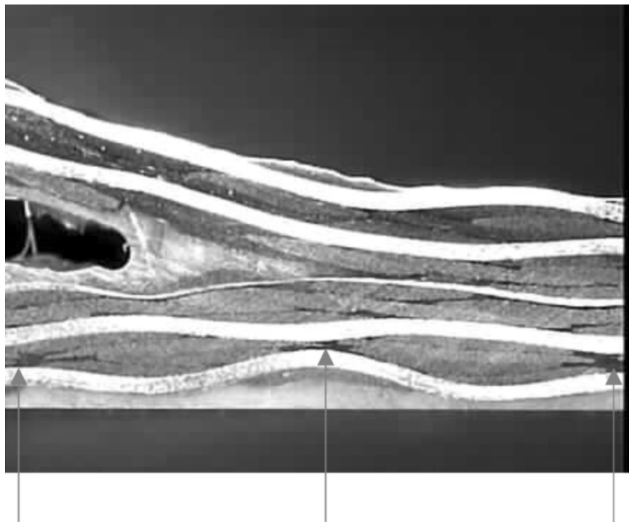

Fig. 9 Mechanical interlocking due to the presence of openness (indicated by arrows).

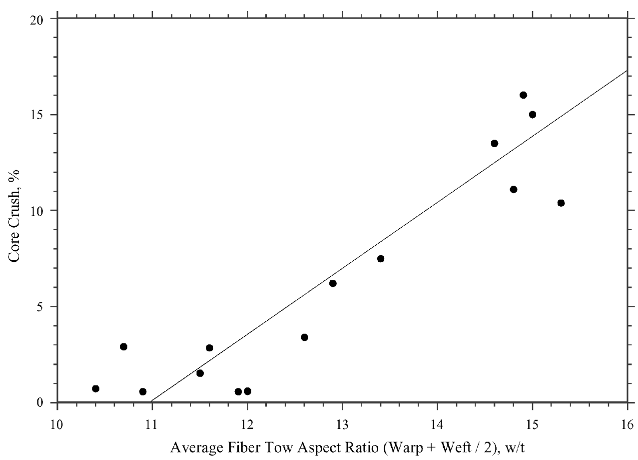

Fig. 10a Core crush as function of fiber tow aspect ratio in prepreg.

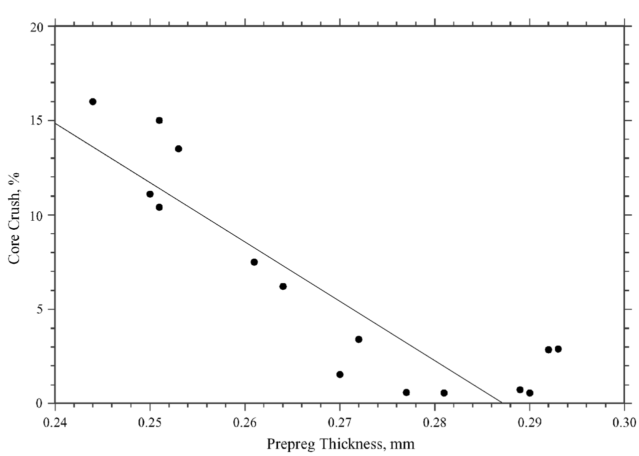

Fig. 10b Core crush as function of prepreg thickness.

cure. Because of the different surface resin amounts, prepregs made from the flat tows are noticeably tackier than those made from the rounder tows.

The photomicrographs in Fig. 8d show the microstructure with all of the earlier mentioned characteristics frozen into the final cured laminates. The rounder fiber tows on the left side indeed show greater fabric contact, more mechanical interlocking, and less surface resin between plies after autoclave cure.

C. Fiber Tow Shape in Prepreg vs Core Crush

Figures 10a and 10b show the degree of core crush against fiber tow shape parameters, average tow aspect ratio and prepreg thickness, respectively. For various prepregs studied here with the same resin and fiber type, the degree of core crush decreases almost linearly with the decrease in tow aspect ratio (Fig. 10a) or with the increase in prepreg thickness (Fig. 10b). As shown in Figs. 10a and 10b, both the average tow aspect ratio and prepreg thickness correlate well with the degree of core crush. This clearly shows the rounder the fiber tow is, the less the tendency for core crush. Various approaches (not identified for proprietary reasons) were used in this study to manipulate the tow shapes reflected in the data points of Figs. 10a and 10b. Figures 10a and 10b indeed demonstrate that core crush is strongly connected to the fiber tow shape regardless what tow manipulation techniques are applied. The tow and fabric architectures being physically related to the prepreg surface roughness ultimately control prepreg frictional resistance and, thus, core crush. As long as the final fiber tow shape is maintained at certain levels, the possibility of core crush can be significantly reduced.

Although the prepreg thicknesses varied within a substantial range as shown in Fig. 10b, the variations of the final cured laminate thickness were not significant. This was likely due to the meshing or nesting effects of weave peak/valley between adjacent prepreg plies. As a result of such effects, the tow and prepreg thickness variations were smoothed out after autoclave cure to reach more or less the same cured laminate thickness.

The strong dependence of core crush on tow aspect ratio also has important implication on fiber tows larger than the 3K type. Such

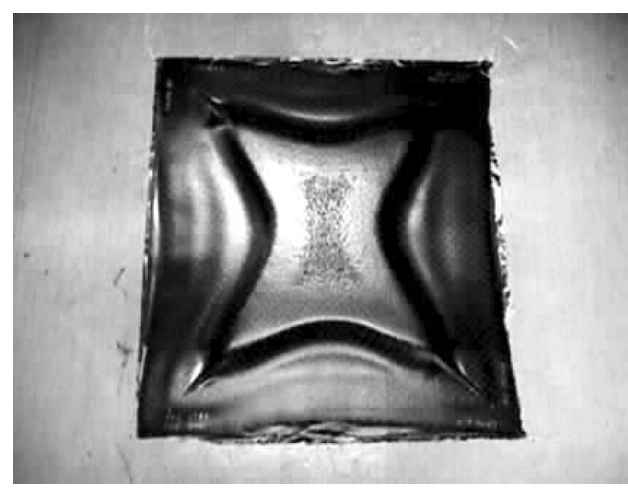

Fig. 11 Sandwich panel with 12K fiber showing core crush of approximately 50%.

Fig. 12 Sandwich panel using developed core-crush resistant prepreg yielding 0% core crush.

large tows, for example, 12K, 48K, are expected to give substantially higher core crush than the 3K fiber if the resin were kept the same. This is because the fabric surface roughness would be dramatically reduced with the increase in tow filament count to lower the prepreg frictional resistance. Limited tests performed in this study showed that a prepreg with 12K fiber tows (aspect ratio of 60) and the same resin as the one used for the 3K fiber-based prepregs produced a high core crush value of approximately 50% (Fig. 11). This again demonstrates that the tow and fabric architectures are truly important factors in controlling core crush.

Based on understanding of the results reported, a core crush resistant prepreg was developed through manipulation of fiber tows to a rounder configuration, which has the target tow aspect ratio at around 11. Figure 12 shows a test panel using the developed core crush resistant prepreg (tow aspect ratio 11, prepreg thickness 0.28 mm, and prepreg openness 5%) successfully eliminates core crush.

Conclusions

In this study, the mechanisms controlling the core crush sequence were clarified at the individual ply level. It was shown that the prepreg frictional resistance is the key factor in controlling core crush. Based on such understandings, conceptual approaches in solving the core crush problem were formulated. Without changing the resin in prepregs, these approaches manipulated fiber tows to a rounder configuration that promoted rougher prepreg surface and, thus, yielded higher prepreg frictional resistance to reduce core crush. Excellent correlation between the fiber/fabric architectures and core crush test results validated the conceptual approaches in developing prepregs to effectively resist core crush.

Acknowledgments

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