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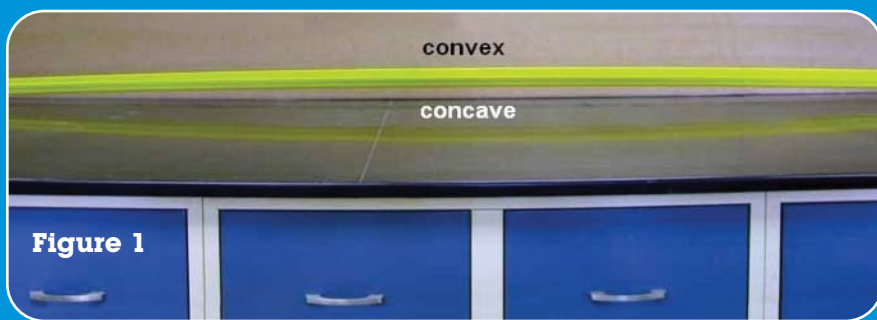
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When Pultruded L

By Kevin Spoo

Bow or camber in composite parts is a problem molders fight every day. This occurs as a result of resin shrinkage being constrained by reinforcements used in the part construction. Resin degree of cure, shrinkage, part shape, fiber volume percent, and fiber orientation are five factors that determine which way the part moves as it cures.

In the pultrusion process, die drag, pre-former alignment, puller pad alignment, and creel tension typically override the five factors previously mentioned. This list of parameters is not exhaustive but it should demonstrate issues unique to pultrusion. Of course, line speed, peroxide package, internal mold release, and filler content can affect bow and will be briefly discussed, but for now they will be lumped in with the resin system. Figure 1 shows an all too familiar and unpopular sight.



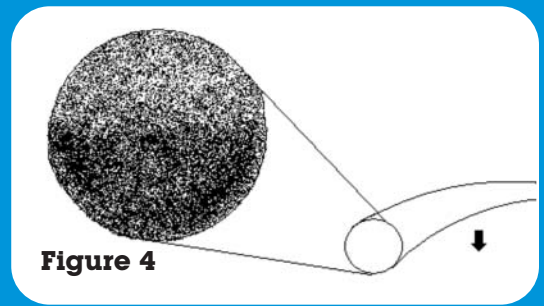
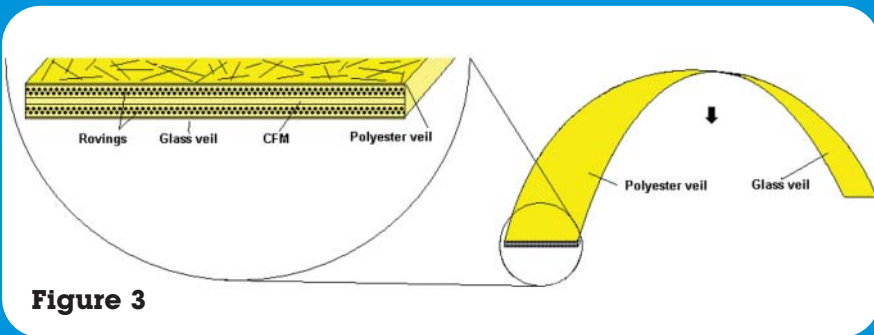
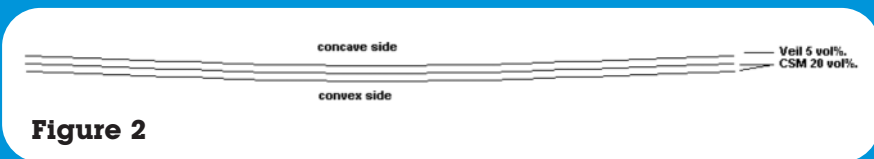
An example of bow we are all familiar with is that of the unbalanced laminate (see Figure 1). The resin-rich side of the laminate containing the veil has higher resin content (lower glass content) than the other side of the laminate. When the resin shrinks, the veil side is unable to constrain the

shrinkage as effectively as the CSM (chopped strand mat). Therefore, the laminate shrinks more on the veil side. This causes a bow in the laminate with the veil side being on the concave side of the laminate and the CSM on the convex side.

Dominate factors

In the pultrusion process, other factors dominate how a laminate bows. As the resin impregnated reinforcement bundle enters the die, there is considerable hydraulic action at the entrance of the die as excess resin is squeezed out of the bundle. This creates a straining of fibers on the outside perimeter of the fiber bundle. While the bundle is inside the die, heat causes an expansion

Parts Take a Bow



of this bundle and gelation of the resin. The rubbing of this gelled resin creates considerable drag inside the die and straining of the fibers until ultimately the resin becomes hard enough and releases from the die wall.

Figure 2 shows an example of this effect. In the case of this flat unbalanced laminate, both the upper and lower surfaces of the laminate “see” the same amount of drag in the die. This drag is actually a load on the fibers causing them to strain slightly. The strain occurs on both sides of the laminate but is more effectively transferred to the unidirectional fibers in contact with the surface of the die than with the unidirectional fibers located underneath the CFM (continuous filament mat) on the other side of the laminate. When the laminate exits the die, gets beyond the puller pads, and cools, all fibers will want to relax to a stress-free state as the resin shrinks. The unidirectional fibers on the surface (having been strained the most and having the highest volume percent of fiber at the surface) will dominate the movement of the laminate so that when they relax (shorten) they will be on the concave side and the CFM will be on the convex side. This is opposite what we might expect in a press molding operation.

Figure 3 shows another example. In this case we use the same flat laminate but arrange the fiber in a more balanced lay-up. However, on one side of the laminate is a glass veil and on the other side of the laminate is a polyester veil. Assume in this case that both veils occupy the same volume in the laminate. The glass fiber veil results in considerably more drag in the die, but it also does a good job of keeping the die surface clean. The polyester veil results in less drag in the die but is

sometimes prone to sloughing. Because of this higher drag on the glass veil side of the die, the fibers underneath the veil see more strain than the fibers underneath the polyester veil. When the part exits the die and all fibers relax, the part will bow with the glass veil on the concave side and the polyester veil on the convex side. This occurs despite the higher polymer content on the polyester veil side.

Changing glass fiber mats

An interesting experiment a pultruder can do to determine the magnitude of drag and how much it affects bow is to run a thin piece of Teflon through the die on one side of a balanced laminate. The side with the Teflon will see little drag whereas the other side will see a typical amount of drag. After the part passes through the die, puller pads and saw, remove the Teflon and the part will bow with the Teflon on the convex side. This is an easy way to get a qualitative idea of how much die drag contributes to bow versus other contributing factors such as pre-former alignment, puller pad alignment, laminate lay-up, etc.

A very real phenomenon often seen in the pultrusion operation is the effect of changing glass fiber mats. Glass fiber mat varies in a number of ways, but three of these features can have a dramatic effect on bow fiber orientation, fiber loft, and mat weight. Fiber orientation can be as high as 60 percent in the transverse direction with one product while another vendor’s mat will have only 40 percent orientation in the transverse direction.

With orientation playing a big role in bow, changing mat products can have profound effects. Secondly, loft that affects glass fiber content and hydraulic action at the die entrance affects bow. Loftier mats will have less glass fiber volume in the area of the part they occupy but will usually require a bit more effort to squeeze out resin at the die entrance.

This difference is best seen in commonly available A-glass vs. E-glass continuous filament mats. Glass fiber mats are available in a variety of areal weights. Designing a part for a 1oz./ft² mat and then changing to a 1.5oz./ft² will most certainly have an impact on bow of a non-symmetrical part. Fiber diameter and the degree to which the fiber bundles are filamentized will affect bow.

Asymmetrical parts

Before moving on to asymmetrical parts we should look at one more example of bowing in pultruded parts that may not be obvious. Figure 4 shows a 3/8-inch round rod. Let us assume the creel rack has minimum tension and a low viscosity resin with a higher temperature peroxide is used. The pultruder has gone to exceptional lengths to align the puller

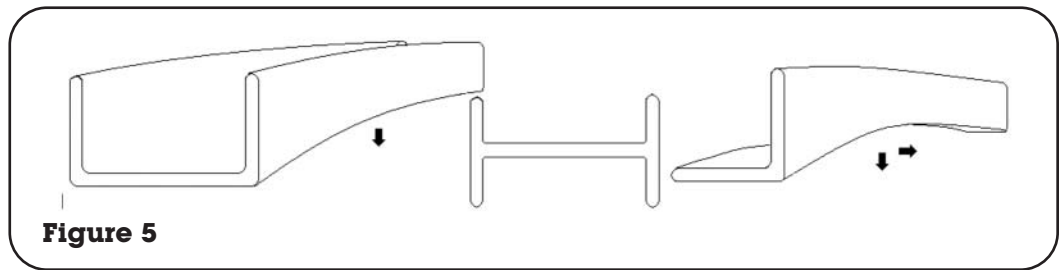


Figure 5

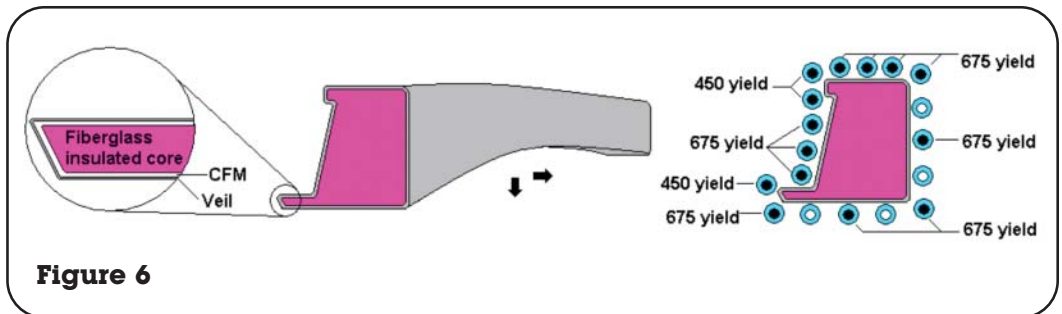


Figure 6

pads, die and pre-former, yet the rod still has a downward bow.

What has happened in this case is the heat of the die resulted in a terrific viscosity drop prior to gelation. Gelation has been prolonged by the use of a higher temperature peroxide. In the interval while the resin is still liquid, some glass fiber settling occurred causing the bottom half of the rod to have slightly higher glass content than the upper part of the rod. The drag created by pull force is equally distributed around the rod, but the higher volume of fibers on the bottom mean that more fibers are strained on the bottom than on the top of the rod.

As a result, the rod has a downward bow. There are many corrections for this type of problem, including the addition of clay to reduce fiber settling, use of a "hot" peroxide to reduce resin liquid time (shorten gel time), or the use of off-set pre-formers or puller pads.

The same principles discussed earlier apply to asymmetrical parts, but the asymmetry of the part plays a major role in part bow. Owens Corning's experience making window lineals in the mid-1990s provided a unique opportunity to understand this phenomenon.

An example most pultruders will recognize are three familiar shapes shown in Figure 5. Assuming a balanced lay-up and perfect alignment the parts will bow as shown in Figure 5.

The channel is symmetrical about the vertical neutral axis but unsymmetrical about the horizontal neutral axis. More fibers are stressed below the horizontal neutral axis of the channel than above so the part will exhibit a bow with the web on the concave side and the upper part of the legs on the convex side. If the web of the part was shifted toward the center of the legs of the channel and thus forming a beam shape, stresses would be distributed evenly and no bow would occur.

The same is true for the angle. It is unsymmetrical about both horizontal and vertical axes. Considerably more stress occurs below the horizontal neutral axis of the angle (similar to the channel) and also to the right of the vertical neutral axis. This is where one would expect the concave side to be due to the high stress on that side. Thus the angle bows in two different directions.

The solution to fixing bow in these parts is to run an unbalanced lay-up, offset puller pads, or offset pre-formers. Other solutions can reduce bow but often compromise other aspects of processing, part design or performance. These include slowing the line speed, reducing glass reinforcement levels, and lowering resin viscosity or using "hot" peroxides.

The fact that a part continues to cure and cool between the die and the puller is an advantage that reduces bow, but the stresses still remain



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“locked” in place by the resin. Some of these solutions seem like good fixes at the time but as soon as the pultruded part goes through some additional heat cycle like a paint bake, it may come out looking like a pretzel or spaghetti.

Making a straight unsymmetrical part with an unbalanced lay-up is most easily demonstrated with the following example. During the making of window lineals in the early 1990s, Owens Corning realized that increasing line speed would result in part bow. The part shape could not be changed, surface quality could not be compromised, there was very little reinforcement in these parts (see Figure 6) and there was no unidirectional reinforcement. With geometry similar to the angle described earlier, the lineal bowed as shown.

The solution proved to be unique, but the underlying concept can be applied to all pultrusions. Knowing that unidirectional rovings have the greatest effect on bow, rovings were incorporated in the part design opposite the concave side of the part.

The right-hand portion of Figure 6 shows the spacing of the eyelets through which rovings of various yield were run. Filled holes represent a roving. Unfilled holes represent a blank space. Roving yields are indicated. Very high yield (low tex) rovings were chosen so as to not “print” through the window lineal. After roving placement, continuous filament mat was wrapped around the perimeter of the shape. Proper spacing of the rovings could resolve any bow inherent in the design of the various window lineal shapes.

An added advantage was that placement of rovings in the corners reduced sloughing in those areas prone to this phenomenon. Operator training and flexibility of roving spacing meant that as other raw materials varied (specifically the core), operators could move the rovings around to maintain straightness specifications. In this case the spec required a bow no greater than 1/8-inch per 8ft. lineal. Correcting the bow problem allowed line speeds to be increased from 3 to 6ft/min. because the chemistry was already robust enough to allow this.

Stitched fabrics & carbon fiber

In addition to unidirectional glass fibers, glass mats, and veils, some pultruders will use stitched fabrics or carbon fiber. The CTE (thermal coefficient of expansion) of carbon and glass are dramatically different and thus affects bow differently as the pultruded part cools. Certain fabric constructions can actually induce a true “twist” in a part rather than simply a bow in two different directions. These product types present some unique problems/solutions that are beyond the scope of this article but which the reader should be aware.

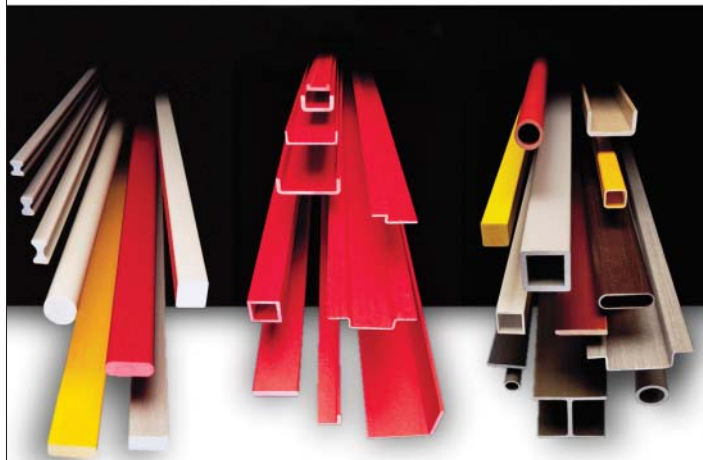
A simple tool we used to measure die drag and correct bowing problems is a pull force gauge. Without this tool, attempts to quantify other process changes intended to correct bow would have been futile. There are almost as many designs for pull force gauges on pultrusion machines as there are process engineers to design them, so I won't attempt to elaborate more on this.

Most of the discussion has focused on the principles of how bow is induced in pultruded parts and how to correct certain situations. Stress induced bow can be reduced in many other ways not previously discussed. Proper mold release selection, creel tension, die entry radius, die surface smoothness, temperature profile, resin selection, filler selection, etc. affect bow not only on the pultruded parts already discussed, but all pultruded parts. **CF**

Kevin Spoo is a senior scientist at Owens Corning. Prior to OC, he worked for Phillips Petroleum on thermoplastic pultrusion and as a resin chemist for several resin companies. He spent six years with a major pultrusion company: 740.321.7772; kevin.spoo@owenscorning.com.



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