Composite Laminates

Theory and practice of analysis, design and automated layup

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Preface

Laminate design has always been a mystery to us. How is it done, we would ask designers. Their answers are often, very complicated. But that was not the question. In this book, we will try to make it understandable and make it simple.

In the early 1960's when boron and carbon composites were discovered, engineers in aerospace companies decided to make laminates out of 4 ply angles; 0, ±45, and 90. Then there were a number of rules to further define how these ply angles must follow. Examples include having mid-plane symmetry (to avoid warping), the 10 percent rule (to ensure at least one ply for each angle), balanced laminates (to maintain orthotropy, no anisotropy), ply drop to be done with mid-plane symmetry (thus 2 symmetrically located plies to be dropped at one time), and so on.

As a result, the sub-laminates with any degree of orthotropy are 6 to 10 ply thick, elements with different ply composition cannot be easily reconciled, ply drop is a major challenge, optimization is not possible, there is no easy answer to how much weight is saved, and the cost of manufacturing soars. In addition, the structure can be overweight, weaker, and prone to delamination. We intend to reduce these risks.

Stress analysts will determine the internal loads and the stacking sequences of the sub-elements within each element of a structure. Designers working with CAD would try to produce this composite structure using the best manufacturing processes available to them. They will have to match the desired laminates as their thickness and ply orientation change between elements. This process is complicated as rightfully claimed by designers. There are too many ply angles, too many stacking sequences, and it is difficult to drop plies, and too complicated to reconcile differences in laminate design between elements. It is impossible to optimize. We will propose a new method.

In our book, we have taken a different approach for the design of composite laminates. We can simplify the process if we use fewer angles, fewer plies, fewer constants, and cross-ply layup only. For example, our discovery of trace with respect to carbon composites, described in Chapter 1, gave us the mathematical foundation to separate material from geometry entities of a laminate. Trace is the one and only constant to represents material, and ply composition such as [0/±45/90] is purely geometric and can be represented by a universal trace-normalized stiffness matrix. This universal values work for all modern composites except glass composites. For laminate stiffness one constant will be sufficient, need not be 4 for the usual unidirectional ply.

Failure, as described in Chapter 2, is no longer dependent on ply orientations if we use omni failure envelopes. The most conservative inner envelope will cover all ply orientations. This envelope is isotropic. So we can convert regular strain to principal strain. Thus one omni envelope in principal strain space is invariant and the unit circle criterion is just the circle that passes through the normalized principal strain failure values under uniaxial tensile and compressive strains. Only 2 strength parameters are needed, not 5 or more for the most popular failure criteria. We also use a strength ratio R (similar to a safety factor) to scale the thickness of every point in the structure (as in Chapter 6). With these simplified and conservative methods, laminated structures can be sized in a straightforward manner and the best laminates listed by routine sorting (ranking) based on weight savings over aluminum and ease or cost of fabrication. A further simplified version is to use the lower of the tensile and compressive failure strain. Then the unit circle criterion has only one parameter (not two). With that, flex test of [0] or [0/90] coupons will be sufficient to tell us the value of trace and the safe working or failure strain. Good enough to proceed with design, so much more agile to reach the optimum than the conventional that carries the burden of 4 stiffness, 5 strength, and hundreds of coupons.

In Chapter 3, we propose the use of as few ply angles as possible, 3 or 2 instead of 4. With reduction in ply angles, the thickness of sub-laminates will reduce also. Laminates with different ply angles can be substituted, some exactly and others approximately. We also recommend the use of thin plies. One regular ply can be replaced two or more thin plies. For example, with two thin plies and two angles, one bi-axial ply can be [±35]. Such bi-axial ply is available from Chomarat for many enclosed angles. Then instead of sub-laminates in 6 to 10 plies, they can have them in 1, 2, or 3 plies.

Laminate homogenization through the thickness direction is most easily achieved with stacking of the same sub-laminates, say, 8 or more times. With thin plies, homogenization is easier to achieve. Not so much for 6 to 10 ply ones. Homogenized laminates are automatically symmetric. Mid-plane symmetry is no longer necessary. Ply stacking can be continuous or do not pause at the mid-plane. Such stacking is faster and less prone to error. More importantly, ply drops can be done one at a time, not two symmetrically. Single ply drops can be located anywhere in the laminate, in the middle or at the outer surface. It is no longer complicated. Patches can be placed in any location if the same sub-laminate is used.

In Chapter 4, a special case of laminate architecture in grids is covered. Composite grids are totally different from aluminum grid because composite ribs are made of unitape while aluminum ribs are the same aluminum as the base plate. A factor more than 4 in specific stiffness is in favor of composite grids because of this. We have found that bi-axial [±35] grid with [±80] skin to be competitive in many applications. In addition, the use of a bi-material tape can produce interlocked grids with inherent damage tolerance not possible with conventional laminates. This patent pending process is unique that requires no special machine and tooling, and produces two continuous phases of grids integrally interlocked. It is now possible to mitigate the severe penalty for lack of damage tolerance imposed on conventional laminates.

In Chapter 5, the tapering of beams is covered. With homogenization, the optimum profile can be easily determined. In fact, the starting material for this profile determination should be that of a metal like aluminum. For composite beams, the same profile would be optimum in weight-savings for a fixed deflection. A cosine function to certain exponent has often been found to be optimum. It results in a drastic taper with a ratio of the thickest to the thinnest by 4 or more, difficult to achieve if the beam is not homogenized. Combined with thin plies, transition between zones with different ply layup is made easy. For regular plies with sub-laminates with 6 to 10 ply thick, smooth transition becomes very difficult to accomplish. Master curve relations for beams have been found between weight savings and trace. It makes design as simple as scaling. Such relations have been found for both statically determinate and indeterminate beams.

In Chapter 6, an approach for laminate selection based on trace and on a unit circle failure criterion is described. Only 3 constants are needed (trace, plus tensile and compressive strengths), not 9 or more. A total of 131 independent laminates based on 29 quad-axial sub-laminates, 3 families of 20 of tri-axial sub-laminates each, 15 bi-axial sub-laminates, and 27 Stanford 2-roll sub-laminates (all described in Chapter 4) were analyzed for a give structure design for different loading cases. The resulting weight of each laminate are sorted by descending order. The best laminate can be identified based not only on the weight but also on the number of plies of the sub-laminate, number of ply angles, cross-ply ratios, and other considerations. This fully automated procedure has features that the conventional optimization may not have; namely, all 131 laminates are ranked, not just one that is the lightest in weight. Also other design considerations such as the number of plies and others have direct impact on the strength and toughness of the laminate as well as the ease of fabrication.

In Chapter 7, the utility of a proprietary mesh generation software, TrueGrid, for composite structures is described. Mesh for composite structures must be consistent with automated tape laying, fiber placement, and tape winding machines. The same mesh will be used for stress analysis. This will make composite structure more likely to be laid up that is consistent with the designed stress and weight distribution. This mesh is simple to adopt so taper can be done by scaling, and is no longer conceptually complicated.

In the e-book version of this book, tools for design and testing are provided for students to master the subject matter at the end of each chapter. These tools can generate data on many important characteristics of composite materials and structures. Nearly all figures in our book are generated with these tools. Transformation properties, optimum laminate and grid design, and sizing of beams, shafts, plates, and vessels provide good examples of learning. Proficiency in using these tools builds confidence in composite materials, and power to present ideas to win proposals.