# Design of Composite Laminates

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Laminate selection is one of a critical keys in making composite materials competitive with other materials and processes. We have discovered several aspects in this design procedure that can make composite laminates better in many aspects. The traditional use of 0, ±45 and 90 with rules that require 10 percent minimum of each ply angle, and mid-plane symmetry have created sub-laminates up to 10-ply thick, such as a hard laminate in $[0_5/\pm 45_2/90]$ and soft laminate in $[0/\pm 45_4/90]$. Optimization of such thick laminates becomes impossible because the permutations of stacking sequences are over 20,000. The use of tri- and bi-axial fabric/tape offers new opportunities to achieve through-the-thickness homogenization leading to higher strength and delamination-resistant laminates. With trace, master/universal laminates are easily derived, and it makes stress analysis, and ranking of sub-laminates in place of optimization straightforward. Thus a new way of display the best sub-laminate has been automated and is only one-click away. The stiffness of unidirectional composite needs trace as the only one data point for stiffness; and its uniaxial tensile and compressive strength, the only two needed for ultimate strength prediction. This criterion is based on a unit circle approximation of the traditional failure criteria that require nearly a dozen data points. For each boundary-value problem, solution is required for each laminate. When master ply data are used, each laminate solution will be valid for all carbon fiber reinforced plastics (CFRP). Traditional testing for design allowable that requires thousands of coupons can now be reduced to one data point for stiffness, and two for strength. Emphasis is not placed on the difference between pristine coupons made in laboratory, and as-built coupons taken from composite component. There will be constraints in the shape and size of as-built coupon and will limit the type of loading that can be applied. As-built coupon will provide more realistic data for containing manufacturing defects. Trace and resulting master/universal ply will provide a better framework to make the comparison between pristine and as-built coupons. Finally sub-laminates are chosen from 6 families: 1) 29 members from traditional quad-axial in 0, ±45, and 90 ply angles with 6-, 8-, and 10-ply thick; 2) 20 members each of 3 tri-axials in 0 and ±$\varphi$ with three ratios of thicknesses between the ply angles (thus total of 60); 3) 25 members for bi-axials; and 4) 17 members of a starter set of combinations from [±10] and [±35]. A total of 131 sub-laminates have been programmed to rank their relative performances in terms of weight savings relative to aluminum, strength, and speed of fabrication with just one click. It is revealing to us that the best laminates are those with bi-axial and their derivatives. The quad-axials for having sub-laminate thickness up to 10 plies turn out to be worse than tri-axial with intermediate thickness; and tri-axial worse than bi-axial having the lowest thickness. It is therefore a hopeful situation that if we just abandon the traditional quad-axial sub-laminates composite laminates can be more competitive than realized by many of us. For material and processing specialists, having a simpler screening test with one panel of [0] or [0/90] to demonstrate their improved structural performance. Material data sheet can be much quicker to generate and conveys more information (i.e., for all laminates under varied environmental conditions). For design engineers, homogenized laminates are symmetric. Such laminates no longer need mid-plane symmetry. Ply drop can be done at any location along laminate thickness. No longer need two ply drop to occur with mid-plane symmetry. Laminate tapering will be much easier to achieve. For fabricators, continuous stacking without concern of reserve stacking at the mid-plane is easier, faster, and less prone to error. Tapered edges that will reduce edge delamination failure mechanism can be more easily achieved with homogenized laminates. Finally a Stanford proprietary starter set of two bi-axial fabric/tape of [±10] and [±35] cited earlier can reduce stock and storage costs. This starter set can generate sub-laminates with not more than 3-ply thick with 27 highly diversified sub-laminates that can adequately match the traditional 29 quad-axial sub-laminate (which has 6- to 10-ply thick) and other tri- and bi-axial. Such starter set can make high performance composite laminates affordable for large and small organizations.

**Short Biography**

**STEPHEN W. TSAI**

Born in Beijing, July 6, 1929

1961 D.Eng. in Mechanical Engineering, Yale University

1952 B.S. in Mechanical Engineering, Yale University

1990-Present Professor Research Emeritus, Aeronautics and Astronautics, Stanford University

1968-1990 Director of Mechanics of Composites, Air Force Materials Laboratory

1966-1968 Professor, Washington University

1961-1966 Composite Materials Engineer, Ford Aeronutronic

1952-1958 Engineer, Foster Wheeler Corporation

Process and product development of composite materials that may lead to improved design practice and commercialization. His current interests include composite behavior as affected by static, creep and fatigue loading, and products like composite rotors for flywheel systems. Emphasis is on the design, manufacturing and evaluation of the performance and cost. Methodology and supporting software to provide safe service of 30 years under combinations of loads, temperatures and moisture. Also pioneering spreadsheet based composites design tools. His continuing projects (since 2007) include online composites design workshops, which provide intensive, live training to thousands of around the world.

Founding Editor of *Journal of Composite Materials*

Life Member US National Academy of Engineering

Life Fellow of American Society of Mechanical Engineers

*Introduction of Composite Materials*, with H. T. Hahn, Technomic, 1980

*Anisotropic Plates*, with T. Cheron, translated from Russian of book with same title by S. G. Lehknitskii, 1968

*Composite Materials Design and Testing*, with Daniel Melo, Stanford Composites Design Group, 2015;

*Design of Composite Laminates*, with Daniel Melo, Stanford Composites Design Group, 2017

Leadership to improve competitiveness of composites design, testing and manufacturing through science-based models and simulation tools to help research, training and education, and companies.  Composites will further fulfill their unique destiny in reduced weight and cost, unmatched durability and reliability of structures, not possible with metals.  Tsai-Wu is embedded in most commercial finite element codes.  More recent effort in C-Ply has presented to industry to alter many basic practices that have prohibited more optimum use of composites.  Most recent effort on invariant-based theory will further simplify design, testing and manufacturing.