Paradigm Academic Press
Innovation in Science and Technology
ISSN 2788-7030
MAR. 2024 VOL.3, NO.2

Composite Plate Optimization: Integrating Analysis Techniques and Design Iterations for Enhanced Mechanical Performance

Chunjin Ji[1]

[1] Digital Design and Manufacture, University of Edinburgh, Edinburgh, UK

Correspondence: Chunjin Ji, Digital Design and Manufacture, University of Edinburgh, Edinburgh, UK.

doi:10.56397/IST.2024.03.04

Abstract

This essay delves into the comprehensive analysis of composite plate behavior under various loading conditions, focusing on uniaxial loading and the effects of layup design on safety factors. Through a comparative study between Classical Laminate Plate Theory (CLPT) calculations and Finite Element (FE) analysis, discrepancies in stress and strain predictions are identified, attributing them to assumptions made in each method. Furthermore, the essay explores failure prediction using Tsai-Wu criteria and Maximum Stress theory, determining the safety of laminates under different loading scenarios. Additionally, Finite Element analysis is employed to assess the impact of layup design variations on safety factors, leading to recommendations for optimized designs. The limitations of FE models compared to physical tests are discussed, along with alternative approaches such as advanced manufacturing techniques and novel fiber architectures to further enhance safety factors and alter failure modes.

Keywords: composite materials, laminate plate theory, finite element analysis, layup design, failure prediction, fiber architectures, structural integrity

1. Analysis of Composite Plate Exposed to Uniaxial Loading

1.1 Compare CLPT Calculations with FE Analysis

Perform FE analysis and CLPT calculations of a quasi-isotropic composite plate [0/±45/90]s with a ply thickness of 0.2 mm subjected to a shell edge load of 300 N/mm. The ply stresses and ply strains of CLPT calculations and FE analysis are shown in the Table 1-2 and the difference is shown.

Table 1. The ply stresses of CLPT calculations and FE analysis

Stress	CLPT results (MPa)	FE Analysis results (MPa)	Difference
σ_{xx}^{0}	502.01	313.67	-37.50%
σ_{yy}^{0}	-0.29	-0.18	-37.93%
σ_{xy}^{0}	0	0	0
σ_{xx}^{90}	22.86	14.29	-37.50%
σ_{yy}^{90}	-149.58	-93.49	-37.50%
σ_{xy}^{90}	0	0	0
σ_{xx}^{45}	112.57	110.14	-2.16%
σ_{yy}^{45}	74.94	7.05	-90.59%
σ_{xy}^{45}	82.47	11.76	-85.74%

Table 2. The ply strains of CLPT calculations and FE analysis

Strain	CLPT results (%)	FE Analysis results (%)	Difference
ε_{xx}^{0}	0.359	0.22	-37.60%
ε_{yy}^{0}	-0.112	-0.07	-37.50%
ε_{xy}^{0}	0	0	0
ε_{xx}^{90}	-0.112	-0.07	-37.50%
ε_{yy}^{90}	0.359	0.22	-37.60%
ε_{xy}^{90}	0	0	0
ε_{xx}^{45}	0.124	0.08	-35.48%
ε_{yy}^{45}	0.124	0.08	-35.48%
ε_{xy}^{45}	-0.471	-0.29	-38.43%

The results show that the strains and stresses of FE analysis are lower than those in the CLPT calculations. In addition, it can be seen from the Table 1-2 that the difference of stresses and strains in the 0° and 90° plies by CLPT calculations and FE analysis is about 37%. The difference between the two methods for the 45° plies are about 35-38%, and the difference for the 45° plies for the axial stresses are only about 2%. However, the difference between transverse stress and shear stress in the 45° plies are quite high, approaching 100%. Both theories assume that the layers are bonded perfectly with no slip, where the strains of the plies are consistent.

The reason of difference is that CLPT assumes that a composite laminate is made up of a stack of thin, flat, and uniform plies bonded together and the stresses across the thickness of each ply are uniform. As the laminate thickness rises, the CLPT's presumptions lose validity, and the forecasts' precision could decline. However, FE analysis can account for delamination by modeling the inter-laminar shear stresses and strains, which can lead to more accurate predictions of the material behavior for non-uniform material properties. In addition, mesh size and element shape can significantly affect the accuracy and efficiency of the FE analysis.

1.2 Analyze If Failure Occurs in the Laminate

Table 3 shows that the failure indices for the Tsai-Wu theory and the Maximum stress theory are both smaller than 1, indicating that the safety factors are larger than 1 and no failure occurs in this circumstance. Because 90° plies exhibit the highest failure index and lowest strength under uniaxial loads, it is expected that they will experience their first ply failure as the external load increases.

Table 3. Through thickness distribution of the failure index for Maximum stress theory and Tsai-Wu theory by FE analysis

	Layer 1	Layer 2	Layer 3	Layer 5	Layer 6	Layer 7	Layer 8
Tsai-Wu	0.126	0.118	0.118	0.239	0.118	0.118	0.126
Maximum stress	0.126	0.098	0.098	0.179	0.098	0.098	0.126

2. Layup Design for Composite Plate with a Hole Under Tension & Shear

2.1 FE analysis for composite plate with a hole under tension & shear

Perform FE analysis to conduct a 16-ply $[(0/90/90/90)_2]_S$ composite plate with a thickness of 2.4 mm (0.15 mm for each unidirectional ply) subjected to a shell load of 100 N/mm and a concentrated force of 1000N in tensile test and subjected to a concentrated force of 1000 N in shear test. The shear test with a pin and the tensile test without a pin are designed.

For each tension and shear loading case, Find the safety factors using Tsai-Wu failure criteria and the results are shown below. Table 4 shows the maximum failure index in each ply of tensile and shear tests. Because the laminate layup is symmetric, only the outcomes of the upper 8 plies are presented.

Table 4. The maximum failure index in each ply

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
Tensile test	0.0531	0.0826	0.0826	0.0826	0.0531	0.0826	0.0826	0.0826
Shear test	0.2536	0.2537	0.2537	0.2537	0.2536	0.2537	0.2537	0.2537

Therefore 0.0826 is the maximum ply failure index in the tensile test and 0.2537 is the maximum ply failure index in the shear test.

The safety factor of the plate is: $\mathrm{S.F} = \frac{1}{\mathrm{C_{max}}}$, where $\mathrm{C_{max}}$ is the maximum ply failure index in the test.

Therefore, the safety factors of the tensile test and shear test are shown below:

$$\mathrm{S.F_{tensile}} = \frac{1}{0.0826} = 12.11$$

$$\mathrm{S.F_{shear}} = \frac{1}{0.2537} = 3.94$$

The total safety factor is: $\mathrm{S.F_{total}} = 12.11 + 3.94 = 16.05$

Fore Tsai-wu criteria, if the failure index exceeds 1, then the laminate is predicted to fail. If the failure index is less than or equal to 1, then the laminate is predicted to be safe under the given loading conditions. Therefore, the safety factor for the Tsai-Wu criterion is calculated as the reciprocal of the failure index. If the safety factor is greater than 1, then the laminate is predicted to be safe under the given loading conditions. If the safety factor is less than or equal to 1, then the laminate is predicted to fail.

The failure indexes of all layers in tensile and shear tests are less than 1, meaning that the safety factors are greater than 1, therefore there is no failure occurring in the laminate.

2.2 Design New Layups to Improve Safety Factor

Using multiple ply angles in a composite laminate can provide a more optimized design with improved performance and safety factor compared to a laminate with only a single fiber orientation (Barbero, E. J., 2017). For example, the 45° and -45° plies provide good resistance to shear loads, while the 0° and 90° plies provide good resistance to tensile and compressive loads. The 30° and 60° plies can provide additional strength and stiffness in specific directions. Further when the interval of ply angle is reduced, the safety factor is increased considerably (Nicholas, P. E., Padmanaban, K. P., & Sofia, A. S., 2012).

Therefore, design two new layup(s) with multiple fiber angles to improve the total safety factor and use the FE results as evidences. The ply thickness and the number of plies remain the same. The first designed layup is $[(0/45/-45/30)_2]$s and the second designed layup is $[(30/-30/60/0)_2]$s.

The failure indices of all plies under tension & shear tests obtained in Abaqus are listed in the Table 5-6. The safety factors of two tests and the total safety factors are shown in the Table 7 with the difference to compare the previous layup with the modified layup.

Table 5. The maximum failure index in each ply of $[(0/45/-45/30)_2]$s plate

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
Tensile test	0.0366	0.0426	0.0341	0.0318	0.0366	0.0426	0.0341	0.0318
Shear test	0.2407	0.1440	0.1470	0.1704	0.2407	0.1440	0.1470	0.1704

Table 6. The maximum failure index in each ply of $[(30/-30/60/0)_2]$s plate

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
Tensile test	0.0281	0.0274	0.0391	0.0298	0.0281	0.0274	0.0391	0.0298
Shear test	0.2135	0.1466	0.1370	0.2061	0.2135	0.1466	0.1370	0.2061

Table 7. The safety factors of plates with new layups

layup	tension	difference	shear	difference	total	difference
$[(0/45/-45/30)_2]s$	23.47	93.81%	4.15	5.33%	27.62	72.19%
$[(30/-30/60/0)_2]s$	25.58	111.23%	4.68	18.78%	30.26	88.54%

The result shows that the total safety factor with new layups in tensile and shear test are greatly improved, especially for the second designed layup, with an 88.54% increase. In the tensile test, the second designed layup raises the safety factor by 111.23% which has extremely high safety factor compared to other design layups. In the shear test, the safety factor of the second designed layup increases by 18.78%, which is higher than the one of the first designed layup. Therefore, the $[(30/-30/60/0)_2]s$ layup is mainly adopted to improve the total safety factor under tension and shear test.

2.3 Limitations of the FE Model as Compared to the Physical Tests

Compared to the physical tests, FE models could have some limitations. The limitations with reasons are shown as follows:

(1) Manufacturing defects

Physical specimens may have material defects such as voids, inclusions, and cracks that can affect the behavior of the material and lead to premature failure. These defects can occur during the manufacturing process and may not be accurately captured by FE models. One reason for this is that FE models typically assume that the material being tested is homogeneous and isotropic, which is not always the case in reality.

(2) Failure defects

FE models may not accurately predict all possible failure modes that can occur in a physical specimen. Composite laminates may exhibit damage mechanisms such as matrix cracks, fiber breakage, fiber-matrix debonding and delamination, which contribute to final failure. FE models may not be able to accurately capture the complex interactions between the material properties, loading conditions, and the geometry of the specimen that contribute to these failure modes.

(3) Boundary conditions and mesh size

In physical tests, the boundary conditions are typically determined by the experimental setup and the fixtures used to hold the specimen. FE models require assumptions to be made about the boundary conditions and mesh size used to represent the physical specimen. The boundary conditions determine how the material is constrained and loaded, and the mesh size determines how finely the material is discretized for analysis. These assumptions can affect the accuracy of the model predictions. If the boundary conditions are not accurately represented in the FE model, or if the mesh size is too coarse, the results may be inaccurate or unreliable.

(4) Environmental effects

Environmental effects such as temperature, humidity, and exposure to chemicals can also affect the behavior of the material. For example, exposure to high temperatures can cause thermal expansion or degradation of the material, leading to changes in its mechanical properties. FE models may not be able to accurately capture these environmental effects, leading to discrepancies between the predicted and actual behavior of the physical specimen.

(5) Loading conditions

The loading conditions applied to the physical specimen can affect its behavior, including the rate at which the load is applied, the direction of the load, and the magnitude of the load. FE models may not be able to accurately capture these loading conditions, leading to discrepancies between the predicted and actual behavior of the physical specimen.

2.4 Other Approachs to Improve the Safety Factor or Change the Failure Mode

(1) Manufacturing technologies used to tailor the fibre placement around the hole

The hand layup process is the usual production method wherein fabric and resin are physically set up layer by layer onto a mould surface to make a preform. Although this technique requires little equipment, it is labor-intensive and inefficient. Because there is less local stress redistribution in the area around the hole of the open-hole plate, early cracks may occur and eventually cause delamination failure (Chen, B. Y., Tay, T. E., Baiz, P. M., & Pinho, S. T., 2013; Pyl, L., Kalteremidou, K. A., & Van Hemelrijck, D., 2019). Steering the fibres along a predetermined path around the hole is an efficient way to increase the strength while attempting to prevent fibre breakage and delamination. Variable-axial (VA) laminates can now be made because to recent improvements in manufacturing techniques that allow fibres to be directed in the plane of a layer (Ribeiro, P., Akhavan, H., Teter, A., & Warmiński, J., 2014). The most popular and effective processes to create these tow-steered trajectories are Automatic Fiber Placement (AFP) (Gomes, V. S., Lopes, C. S., Pires, F. F. A., Gürdal, Z., & Camanho, P. P., 2014), Continuous Tow Steering (CTS) (Kim, B. C., Weaver, P. M., & Potter, K., 2014), and Tailored Fiber Placement (TFP) (Uhlig, K., Bittrich, L., Spickenheuer, A., & Almeida Jr, J. H. S., 2019). AFP can produce structures with complex geometry (Lopes, C. S., Gürdal, Z., & Camanho, P. P., 2010). However, the most frequently observed flaws in AFP-made parts are local fibre wrinkling, tow gaps, and overlaps. Based on the AFP process's shortcomings, Kim et al. created the CTS technique with the goal of resolving these issues (Kim, B. C., Potter, K., & Weaver, P. M., 2012). They demonstrated how the CTS approach could perhaps lessen processing flaws like fibre wrinkling, resin-rich regions, and fibre discontinuities. Yet, compared to AFP, CTS's productivity and dependability are still in their infancy. For fiber-reinforced structures, a novel type of AFP is called customised fibre placement (TFP). By using this technology, prepreg fibre tows can be fitted with the optimal quantity of fibres needed locally, in the placement direction, and with the mechanical properties needed. It can be used the placement equipment in a more flexible manner by adding the necessary customised limitations to the fibre installation procedure (Zhang, L., Wang, X., Pei, J., & Zhou, Y., 2020).

(2) Fibre architectures

As an improvement over 2D composites, three-dimensional (3D) woven composites have been developed, which have better out-of-plane properties. It has the unique ability to resist delamination and the formation of transverse matrix cracks due to through-thickness reinforcement (Gerlach, R., Siviour, C. R., Wiegand, J., & Petrinic, N., 2012). In 3D composite materials, the transverse fibres retain the warp and fill yarns, which together have a significant impact on the impact behaviour of the composites. The transverse yarn increases areal density, resulting in strong transverse fracture toughness.

References

Barbero, E. J., (2017). *Introduction to composite materials design*. CRC press.

Chen, B. Y., Tay, T. E., Baiz, P. M., & Pinho, S. T., (2013). Numerical analysis of size effects on open-hole tensile composite laminates. *Composites Part A: Applied Science and Manufacturing, 47*, 52-62.

Gerlach, R., Siviour, C. R., Wiegand, J., & Petrinic, N., (2012). In-plane and through-thickness properties, failure modes, damage and delamination in 3D woven carbon fibre composites subjected to impact loading. *Composites Science and Technology, 72*(3), 397-411.

Gomes, V. S., Lopes, C. S., Pires, F. F. A., Gürdal, Z., & Camanho, P. P., (2014). Fibre steering for shear-loaded composite panels with cutouts. *Journal of Composite Materials, 48*(16), 1917-1926.

Kim, B. C., Potter, K., & Weaver, P. M., (2012). Continuous tow shearing for manufacturing variable angle tow composites. *Composites Part A: Applied Science and Manufacturing, 43*(8), 1347-1356.

Kim, B. C., Weaver, P. M., & Potter, K., (2014). Manufacturing characteristics of the continuous tow shearing method for manufacturing of variable angle tow composites. *Composites Part A: Applied Science and Manufacturing, 61*, 141-151.

Lopes, C. S., Gürdal, Z., & Camanho, P. P., (2010). Tailoring for strength of composite steered-fibre panels with cutouts. *Composites Part A: Applied Science and Manufacturing, 41*(12), 1760-1767.

Nicholas, P. E., Padmanaban, K. P., & Sofia, A. S., (2012). Optimization of dispersed laminated composite plate for maximum safety factor using genetic algorithm and various failure criteria. *Procedia engineering, 38*, 1209-1217.

Pyl, L., Kalteremidou, K. A., & Van Hemelrijck, D., (2019). Exploration of the design freedom of 3D printed continuous fibre-reinforced polymers in open-hole tensile strength tests. *Composites Science and Technology, 171*, 135-151.

Ribeiro, P., Akhavan, H., Teter, A., & Warmiński, J., (2014). A review on the mechanical behaviour of curvilinear fibre composite laminated panels. *Journal of Composite Materials, 48*(22), 2761-2777.

Uhlig, K., Bittrich, L., Spickenheuer, A., & Almeida Jr, J. H. S., (2019). Waviness and fiber volume content analysis in continuous carbon fiber reinforced plastics made by tailored fiber placement. *Composite Structures, 222*, 110910.

Zhang, L., Wang, X., Pei, J., & Zhou, Y., (2020). Review of automated fibre placement and its prospects for advanced composites. *Journal of Materials Science, 55*(17), 7121-7155.