COMPOSITE AIRCRAFT CERTIFICATION, TSAI'S MODULUS – DD CASE STUDY

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ABSTRACT

Due to their material properties and behavior, carbon fiber reinforced plastics are highly suited for use in applications where low structural mass is desirable. However, today's carbon composite aircraft cannot use the full potential benefits due to limitations in allowed design philosophies, strength knockdown factors on their demonstrated test data results and knockdown factors on material variability. In addition, obtaining material allowables from testing alone is resource intensive and beyond the means of all except the largest aircraft producers. In recent work, it has been analytically proven that composite orthotropic materials have an elastic property, a constant called Tsai's Modulus. It defines a normalizing factor for the elastic moduli of CFRP, leading to a set of materially invariant elastic properties that establish accurate relationships between the elastic moduli of carbon composites, currently neglected in the definition of test campaigns at the lamina level. In a case study involving double-double laminates, the plain and open-hole tension data is first identified experimentally from a [±15/±60] laminate and extrapolated to a [±0/±50] laminate. Tests conducted on a DD [±0/±50] laminate validate the approach. This case study shows that Tsai's modulus is accurate and consistent in the prediction of the static strength of composite materials. Future work would relate to virtual models for durability related safe life generation based on Tsai's modulus.

1 INTRODUCTION

Due to their material properties and behavior, composite materials, esp. carbon fiber reinforced plastics (CFRP) are highly suited for use in applications where low structural mass is desirable. Carbon composites provide:

1. High specific strength
2. High specific stiffness
3. High corrosion resistance
4. Shape conformance to a structural load spectrum
5. Aerodynamic cleanliness
6. High fatigue strength and toughness
7. Capability to design high energy dissipation structures for crashworthiness.

Today's carbon composite aircraft cannot use the full potential benefits due to limitations in allowed design philosophies, strength knockdown factors on their demonstrated test data results and knockdown factors on material variability. The FAA's recommended minimum tests for composites are found in AR03-19 [1]. These tests are statistical in nature and in many cases map those tests that are done for metal structures to composites. Design and use of composite materials make these mapped tests inadequate and inappropriate. We, therefore, argue what then are the right methods for composite aircraft certification.

In addition, obtaining material allowables from testing alone is resource intensive and beyond the means of all except the largest aircraft producers. In addition to the inefficiency of the current design and certification procedures of composite structures, which is a sufficient motivation for the development of new composite qualification methods for aircraft design, the fact that these procedures are based on legacy laminate configurations strongly limits the introduction of new materials and design concepts, such as the double-double (DD) technologies. The understanding of the physical behavior of CFRP and the use of precise relationships between their material properties has not only the potential to make design and certification more affordable, but it also opens-up new possibilities for application of advanced materials and novel laminate configurations. Tsai's modulus [2] – the trace of the in-plane stiffness matrix – and omni envelopes [3, 4] in combination with fracture mechanics concepts [5-7] establish the required relationships towards efficient and reliable certification procedures for CFRP structures, which are independent of the material form and laminate configuration.

2 CERTIFICATION

Aircraft certification is a means to prove that a structure, designed, built, operated, and maintained using the certified processes would be safe in its entire mission profile for the lifetime of its certification. Historically, the Federal Aviation Administration (FAA) in the USA and the European Aviation Safety Agency (EASA), in Europe and many other countries, are the two main regulatory authorities in the world that have set forth the standards for aircraft certification that are currently used world-wide. Once an aircraft is certificated, the operational experience of its fleet is recorded, and such records have been analyzed by the FAA and EASA generating a vast database of the operational and maintenance life of the aircraft.

The experience with metal aircraft certification has pointed to some challenges in the certification of composite aircraft, due to which starting in the 1970's to 1990's significant work was carried out to understand the predictability of safety of composite aircraft. Early composite aircraft designs used some thumb-rules, guided by engineering opinion as opposed to analytical understanding: one of these rules is the 10% rule, which says that at least 10% of fibers in any structure should be in one of the 0/90/±45° fiber angles. We call the laminates made using this layup legacy quad laminates (LQL), and they are comprised of a sequence of 0/90/±45° plies.

Variability in composite constituents such as epoxies, their chemical composition and structural behavior, fibers and the production techniques of composites has historically ebbed on the advantage of composite materials. Lack of standardized data and capability of reproducing that data in production conditions is another issue marring the work till late 1990's.

In the 2000's, significant investment by companies in production techniques, standardization of material systems, development of new fibers, etc., has helped this aspect. Today, there is a public database by NCAMP, at Wichita State University, of standardized materials which are accepted by FAA and EASA. The old composite design philosophies, in absence of their theoretical basis, such as the 10% rule, are still used as standard operating procedures in the design of their parts.

There is a significant issue with the current databases that are used by the Composites Materials Handbook 17 (CMH17) [8]; this relates to the fact that all the data present in public databases such as NCAMP and CMH17 are based on LQL tests.

3 TSAI'S MODULUS

In recent work, it has been analytically proven that composite orthotropic materials have an elastic property, a constant called Tsai's Modulus (Tr). Tr is unique for a material system and fiber combination and can, therefore, be used to generate the material behavior of any orthotropic carbon composite from a single test data. Tr can be perceived as the sum of all the stiffness components of a laminate. It has also been shown that properties of any carbon composite laminate normalized using Tr lie within the band of experimental error of their test data. This leads to the definition of a master-ply which is merely a laminate that has been normalized using its Tr and is only a property of its laminate sequence. Conversely, doing a single test of any laminate, to evaluate its Tr, and then multiplying the required master-ply data with Tr one can arrive at the "real" test validated laminate properties of that required ply sequence.

Therefore, the determination of Tr from a statistically valid single test data and then using Tr to generate virtual allowable models has the capability to reduce test certification burden. If the generation of virtual allowables using our process can be regression tested using minimum test data as a means of analysis corroborated by test, it will eliminate the excessive statistical testing for other combinations of ply angles of the same material system. Therefore, the theory of Tr, applied to aircraft certification holds the promise to reduce certification burden of future carbon composite aircraft.

4 MATERIAL ALLOWABLES

Important steps can be made towards reduced testing requirements based on the improved knowledge of the physical behavior of composite materials. For instance, the building-block approach, as it is currently employed in aircraft design and certification of composite structures, does not consider the relationship between material parameters or the physical behavior of composite laminates. The observation that Tr defines a normalizing factor for the elastic moduli of CFRP, leading to a set of materially invariant elastic properties – the master-ply [3] – leads to accurate relationships between the elastic moduli of CFRP (Fig. 1) that are currently neglected in the definition of test campaigns at the lamina level. In addition, since Tr is an invariant with respect to the material axes, its value is the same of a multidirectional laminate of the same material system. Consequently, Tr defines the only elastic property allowable.

$$\boxed{\mathrm{Tr} = E_1/0.880}$$

Laminate factors	E_x^o/Tr	E_y^o/Tr	G_{xy}^o/Tr	ν_{xy}^o
Universal [0]	0.880	0.052	0.031	0.320
[0/90]	0.468	0.468	0.031	0.036
[π/4]	0.336	0.336	0.129	0.308
[0_7/±45/90]	0.662	0.175	0.070	0.310
[0_5/±45_2/90]	0.518	0.208	0.109	0.423
[0_2/±45/90]	0.445	0.289	0.109	0.308
[0/±45_4/90]	0.217	0.217	0.187	0.552
[0/±45]	0.370	0.155	0.161	0.734
[0/±45/0]	0.499	0.141	0.129	0.701
[0/±30]	0.510	0.074	0.129	1.220
[0/±30/0]	0.611	0.072	0.104	1.079
[±12.5]	0.764	0.053	0.066	0.913

Figure 1: Laminate factors obtained from Tsai-normalized elastic constants. The laminate elastic properties can be simply obtained by the product of the value of Tsai's modulus (Tr) – the only elastic property allowable – by the desired laminate factor.

Because the use of Tsai's modulus enables an accurate and precise estimation of the elastic properties of multidirectional laminates from one elastic property only (Fig. 1), it is evident that the current design and certification processes can be substantially simplified (Fig. 2) without posing risk to the safe design of structures at larger scales.

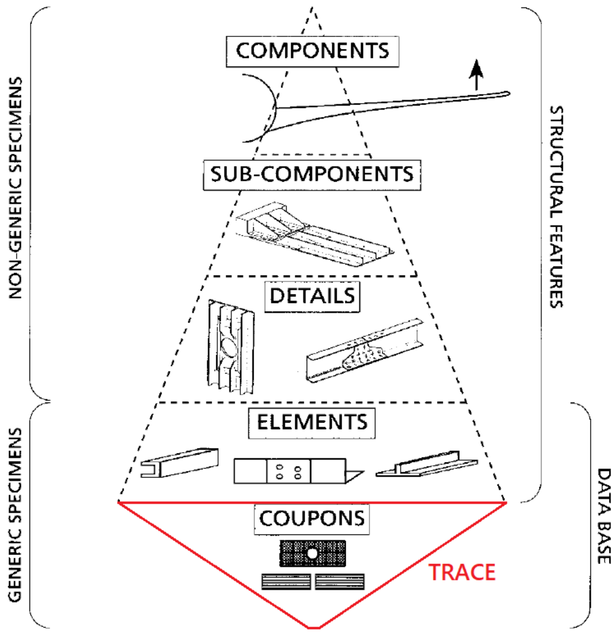

Figure 2: Reduced material allowables with Tsai's modulus (adapted from CMH17 [8]).

In a case study involving double-double laminates, made from [±Φ/±Ψ] stacking sequences, the plain and open-hole tension data is first identified experimentally from a DD [±15/±60] laminate. Using Tsai's modulus, one laminate only (no unidirectional ply data) is necessary for generation of the allowables. Then, an omni failure criterion [4], a fracture mechanics model [5] and a Finite Fracture Mechanics criterion [6] is used to extrapolate the mean and B-Basis values for other laminates. Fig. 3 shows the notched data for a DD [±0/±50] laminate extrapolated using the test data obtained from the DD [±15/±60] laminate. Tests conducted on a DD [±0/±50] laminate are shown for validation. It is impressive how the mean values extrapolate so well from one laminate to the other. On the other hand, the B-Basis values are conservative, mainly because the DD [±15/±60] laminate shows more scatter in the test results.

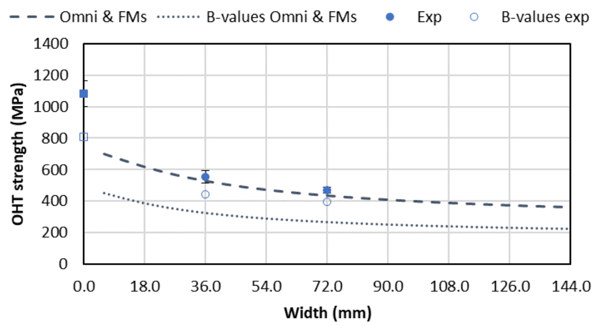

Figure 3: Extrapolation of notched data to a DD [±0/±50] laminate using data identified from a DD [±15/±60] laminate and comparison with experimentally determined plain and open-hole tension test results (Exp) and corresponding B-Basis values (B-values).

5 REQUIREMENT OF TEST MATRIX DEVELOPMENT

The current guidance from regulatory authorities for composite aircraft certification requires a detailed test matrix from raw materials all the way up to full aircraft. The bulk of these can be separated into coupon level tests related to the material behavior under static loads, dynamic loads, environmentally varying conditions, and production processes. Most of these tests have accelerated test procedures that have been validated by test data from CMH17 [8]. The accelerated procedures enable the shortening of the time taken to conduct these test procedures. In addition to these, tests on adhesives used in the manufacture of the aircraft and design details of the aircraft are also evaluated.

Durability, fatigue, and safe life estimation of composite structures is crucial to the determination of the structural integrity of an aircraft. Guidance material from regulatory authorities requires a fatigue test to be carried out on the structure and structural specimens at an enhanced load factor [9]. Test data reduction provides the estimation of safe life of that composite part.

For larger parts, a qualified test procedure that uses analysis justified by test is usually acceptable to the certification authorities. This usually involves finite elements analysis (FEA) using the coupon test matrix of a full part and the part test.

Even though most of these test procedures are standardized by internationally accepted norms such as those from ASTM International, these often show a variability in test results. The statistical variability can be reduced by the state-of-the-art production processes, one of these is a proprietary process of ZeroVoid® composites by NASHERO that has proven to give consistent results with statistical variance well below 3% and imperceptible void content. The variance in test results is cited by the regulatory authorities as a reason to redo many tests to the certification applicants. The goal of redoing the tests is to capture the variance and therefore ascertain the level of confidence in the properties of the material, process variations, and environmental effects. The resulting properties are classified as B-Basis and A-Basis [8]. Tr with master-ply definition and laminate data extrapolation can significantly reduce the replication of such tests.

6 GREEN AVIATION

Double-double laminates are a direct result of optimization of a structure based on Tr and structural load cases [10]. The resulting DD laminates have proven to have lower warpage and superior behavior as compared to their equivalent LQL brethren [11]. Thermal cycling of the process was also carried out and resulted in lower deformation of the resulting laminates compared to an equivalent LQL. We have also shown that in a realistic exercise structural mass savings are of around 50% of the structural mass. Therefore, a design driven by Tr and double-double laminates has shown to give superior laminates. This opens a significant weight saving opportunity in aviation, not available to date with any competing technologies [12]. The greenhouse emissions from commercial aviation amount to 13% of global emissions. Optimizing commercial aviation structures using DD, one can potentially reduce global emissions from commercial aviation by 32.16%.

7 CONCLUSIONS

Tsai's modulus has been shown to be accurate and consistent in the prediction of the static strength of composite materials. Virtual allowable models that use fracture mechanics have shown correlation of results with Tsai's modulus. Such theories show significant promise to reduce certification burden by supporting the certification paradigm of analysis supported by test. Thanks to the understanding of the physical behavior and relationships between material properties of CFRP, as well as other advanced composites, the new possibilities for more efficient design and certification are endless. This has the great potential of making composite aircraft structures more affordable and competitive, and embracing such philosophy can lead to the next game changer of this industry.

Future work would relate to virtual models for durability related safe life generation based on Tsai's modulus. Tsai's modulus eases laminate sequence optimization due to the reduction of number of variables to just three, Tsai's modulus, and two angles, Φ and Ψ.

Tsai's modulus coupled with DD type of layups can help in simplifying laminae ply drops and therefore reduce the weight of aircraft. There is no other technology that can currently claim to save over 35% of structural mass of future aircraft w.r.t. carbon composite airliners of today.

REFERENCES

[1] DOT/FAA/AR-03/19, *Material Qualification and Equivalency for Polymer Matrix Composite Material Systems: Updated Procedure*.

[2] A. Arteiro, N. Sharma, *et al.*, A case for Tsai's Modulus, an invariant-based approach to stiffness, *Composite Structures*, **252**, 2020, 112683 (doi: 10.1016/j.compstruct.2020.112683).

[3] S. W. Tsai and J. D. Melo, An invariant-based theory of composites, *Composites Science and Technology*, **100**, 2014, pp. 237-243 (doi: 10.1016/j.compscitech.2014.06.017).

[4] S. W. Tsai and J. D. Melo, A unit circle failure criterion for carbon fiber reinforced polymer composites, *Composites Science and Technology*, **123**, 2016, 71-78 (doi: 10.1016/j.compscitech.2015.12.011).

[5] P. P. Camanho and G. Catalanotti, On the relation between the mode I fracture toughness of a composite laminate and that of a 0° ply: analytical model and experimental validation, *Eng Fract Mech*, **78**, 2011, pp. 2535-2546 (doi: 10.1016/j.engfracmech.2011.06.013).

[6] P. P. Camanho, G. H. Erçin, G. Catalanotti, S. Mahdi and P. Linde, A finite fracture mechanics model for the prediction of the open-hole strength of composite laminates, *Compos Part A-Appl S*, **43**, 2012, pp. 1219-1225 (doi: 10.1016/j.compositesa.2012.03.004).

[7] C. Furtado, A. Arteiro, M. A. Bessa, B. L. Wardle and P. P. Camanho, Prediction of size effects in open-hole laminates using only the Young's modulus, the strength, and the R-curve of the 0° ply, *Compos Part A-Appl S*, **101**, 2017, 306-317 (doi: 10.1016/j.compositesa.2017.04.014).

[8] *Composite Materials Handbook*, Polymer Matrix Composites, Vol. 3, Department of Defense, 2002.

[9] DOT/FAA/AR-10/6, *Determining the Fatigue Life of Composite Aircraft Structures Using Life and Load-Enhancement Factors*.

[10] S. Tsai, N. Sharma, A. Arteiro, S. Roy and B. Rainsberger, *Composite Double-Double and Grid/Skin Structures – Low Weight/Low Cost Design and Manufacturing*, Stanford University, Stanford, 2019.

[11] S. Shrivastava, N. Sharma, S. W. Tsai and P. M. Mohite, D and DD-drop layup optimization of aircraft wing panels under multi-load case design environment, *Composite Structures*, **248**, 2020, 112518 (doi: 10.1016/j.compstruct.2020.112518).

[12] S. W. Tsai, *et al.*, *DOUBLE–DOUBLE: A New Perspective in The Manufacture and Design of Composites*, S. W. Tsai (editor), Stanford University, Stanford, 2022.