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A novel invariant-based design approach to carbon fiber reinforced laminates

Jose Daniel D. Melo [a,*], Jing Bi [b], Stephen W. Tsai [c]

[a] Department of Materials Engineering, Federal University of Rio Grande do Norte, Campus Central, 3000, Natal, RN 59078-970, Brazil
[b] Dassault Systemes SIMULIA, 1301 Atwood Ave, Johnston, RI 02919, United States
[c] Department of Aeronautics & Astronautics, Stanford University, Durand Building, 496 Lomita Mall, Stanford, CA 94305-4035, United States

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ABSTRACT

An invariant-based design procedure using trace-normalized plane stress stiffness matrix and unit circle failure criterion for carbon fiber reinforced polymer (CFRP) is presented and compared to the traditional design approach. Using the invariant-based design approach, the optimal stiffness-based layup solution is material independent and thus valid for any CFRP. Then, trace of the plane stress stiffness matrix is the only material property needed for strain scaling. Moreover, the unit circle failure criterion is invariant with respect to ply orientation and requires only the unidirectional longitudinal tensile and compressive strains-to-failure, which greatly simplifies testing. In this study, smooth and open-hole plates are evaluated using the traditional design approach and invariant-based design procedures. The results show that the invariant-based design approach greatly simplifies the design procedure of CFRP structural components.

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1. Introduction

Because of their superior properties, carbon fiber reinforced polymer (CFRP) composites are the material of choice for a variety of structural applications, which demand high strength- and modulus-to-weight ratio and corrosion resistance. However, the inherent anisotropy of these materials – fundamental to design flexibility and to their superior properties – makes their mechanical characterization complex, costly and time consuming. For unidirectional plies under in-plane loading, there are four independent stiffness parameters to be measured; *i.e.*, longitudinal, transverse and shear moduli and Poisson's ratio; and five strengths for criteria such as Tsai-Wu [1]; *i.e.*, longitudinal and transverse tensile and compressive, and shear. Likewise, finding an optimal design of composite laminates is significantly complicated due to the large number of possible combinations of material properties and stacking sequences.

Numerous studies for design optimization of composite structural components have been presented in the literature [2–14]. While some optimization approaches may assume a fixed geometry (topology) of the component and concentrate the effort on optimizing laminate properties, others focus on both optimum layup configurations and thickness profiles. Design constraints may include maximum stiffness and minimum weight [3] or stiffness and aeroelastic requirements [4,5]. In some cases, the layup is fixed and only thickness optimization is performed [15–17]. In other cases, the focus is mainly placed on stacking sequence optimization [18–26], sometimes with a fixed number of ply orientations [27–29]. Considering the specific material properties for each optimization study, scaling for different materials is usually not possible, and thus, the solution is material specific.

Recently, an invariant-based approach was proposed to describe elastic properties and failure of carbon fiber reinforced composite laminates [30]. The plane stress stiffness matrix components have been shown to be invariant when normalized by its trace. Thus, a "master ply" was defined using trace-normalized stiffness components to describe the stiffness properties of all CFRPs. A unit circle was also proposed as an invariant failure envelope in strain space to all CFRPs [31]. The criterion is based on uniaxial tensile and compressive strains-to-failure of a unidirectional ply. Thus, the number of independent parameters to be determined is greatly reduced as compared to typical failure criteria currently used. In addition, these tests are simpler to perform when compared to shear tests, normally required in most failure criteria.

The purpose of the present work is to describe a design procedure using the invariant-based approach to the optimal design of

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[*] Corresponding author.
E-mail address: jddmelo@gmail.com (J.D.D. Melo).

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structural components made of carbon fiber reinforced composite materials and compare it to a traditional design method.

2. Background

Carbon fiber tapes have been shown to share common stiffness properties if they are normalized by their respective trace of the plane stress stiffness matrix, where *Tr* [*Q*] is given by Eq. (1) [30,32].

$$\mathrm{Tr}[Q] = Q_{xx} + Q_{yy} + 2Q_{ss} = Q_{11} + Q_{22} + 2Q_{66} \qquad (1)$$

In Table 1, trace-normalized stiffness factors are shown for fifteen different carbon fiber composites [32]. Although the elastic constants for the various materials are very different, their trace-normalized properties are very similar. Thus, their mean values have been used to define a “master ply”.

The master ply properties shown in Table 1 are valid for unidirectional CFRP tapes. For glass/polymer composites, the fiber dominance on ply trace is less than that of carbon composites, due to the much lower elastic modulus of glass fibers as compared to carbon fibers. Also, fiber volume fractions in these materials are normally lower than those of typical CFRPs. Thus, there is a greater variation in trace normalized stiffness components among different glass/polymer composites and a master-ply may not be a good representation of these materials.

In-plane and flexural laminate stiffness of composite laminates – [A] and [D] – can be normalized according to Eq. (2) so that material and geometry contributions are separated and [A*] and [D*] will have the same units.

$$\begin{aligned}[A^*] &= \tfrac{1}{h}[A] \\ [D^*] &= \tfrac{12}{h^3}[D]\end{aligned} \qquad (2)$$

The terms of [A*] are not dependent on stacking sequence, but those of [D*] are. However, the traces of both [A*] and [D*] have the same value, thus invariant to stacking sequence as shown in Fig. 1, where stiffness components are presented as a function of ply orientation for a [0/+θ/−θ] laminate. These trace values are also the same as trace [Q].

In case master ply properties are used, all stiffness properties are trace normalized. Thus, the curves will be valid not only for a specific material as in Fig. 1, but to any CFRP composed of UD plies (Fig. 2). The curves for a specific material can be obtained if the stiffness components are multiplied by trace [Q] for that material.

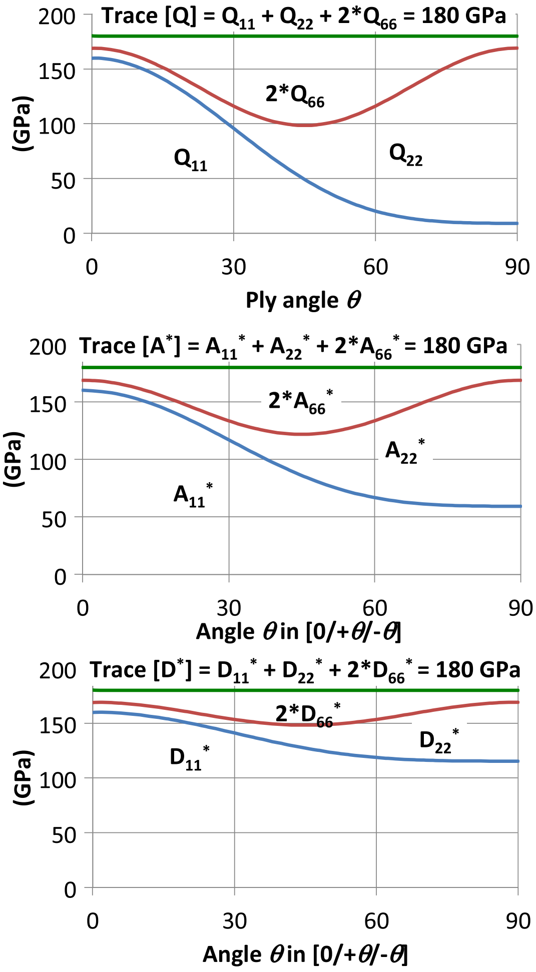

Fig. 1. Unidirectional ply and in-plane and flexural stiffness components as a function of ply orientation for IM7/8552.

Thus, with trace normalized stiffness components, design optimization is more efficient since once the best laminate is defined, the solution is general, not limited to a specific material.

Table 1
Elastic properties and trace normalized plane stress stiffness components for various carbon composites.

Material	E_x (GPa)	E_y (GPa)	ν_x	E_s (GPa)	Q^*_{xx}	Q^*_{yy}	Q^*_{xy}	Q^*_{ss}	Tr (GPa)
IM6/epoxy	203	11.20	0.32	8.40	0.8791	0.0485	0.0155	0.0362	232
IM7/977-3	191	9.94	0.35	7.79	0.8825	0.0459	0.0161	0.0358	218
T300/5208	181	10.30	0.28	7.17	0.8805	0.0501	0.0140	0.0347	206
IM7/MTM45	175	8.20	0.33	5.50	0.9014	0.0422	0.0139	0.0282	195
T800/Cytec	162	9.00	0.40	5.00	0.8955	0.0497	0.0199	0.0274	183
IM7/8552	159	8.96	0.32	5.50	0.8888	0.0501	0.0160	0.0306	180
T800S/3900	151	8.20	0.33	4.00	0.9034	0.0491	0.0162	0.0238	168
T300/F934	148	9.65	0.30	4.55	0.8878	0.0579	0.0174	0.0271	168
T700 C-Ply 64	141	9.30	0.30	5.80	0.8713	0.0575	0.0172	0.0356	163
AS4/H3501	138	8.96	0.30	7.10	0.8567	0.0556	0.0167	0.0438	162
T650/epoxy	139	9.40	0.32	5.50	0.8724	0.0590	0.0189	0.0343	160
T4708/MR60H	142	7.72	0.34	3.80	0.9029	0.0491	0.0167	0.0240	158
T700/2510	126	8.40	0.31	4.20	0.8827	0.0588	0.0182	0.0292	144
AS4/MTM45	128	7.93	0.30	3.65	0.8939	0.0554	0.0166	0.0253	144
T700 C-Ply 55	121	8.00	0.30	4.70	0.8746	0.0578	0.0173	0.0338	139
Std dev	24.6	1.0	0.029	1.5	0.0132	0.0053	0.0016	0.0056	
Coeff var%	16.0	10.9	9.0	27.2	1.5	10.1	9.6	17.9	
Master ply					0.8849	0.0525	0.0167	0.0313	1.0

Note: Q^*_{ij} are the trace-normalized plane stress stiffness components.

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