Get rid of old legacy laminates !

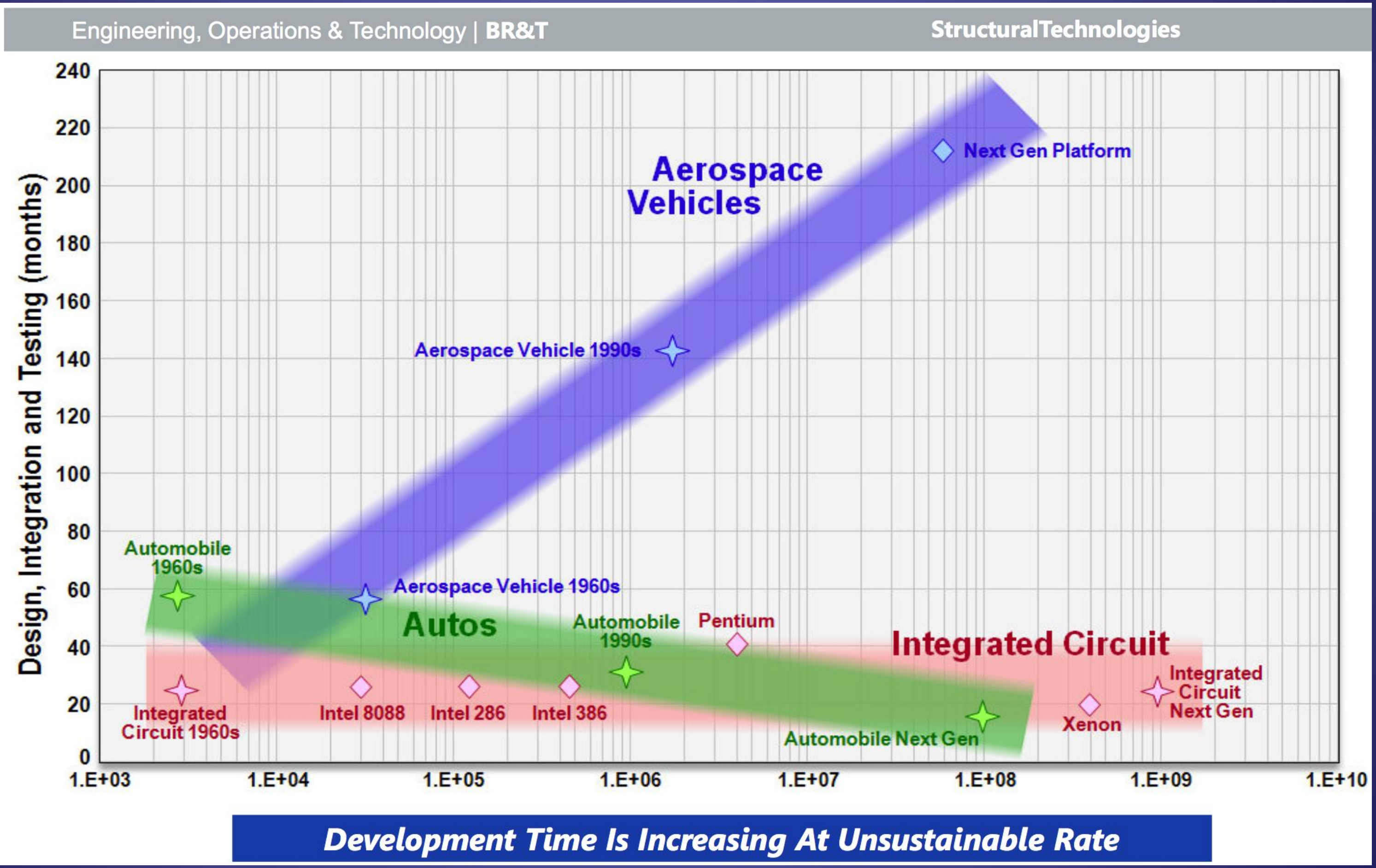
Some considerations on a new design paradigm

<u>Th. Massard[1,2]</u>*, S.W. Tsai[2], R. Harry [3], Ph. Sanial[4]
1 - CEA, Cab HC, 91191 Gif s/Yvette, France
2- Stanford University, Department of Aeronautics and Astronautics, Palo Alto, Ca, USA
3 – *retired*, Université de Bordeaux , 33405 Talence, France
4- Chomarat – 07160 Le Cheylard
* Corresponding author (thierry.massard@cea.fr)

Outline

- What is a traditional design method ?
- Why quad design has some limitations ?
- What is a double-double laminate DD ?
- Why should you use DD laminates ?
- How can you design efficient DD laminates ?
- How can you build DD laminates ?
- Some perspectives and on-going works...

An unsustainable rate for design and testing of aero composite structures



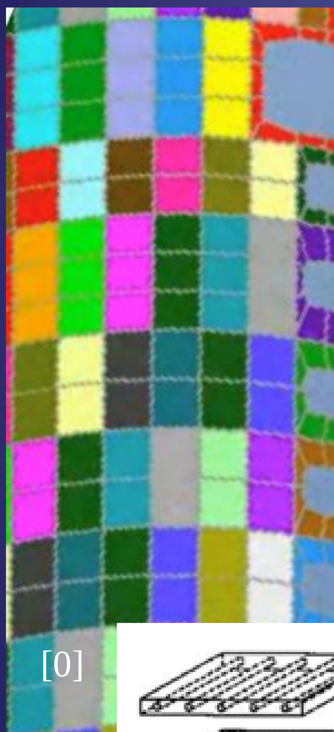
Traditional design method for laminates

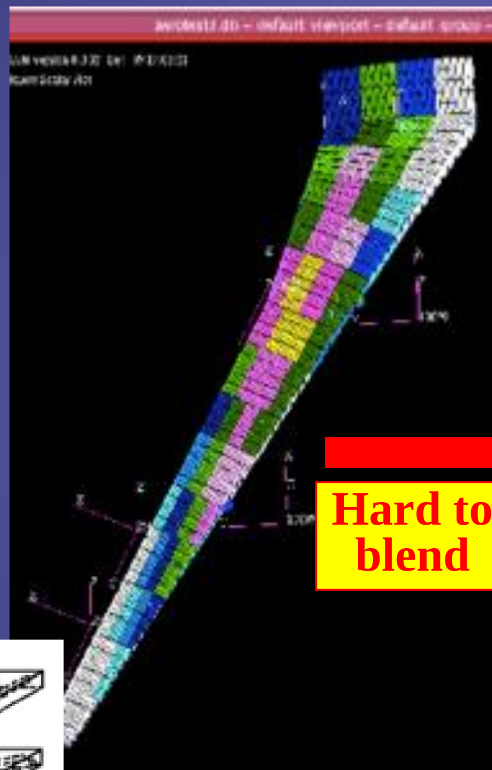
- Using all lamination possibilities can lead to unsymmetric, unbalanced laminates with coupling effects (bending/twisting, shear/tension-compression, etc...)

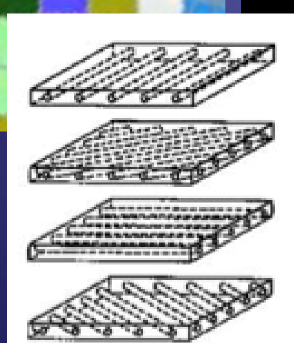
  [A], [B], and [D] are full

- Often design recommandations rule that laminates should be balanced and symmetric

Some limitations for quad laminates: discrete, hard to blend, not optimized







$[0_3/\pm45_2/90]_{2S}$
(38/50/12)

[0]
[0]
[0]
[45]
[45]
[-45]
[-45]
[90]

Hard to blend

Cannot be optimized

1000's stacking permutation

45
0
-45
0
45
0
-45
90
45
0
-45
0
45
0
-45
90

Delam prone

No clue ply drop

No clue wt/Alum

No clue manu-facture

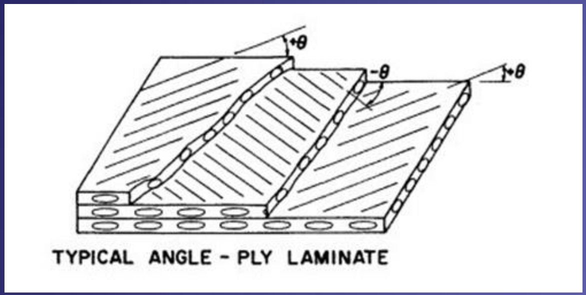
Often given in %age of each orientation, rule recommend at least 5% of each orientation to be used. But real life is in plies not in %age !

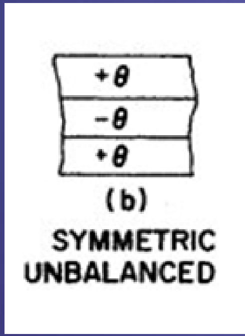
Lagacy quad

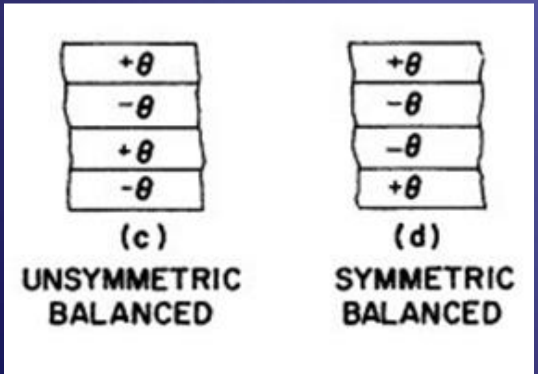
it's a small world after all

- 4 ply sub-lam 1 possible lam. *min gage 1mm*
- 5/6 ply sub-lam 4 possible lam. *min gage 1,5mm*
- 8 ply sub-lam 10 possible lam. *min gage 2mm*
- 10-ply sub –lam. 12 possible lam. *min gage 2,5 mm*
- 12-ply sub-laminate 25 possible lam. *min gage 3mm*

Angle-ply laminates







- If an angle-ply laminate has an even number of plies, then $A16 = A26 = 0$.
- If the number of plies is odd, and it consists of alternating $+\theta$ and $-\theta$ plies, then not only is it symmetric ($[B] = 0$), but also $A16$, $A26$, $D16$, $D26$ ->0 as the number of layers increases for the same laminate thickness.
- Similar to symmetric cross-ply laminates, but with higher shear stiffness and shear strength properties.

What is a Double – double laminates ?

- A double-double laminate is a stacking of two angle ply laminates [$\pm\theta/\pm\phi$]
- If suffisant number of repeat is achieved then DD laminate is homogeneous and does not have to be symmetric (B ij ->0)
- The minimum gage is always 4 plies = 0,5mm

  (even smaller using thin plies)

An important result with DD laminates

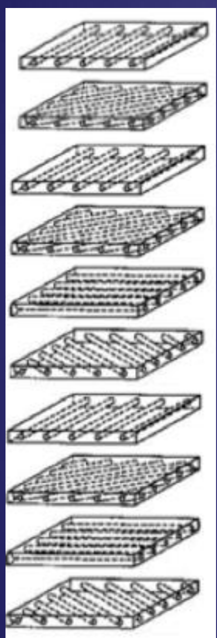
- Which ever stiffness, which ever strength is required, there is always a combination of two angles θ and ϕ giving a double/double $[\pm\theta/\pm\phi]$ with the required properties

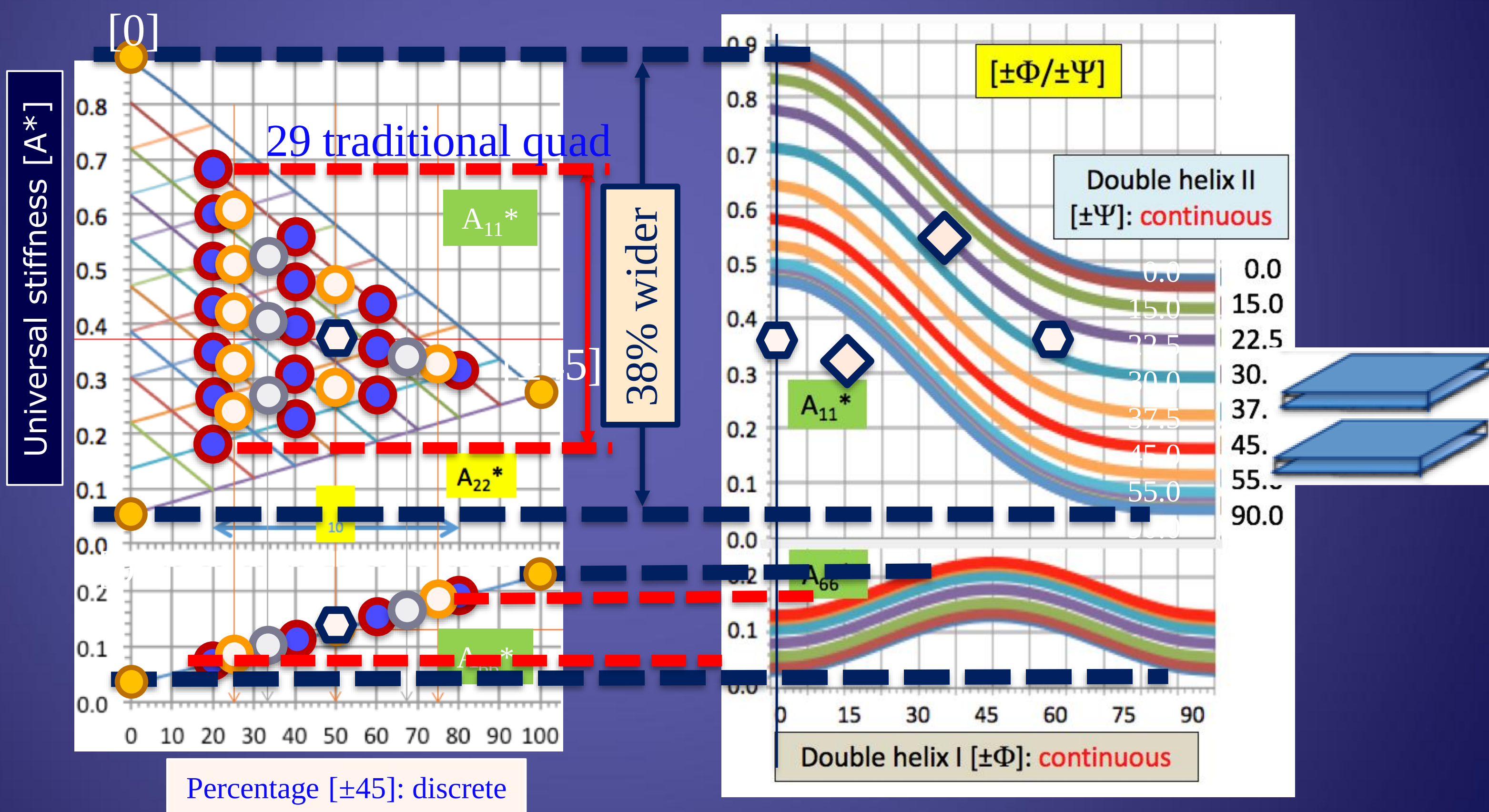
- The laminate is a 4 ply sub-laminate repeated as needed. It is the simpliest possible laminate stacking. No need for symmetry.

Why use DD to replace legacy quad ?

Legacy quad: a discrete collection

Double-double: a continuous field





Stanford patent pending

Design

- Materials

M40J/epoxy
IM6/epoxy
IM7/977-3
T300/5208
IM7/MTM45
T800/Cytec
IM7/8552
T800S/3900
T300/F934
T700 C-Ply 64
AS4/H3501

- Structure

- Loads

N1	N2	N6
1,0	0,0	0,0
-1,0	0,0	0,0
0,0	0,0	1,0
1,0	0,0	0,5
-1,0	0,0	0,5
0,0	0,0	0,5
0,0	0,0	0,5

Easy design with Trace and Unit Circle

- Material characterization is reduced to one test
- Using the Universal laminate, choice of material become very simple
- Failure prediction at FPF or LPF can be easily determine with the Unit circle criterion. Requires only X and X'
- Fast calculation is a key to optimize

Trace

Orthotropic
4 constants

$$Q_{xx} = \frac{E_x}{1 - v_x v_y}, \quad Q_{yy} = \frac{E_y}{1 - v_x v_y}, \quad Q_{xy} = v_x Q_{yy} = v_y Q_{xx},$$

$$Q_{ss} = E_s$$

Square symm
3 constants

$$Q_{xx} = Q_{yy} = \frac{E_x}{1 - v_x^2}, \quad Q_{xy} = v_x Q_{xx}, \quad Q_{ss} = E_s$$

Isotropic
2 constants

$$Q_{xx} = Q_{yy} = \frac{E}{1 - v^2}, \quad Q_{xy} = \frac{vE}{1 - v^2}, \quad Q_{ss} = \frac{E}{2(1 + v)}$$

Trace
1 constant

$$\text{Trace} = Q_{xx} + Q_{yy} + 2Q_{ss}$$

Trace: Center of Composites World

Laminate / Material	Quasi-iso: $[\pi/4]$	Hard1: $[0_5/\pm45_2/90]$
AS4/ MTM45	Stiffness [A*] $\begin{bmatrix} 53 & 17 & 0 \\ & 53 & 0 \\ & & 18 \end{bmatrix}$ Longitudinal A_{11}: 53 Transverse A_{22}: 53 2 shear A_{66}: 18 + 18 Trace: 142 53/142 = 0.37 Fraction of trace	80 32 15 15 142 GPa Poisson Longitudinal → Transverse → Shear → $\begin{bmatrix} 80 & 14 & 0 \\ & 32 & 0 \\ & & 15 \end{bmatrix}$ 80/142 = 0.56 Fraction of trace
	Invariant	
IM7/ 977-3	$\begin{bmatrix} 80 & 24 & 0 \\ & 80 & 0 \\ & & 28 \end{bmatrix}$ Longitudinal A_{11}: 80 Transverse A_{22}: 80 2 shear A_{66}: 28 + 28 Trace: 216 80/216 = 0.37 Fraction of trace	121 49 23 23 216 GPa Poisson Longitudinal → Transverse → Shear → $\begin{bmatrix} 121 & 20 & 0 \\ & 49 & 0 \\ & & 23 \end{bmatrix}$ 121/216 = 0.56 Fraction of trace
	Invariant	

Universal laminates: fractional trace

Laminate / Material	Quasi-iso: $[\pi/4]$		Hard1: $[0_5/\pm45_2/90]$	
	Fraction of trace: [A*]/Trace			Fraction of trace: [A*]/Trace
AS4/ MTM45	$142 \begin{bmatrix} 0.37 & 0.12 & 0 \\ & 0.37 & 0 \\ & & 0.13 \end{bmatrix}$	A_{11}: 0.37 A_{22}: 0.37 A_{66}: 0.13 + 0.13 Trace: 1.00 (Unity)	0.56 0.22 0.11 0.11 1.00	$142 \begin{bmatrix} 0.56 & 0.10 & 0 \\ & 0.22 & 0 \\ & & 0.11 \end{bmatrix}$
IM7/ 977-3	$216 \begin{bmatrix} 0.37 & 0.12 & 0 \\ & 0.37 & 0 \\ & & 0.13 \end{bmatrix}$	A_{11}: 0.37 A_{22}: 0.37 A_{66}: 0.13 +0.13 Trace: 1.00	0.56 0.22 0.11 0.11 1.00	$216 \begin{bmatrix} 0.56 & 0.10 & 0 \\ & 0.22 & 0 \\ & & 0.11 \end{bmatrix}$

2nd independent invariant = $A_{66}^* - A_{12}^* = 0.13 - 0.12 = 0.11 - 0.10 = 0.01$
much easier to measure Poisson A_{12} than shear A_{66}

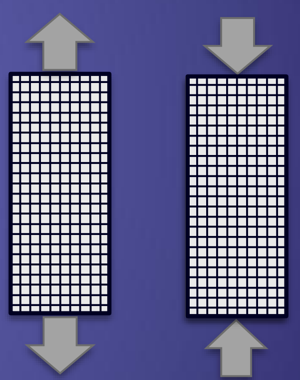
Universal Laminate

- All CFRC can be represented by a normalised material, and all laminate using it are Universal Laminates.
- The normalizing factor is TRACE
- TRACE is a mechanical property of a CFRC
- Knowing TRACE one can deduct all the elastic properties of a composite laminate.
- Characterization of a composite is easy : only one test to measure TRACE

3-parameter CFRP ply data and test method

	A	B	C	D
1	Material	Trace, GPa	X, MPa	X', MPa
2	M40J/epoxy	276	3550	1500
3	IM6/epoxy	232	3500	1540
4	IM7/977-3	218	3250	1600
5	T300/5208	206	1500	1500
6	IM7/MTM45	195	2500	1700
7	T800/Cytec	183	3768	1656
8	IM7/8552	192	2326	1200
9	T800S/3900	168	3000	2500
10	T300/F934	168	1314	1220
11	T700 C-Ply 64	163	2530	1669
12	AS4/H3501	162	1447	1447
13	T650/epoxy	160	2194	1653
14	T4708/MR60H	158	2524	1700
15	T700/2510	144	2172	1450
16	AS4/MTM45	143	1867	1398
17	T700 C-Ply 55	139	2944	1983

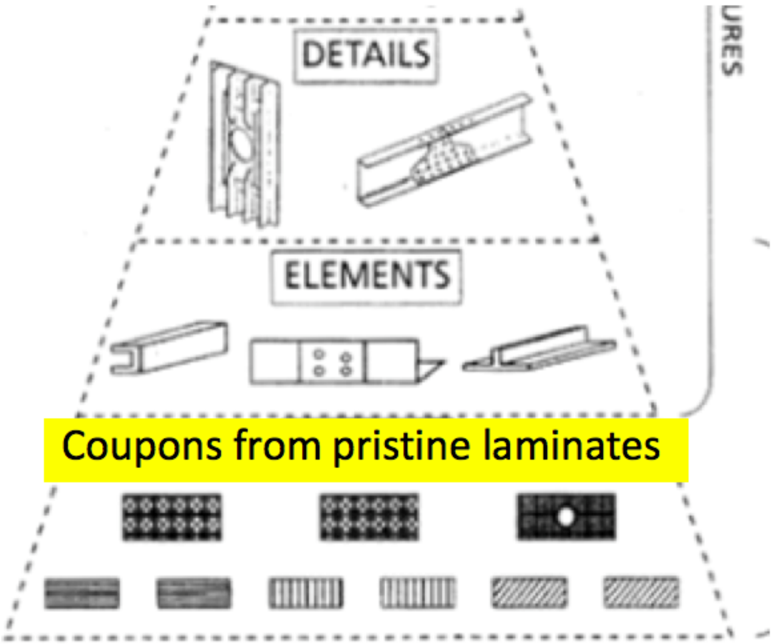
[0/90], or any single laminate



Matrix, processing, and quality are reflected in Trace-X-X’

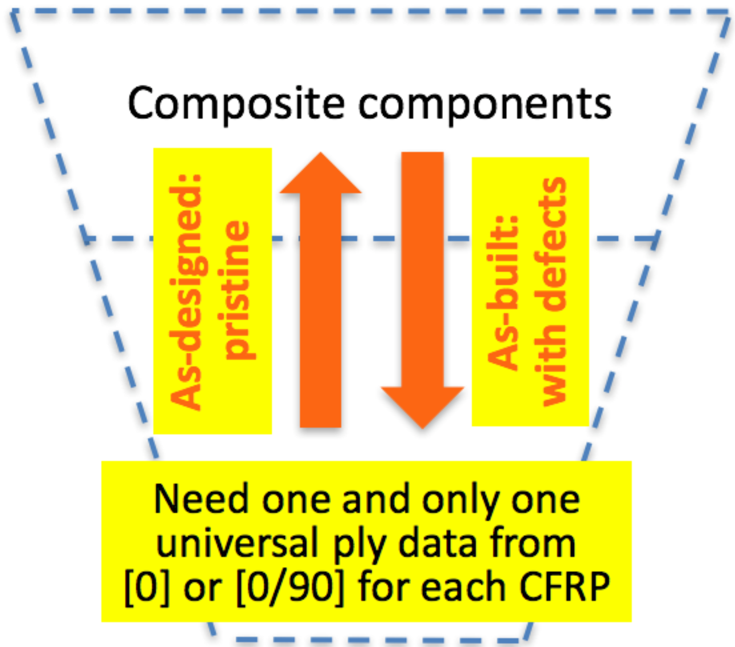
How many coupons? One or zero

Traditional building blocks



Too many coupons
Laminates are not material tests
Too long and too expensive
Prevent new material/process
Make structures non competitive

Trace-based: just like metals

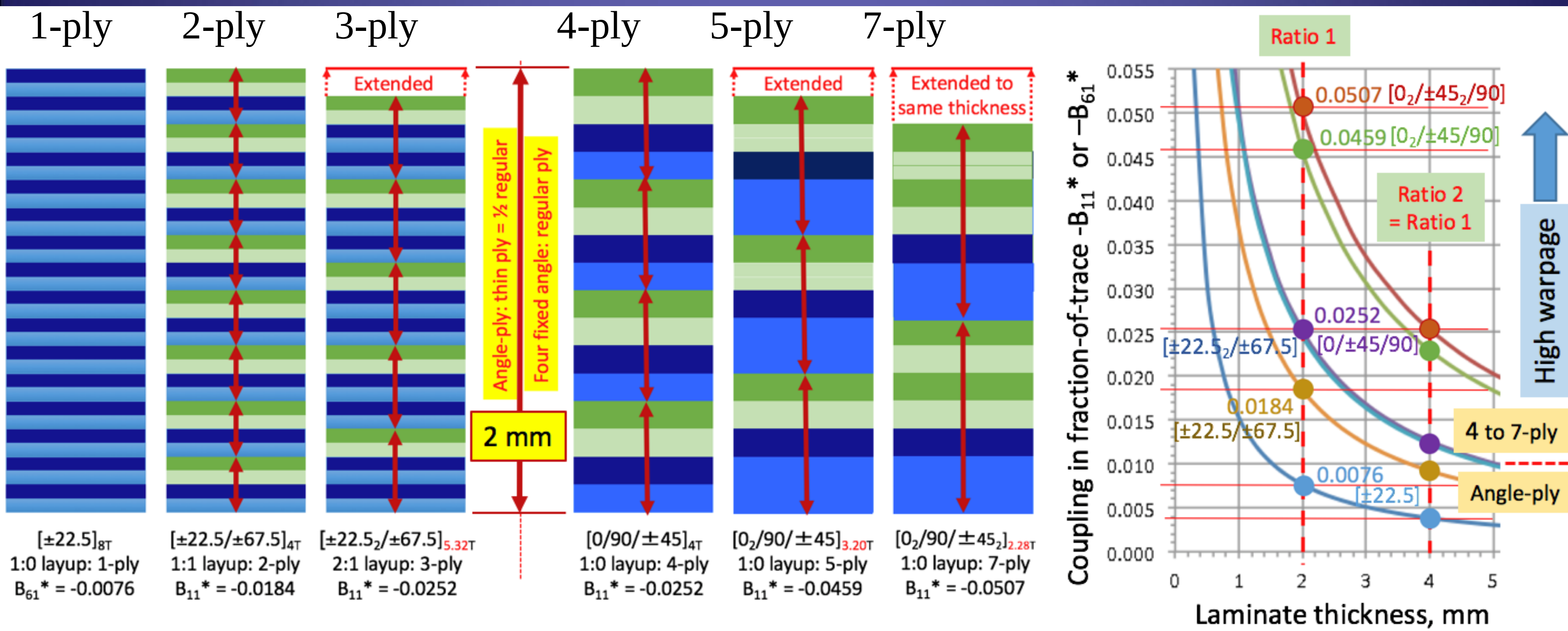


A test program for performance assurance:
1) Test [0] coupons for E_x for trace, X and X'
2) Test Tr, X, X' from as-built laminates with
a) natural defect, & b) induced damage
3) Recalibrate structure with reduced trace

Transverse homogeneity: with Angle-ply

Mid-ply symmetry not required: faster layup, simple ply drop
More repeats: less delamination;
Relative homogenization ≠ h; absolute values = 1/h

Angle-ply 4 fixed angle quad



Design for strength

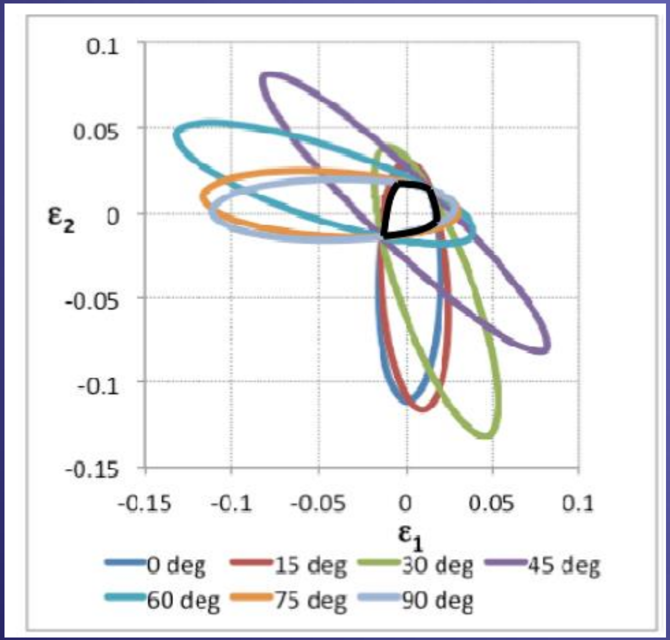
- Design for strength implies to know among all the applied loads, which is the controlling load

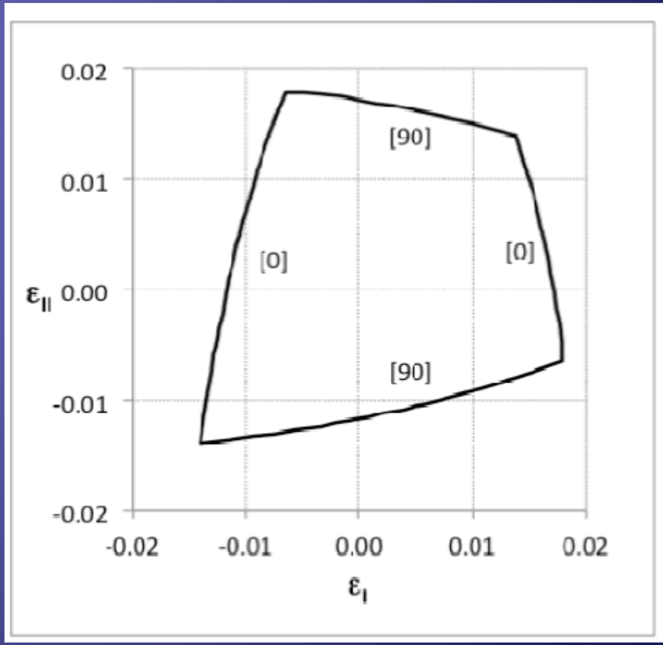
- In the case of a composite solution, the controlling load depends on the laminate solution

- So all the loads have to be considered together in the design, and only when the lamination is chosen, one can identified the controlling load

Simpler failure criterion

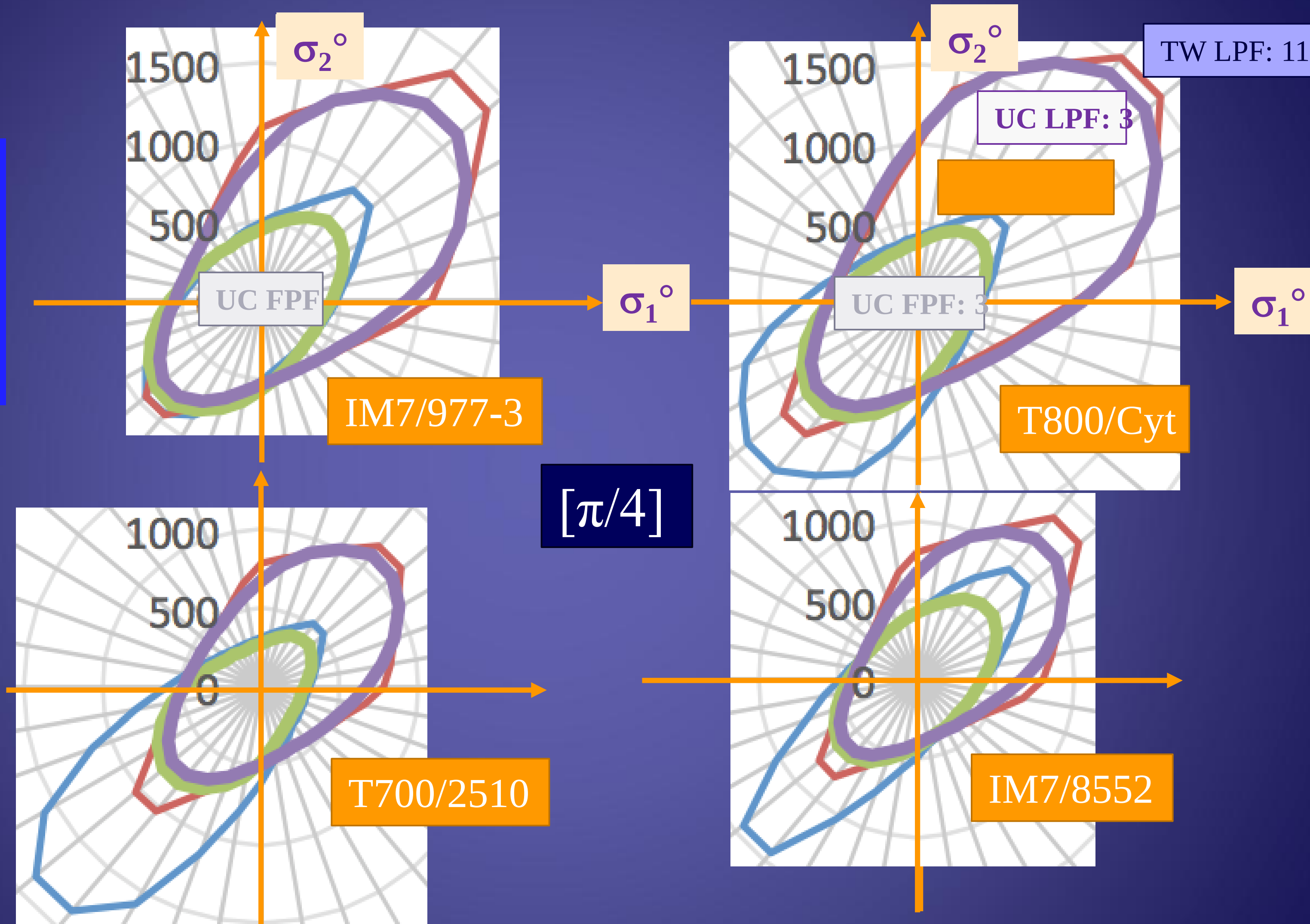
- Omni failure criteria





Omni Stress: Tsai-Wu vs Unit Circle

Unit circle: conservative, fewer, simpler anchor points
No shear test



Tsai-Wu FPF: 10 (E_x, E_y, ν_x, E_s, X, X', Y, Y', S, F_{xy}*)

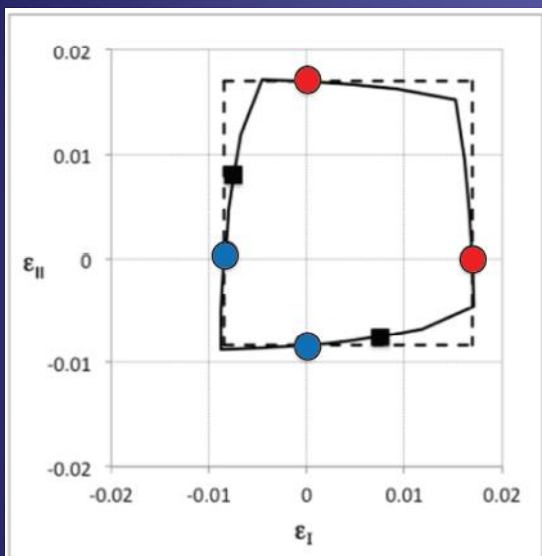
TW LPF: 11 (E_x, E_y, ν_x, E_s, X, X', Y, Y', S, F_{xy}*, E_m)

Unit circle FPF: 3 (Trace, Y, X'); no shear test

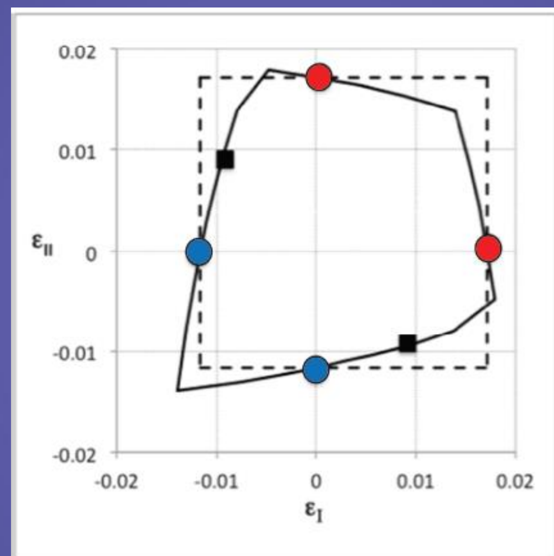
Unit Circle LPF: 3 (Trace, X, X'); no shear test

Unit Circle

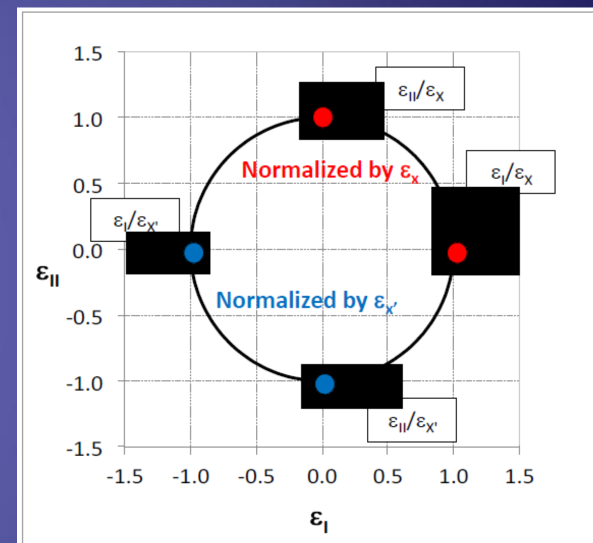
- Omni strain LPF env for two CFRP based on Tsai-Wu (solid line) and max strain (dashed line)



IM7/977-3



T700/2510

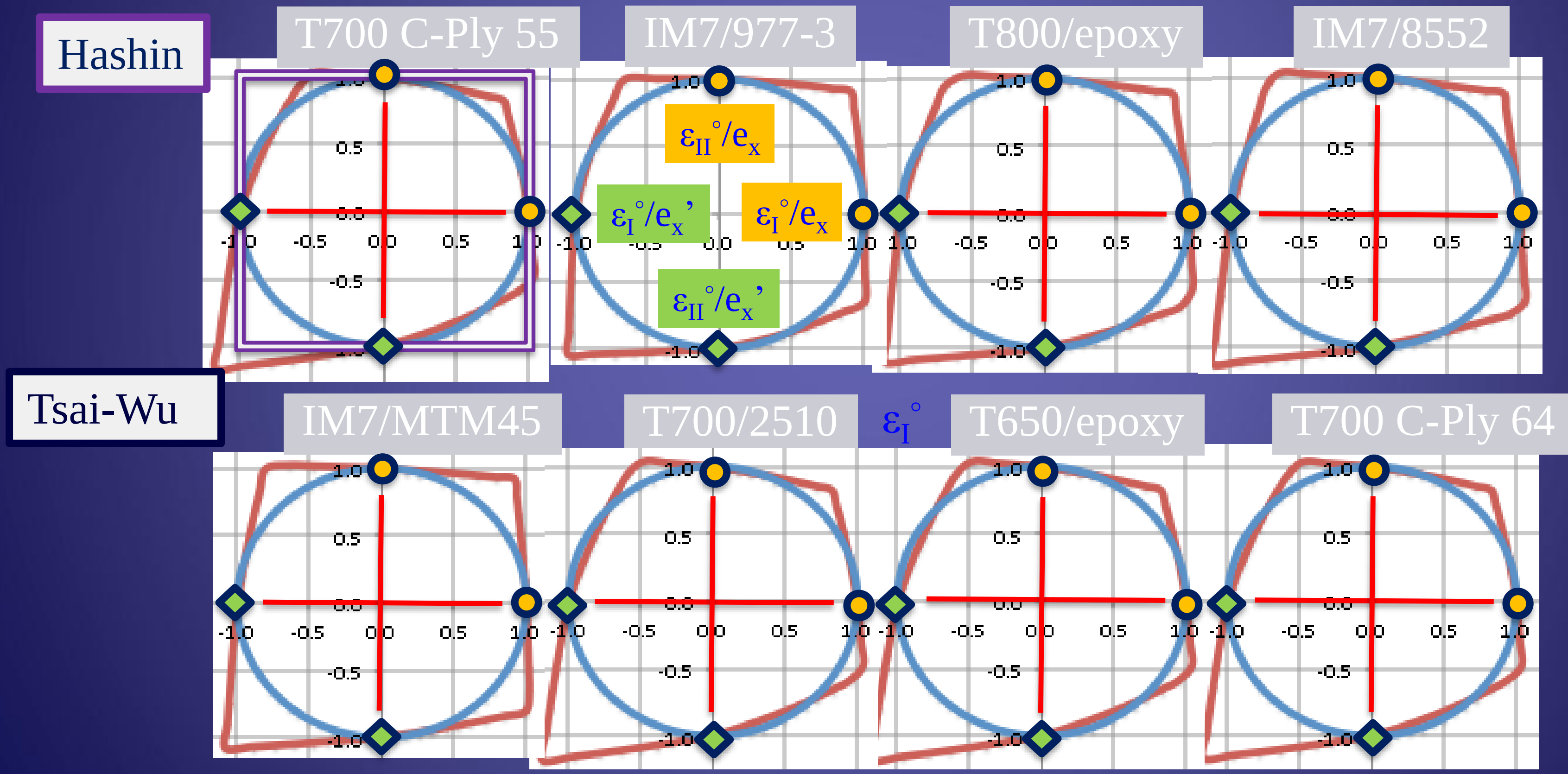


Same anchors points

Ref. Tsai SW and Melo JDD. A unit circle failure criterion for carbon fiber reinforced polymer composites. *Composites Science and Technology* 123 (2016) 71-78.

Unit Circle vs LPF Omni Envelope: CFRP

Normalized by uniaxial tensile and compressive failure strains



Find best laminate:
7 laminates/7 load sets

IM7/977-3				(20/20/60)	(20/30/50)	(20/40/40)	(20/50/30)	(20/60/20)	(20/70/10)	(20/80/0)	0 ±45 90
		20%{[0]	%[±45]				Highest R/lowest wt for one load in set				
Load set	sig1	sig2	sig6	20	30	40	50	60	70	80	max
1	1.0	0.0	0.2	802	872	907	900	841	719	531	907
2	1.0	2.0	0.0	908	1067	1203	1268	1179	914	522	1268
3	1.0	0.0	0.0	353	375	393	406	408	357	230	408
4	1.0	0.0	4.0	59	76	93	109	125	139	150	150
5	-1.0	-2.0	0.0	413	425	419	388	334	260	178	425
6	1.0	0.5	0.0	990	1081	1172	1264	1356	1451	1550	1550
7	0.0	7.0	0.0	284	240	199	161	126	92	61	284
			min	59	76	93	109	125	92	61	125

Lowest R
(highest wt)
7 load sets
each lam

Highest R
(lowest wt)
all 7 lam

Best lam
7 lam/7 load
(20/60/20)

LamSearch : A new tool to scale guide , and rate laminate design

- Design for stiffness :
  - Find the best DD laminate for a given Aij matrix
  - Find the best equivalent stiffness DD for a given quad
- Design for strength
  - For a given seet of loads (7 loads)
    - Find the best Quad laminate
    - Find the best DD laminate
  - Design for pristine material or for material with a hole (damage assesment)

Lamsearch

- **Selection of material**

Material selection				
T300/5208	Trace (GPa)	X (Mpa)	X' (Mpa)	Ex (Gpa)
T300/5208	206	1500	1500	182

- **Best DD replacement**

Legacy Quad				intact		Best fit Double-dble crit(A11,A66)				Conv. Ratio
%[±0]	25	<0-100>	A11	67,5		[±PHI]	26,00	A11	66,8	0,99
%[45]	30	<0-100>	A66	18,5		[±PSI]	88,00	A66	19,4	1,04
%[90]	45	<-deducted	A22	101,9				A22	100,9	0,99

- **Best DD laminate for an objective stiffness [A]**

Given [A]		Best fit double-double				Conv. Ratio
A11	95,0	[±PHI]	77	A11	88,5	1,31
A66	14,5	[±PSI]	13	A66	14,5	0,78
A22	82,5	<- deducted		A22	89,1	0,87

Best Design for strength

Loads

Set 3: Wings, blades

Set 2: Fuselage

Load case	MN/m	MN/m	MN/m
Load 1	2,0	0,0	0,0
Load 2	-1,0	0,0	0,0
Load 3	0,0	0,0	1,0
Load 4	1,0	2,0	0,5
Load 5	-1,0	0,0	0,5
Load 6	0,0	0,0	0,5
Load 7	0,0	0,0	0,5

Legacy quad	Unit circ	Double-double	Unit circ	Ratio
R/smooth	237	R/smooth	249	105%
%[0]	30	[±PHI]	21	
%[±45]	50	[±PSI]	67	
%[90]	20			
Number	1	Number	1	
R/notched	94	R/notched	98	104%
Smth/notd	2,5	Smth/notd	2,6	
%(wt/alum)	57%	%	52%	
A11	77,2	A11	71	
A22	59,1	A22	67	
A66	22,7	A66	22	
A12	22,7	A12	22	
Trace	181,7	Trace	182	
OHT, MPa	188	OHT, MPa	197	105%
OHC, MPa	188	OHC, MPa	197	105%

Best laminate in double-double for 4 load sets

Double-double

IM7/977-3

WIDE BAND

±Φ\±Ψ	52.5	60.0	67.5	75.0
0.0	334	269	179	90
7.5	358	293	203	114
15.0	423	358	269	179
22.5	336	**448**	358	269
30.0	214	310	365	358

Hard, QI, Soft

FUSELAGE

±Φ\±Ψ	52.5	60.0	67.5	75.0
0.0	299	410	304	166
7.5	296	418	333	204
15.0	283	432	392	293
22.5	248	419	408	361
30.0	187	297	332	337

Hard, Soft

WING

±Φ\±Ψ	52.5	60.0	67.5	75.0
0.0	344	418	304	166
7.5	324	**437**	333	204
15.0	268	373	392	293
22.5	191	279	361	361
30.0	113	181	247	301

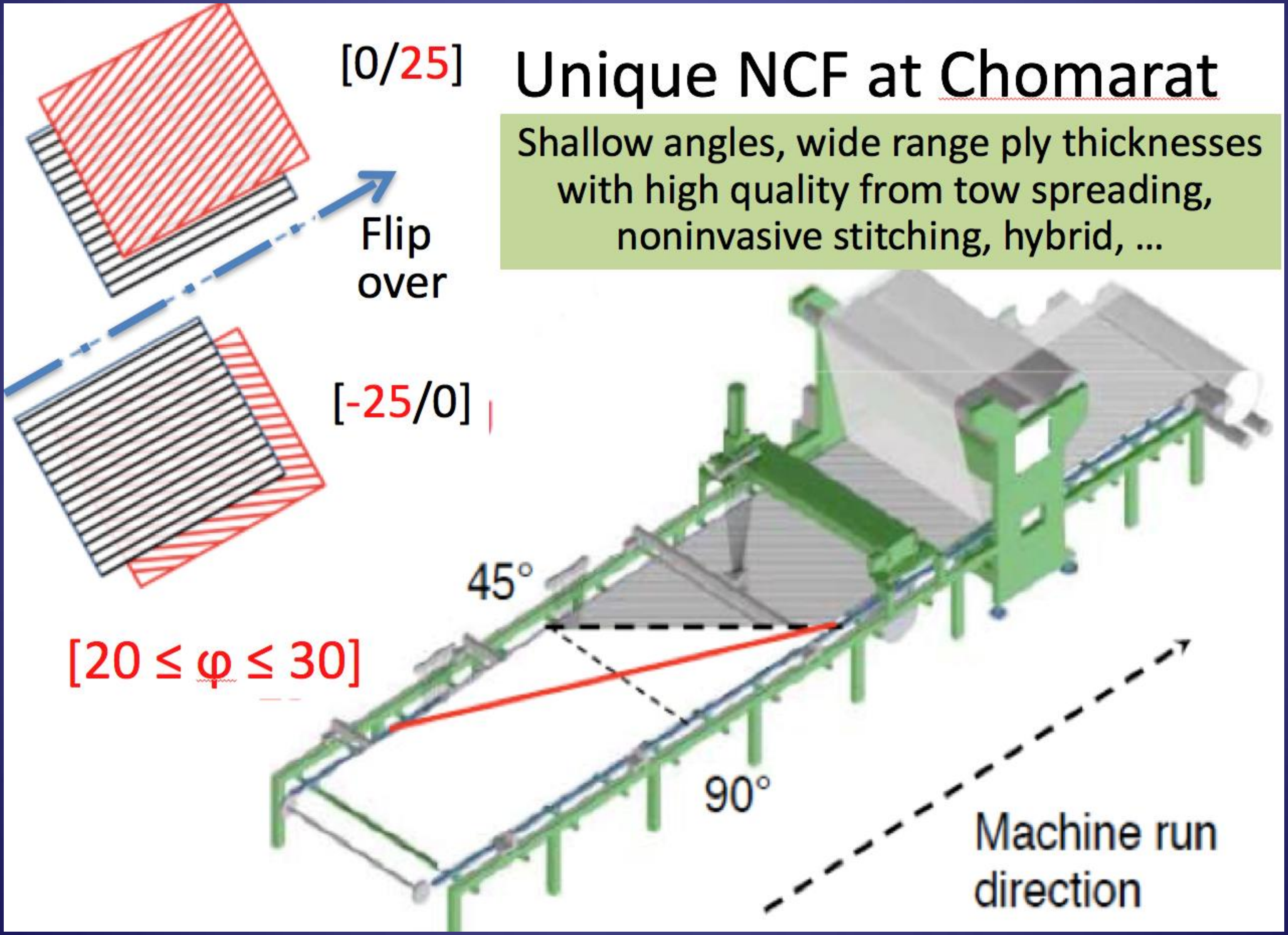
Hard, QI, Soft

SHAFT

±Φ\±Ψ	52.5	60.0	67.5	75.0
0.0	334	269	179	90
7.5	358	293	203	114
15.0	**424**	358	269	179
22.5	383	419	358	269
30.0	228	297	332	337

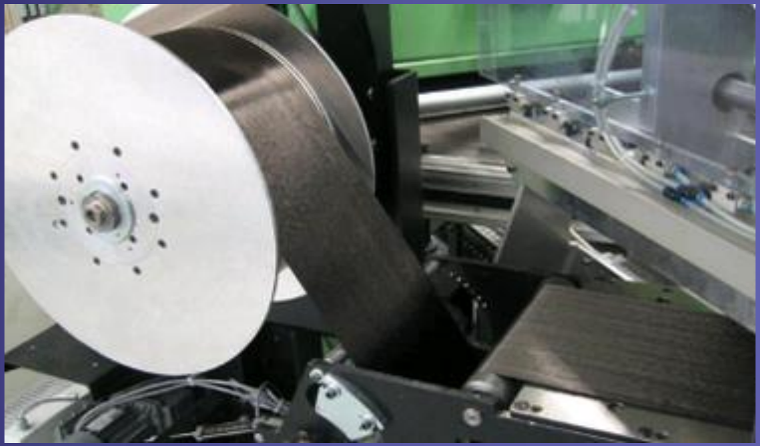
Hard, QI, Soft

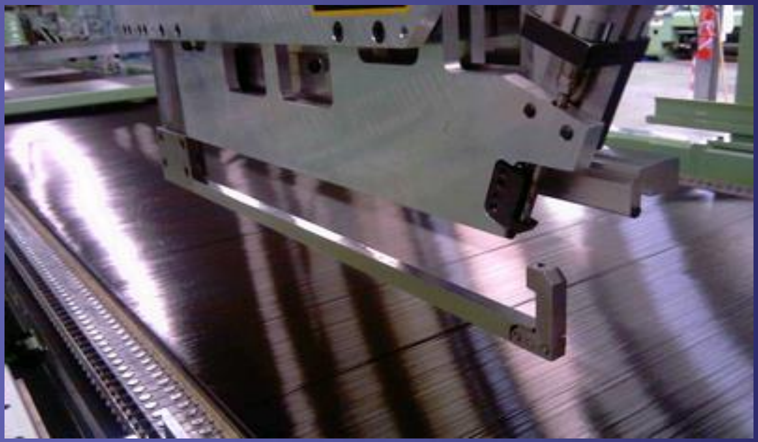
C-Ply: Bi-angle non crimp fabric



NCF Manufacturing Process

- Carbon fiber tape laying





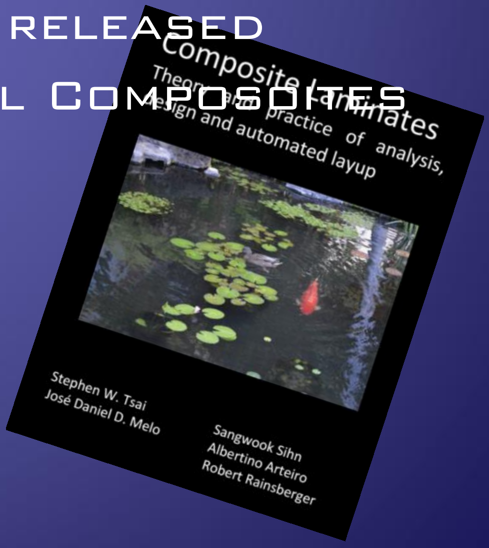
A new design paradigm ?

- Preliminary design and characterization can be faster and cheaper using the 3 data characterization (Tr, X, X')
- Prediction by simulation of A and B allowable of smooth and open-hole coupons is efficient
- Double double angle ply laminate is simple, easy to design and to manufacture and have unique advantages over conventional quad laminates
- Thin ply built-in laminates give natural homogenized properties (n>16, do not require symmetric stacking to prevent wrapping after curing, and allow simple drop ply strategy

Summary and Future Outlook

- Several comparison tests between DD and QUAD are underways on large scale structures
- Design of DD with large number of loads
- Systematic and/or random generation of loads
- New versions of LamSearch to be released

  (watch for Stanford bi-annual Composites design workshop)




COMBO #1 - DOUBLE-DOUBLE ®

Thank you for your attention!

Acknowledgment for support :

References

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- "An invariant-based theory of composites," *Composite Science and Technology* 100 (2014) 237-243
- "A unit circle failure criterion ...," *Composite Science and Technology* 123 (2016) 71-78
- With A. Arteiro, "A trace-based approach to design ...," *J. Reinforced Plastics & Composites* (2016)