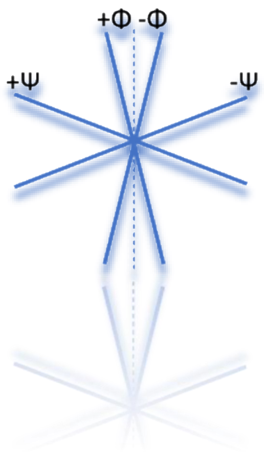
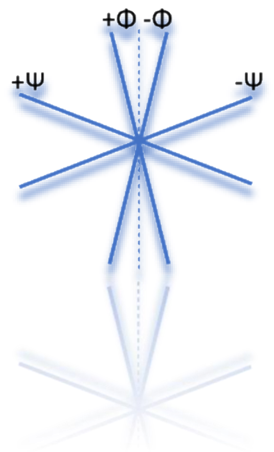


Double Double (DD)

Opening the frontiers between manufacturing, materials and optimum design of composite structures



Double Double (DD)

Opening the frontiers between manufacturing, materials and optimum design of composite structures

Steve Tsai[1] - Thierry Massard[1] - Michel Cognet - Naresh Sharma[2] - Albertino Arteiro[3] Surajit Roy[10] - R. Rainsberger[1] - Antonio Miravete[8] - Waruna Seneviratne[4] - Brúnó Vermes[5] - Jose Daniel Diniz Melo[9] - Carlos Cimini[11] - Tay Tong Earn[6] - Sangwook Sihn[7]

1 – Stanford – Department of Aeronautics and Astronautics
2 - Nashero
3 - Univ Porto
4 - Niar Wichita
5 - Univ. Budapest
6 -Nus Singapore
7 - Univ. Dayton
8- Whycomposites.com
9- Federal University of Rio Grande do Norte
10 – CSU Long Beach
11 - Universidade Federal de Minas Gerais

What are the current Composites Development Limitations ?

Stanford

Time to market for new material introduction

- Large number of coupons to be tested for new material qualification

Design

- Use of 0, 45, -45 90, orientations only in Aerospace
- No rational basis to optimize ply stacking permutation
- Weight penalty linked to minimum gage and mid-plane symmetry

Manufacturing cost

- Complex design with many material definition for the same part
- Low deposition rate
- Autoclave process

Mechanical properties after impact

Mechanical Fasteners (Bearing Strength)

…

Summary

Stanford

What is Double Double (DD)

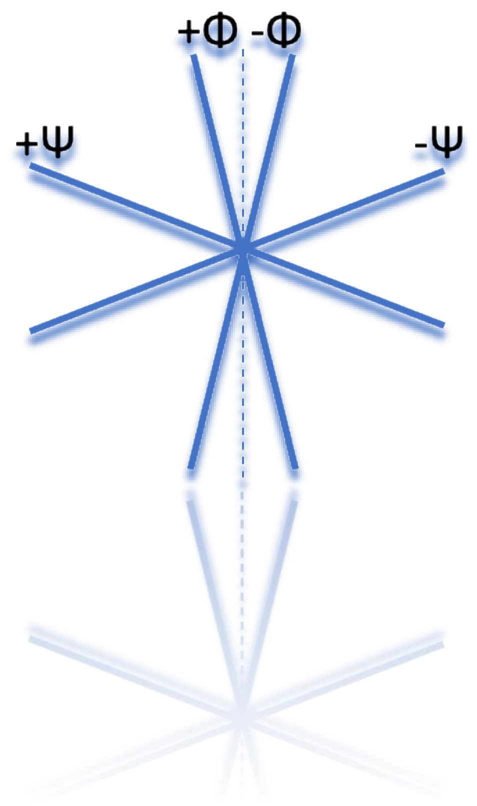
Design Tools for Double Double (DD)

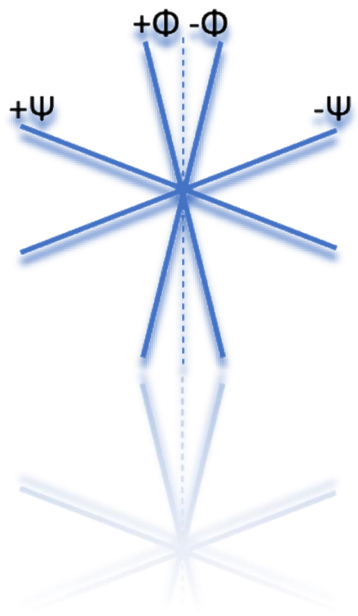
Homogenization & Ply Drop Strategy

Testing & Material Qualification

Manufacturing

Conclusion & next Steps





What is Double Double (DD)

What is Double Double (DD)

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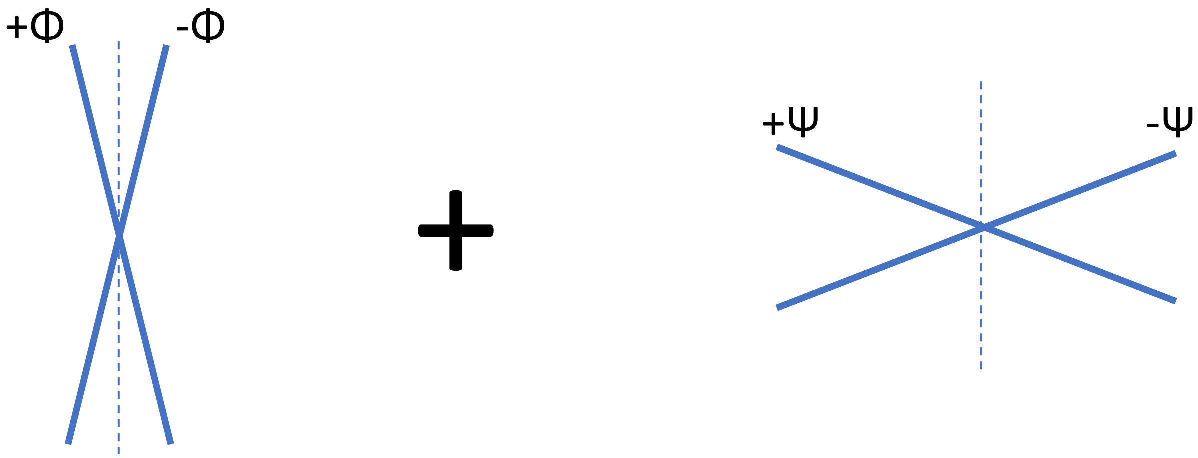
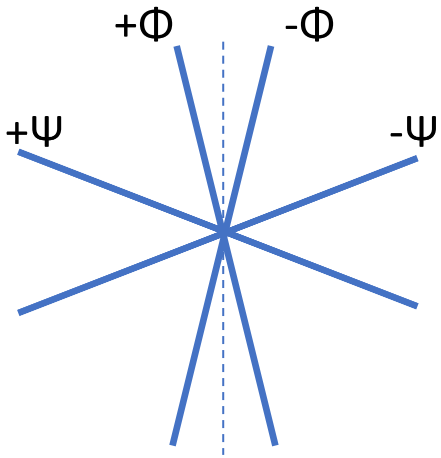
Angle Plies (Double)



Sub Laminate **Double Double ±Φ ±Ψ**



There is always a combination of Φ and Ψ meeting the required properties

Double Double Performance Adjustment vs Quad

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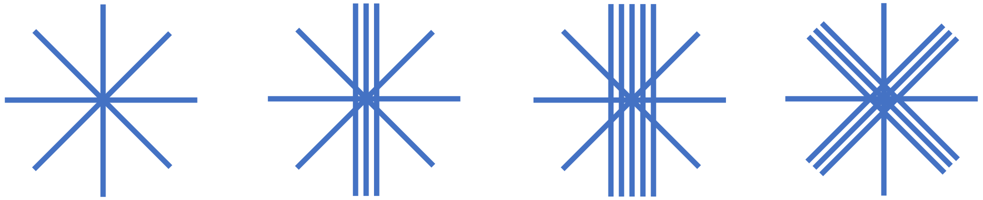
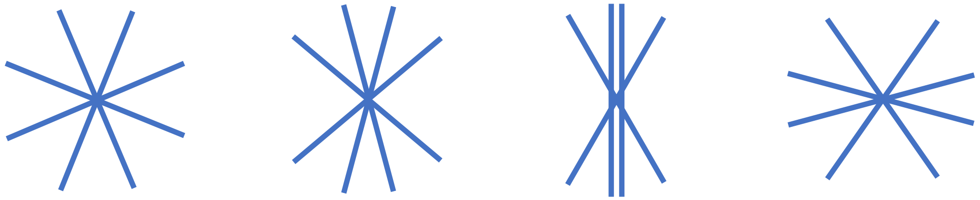
Quad performance is managed by adding 0°, 90° or ± 45° plies. Quad is discrete.



π/4 Hard Soft

Increased number of plies : 4 to 6, 8, 10…

Double Double performance is managed by tuning Φ & Ψ. DD is continuous, adjustible.



DD is always 4 plies, easier Homogenization

Ply drop strategy simple and flexible

DD can match all laminates π/4, soft, hard, preferred direction

Double Double (DD) Key Benefits

Stanford

DD leads to lighter parts

- DD **optimization is continuous** (quad is discrete)
- 4 plies minimum gage allows fine **thickness tuning**

DD laminate is homogeneous if sufficient repeat is achieved, requiring **no mid-plane symmetry**

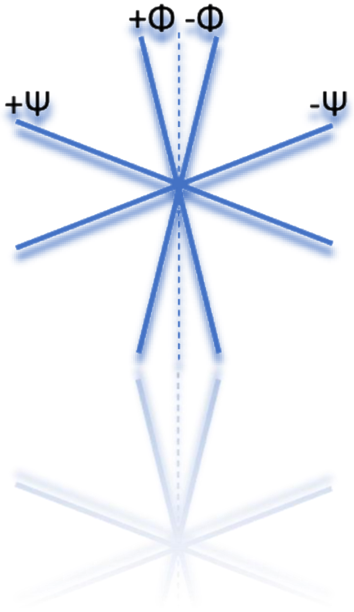
Simple Ply drop strategy thanks to minimum gage and mid-plane symmetry free design

DD optimization by large zone is achieved by **thickness variation with a unique DD as with metal**

Efficient manufacturing and easier repair

- Always the same simple 4-ply sub laminate ±Φ/±Ψ
- DD can be tapered either by additive lay up or subtractive ply drop or machining
- ±Φ and ±Ψ can be prebuilt to speed up deposition rate using Non Crimp Fabrics ie C-Ply™

DD overcomes most of many current major composites limitations



Design Tools for Double Double (DD)

Design Tools for Direct Conversion to Double Double

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- **Excel Lamsearch**
  - Loading case in strength → Best Double Double
  - Up to 49 possible loads
  - For a given Quad Lamsearch provides an equivalent DD in stiffness

- **Matlab Lamsearch**
  - Loading case in strength → Best Double Double
  - Up to 5 possible loads
  - Matlab allows many repeat if necessary, to achieve larger loading case.
  - Buckling optimization

Lamsearch tools are robust, open source and delivers optimized laminates

DD Efficient Optimization Tool : LamSearch

Stanford

R Strength

Load Case

±Φ \ ±Ψ	0,0	7,5	15,0	22,5	30,0	37,5	45,0	52,5	60,0	67,5	75,0	82,5	90,0
0,0	0	1	3	14	43	104	208	279	226	151	75	20	0
7,5		0	2	11	38	96	198	294	246	171	96	41	20
15,0			0	5	25	75	168	312	301	226	151	96	75
22,5				0	9	44	121	249	**360**	301	226	171	151
30,0					1	15	67	[illegible]	272	326	301	246	226
37,5						2	21	82	142	192	227	247	254
45,0							1	21	56	94	123	141	148
52,5								1	15	36	56	70	75
60,0									1	10	21	30	33
67,5										1	7	11	13
75,0											1	5	6
82,5												[illegible]	4
90,0													[illegible]

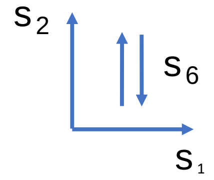
Optimum Strength

Optimum DD Laminate for this specific load case
[±22,5/ ±60]

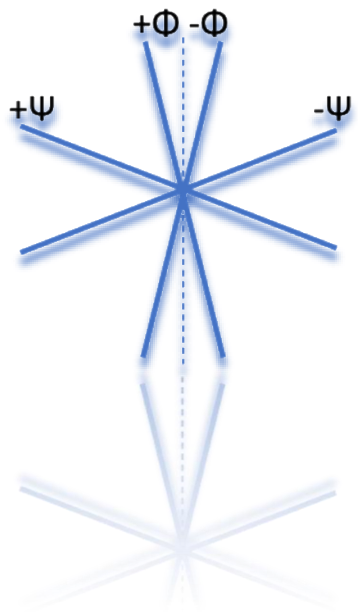
Mpa

Load Set	s_1	s_2	s_6
Load 1	1		
Load 2	-1		
Load 3			1
Load 4	1	0.5	
Load 5	1		0.5
Load 6		0.5	1
Load 7		1	

In plane loads



There is always a combination of Φ and Ψ meeting the required properties



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Homogenization & Ply Drop Strategy

Homogenized Laminate

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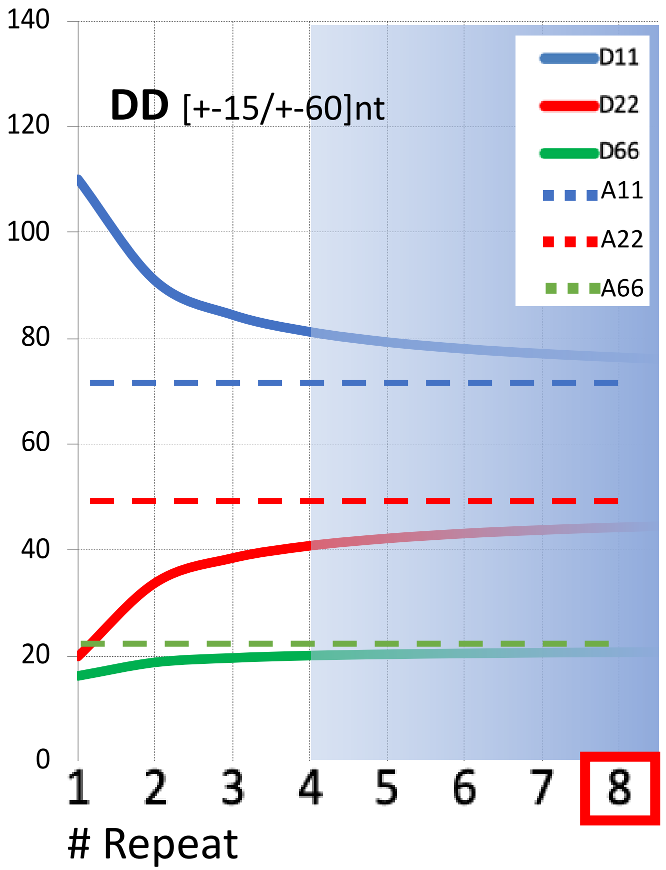

DD reaches homogenization at lower thickness thanks to its constant 4-ply minimum gage

Homogenization eliminate the need for mid-plane symmetry

Single Ply 0.125 mm	Single	#	Minimum (mm)	
	Ply (mm)	Repeat	Gage	Laminate thickness
QI [0/+-45/90]ns	0.125	Sym	1.00	2.00
Hard [0_5/+-45/90]ns	0.125	Sym	2.00	4.00
DD Homogenized	**0.125**	**8**	**0.50**	**4.00**
DD Homogenized Thin Ply	**0.062**	**8**	**0.25**	**2.00**

Homogenized DD the ultimate ply drop solution, unique lightening

DD Homogenization easier to achieve

Stanford

DD reaches homogenization at lower thickness

Tapering is possible for low minimum-gage laminates

Single ply drop possible and can be positioned inside or outer surfaces of laminate

Tapered DD is not sensitive to delamination in fatigue

DD does not have to be mid-plane symmetric

DD is not stacking dependent

[±Φ/±Ψ] / [+Φ/+Ψ/-Φ/-Ψ] / [+Φ/-Ψ/-Φ/+ Ψ] are equivalent

DD Simple Ply Drop Strategy

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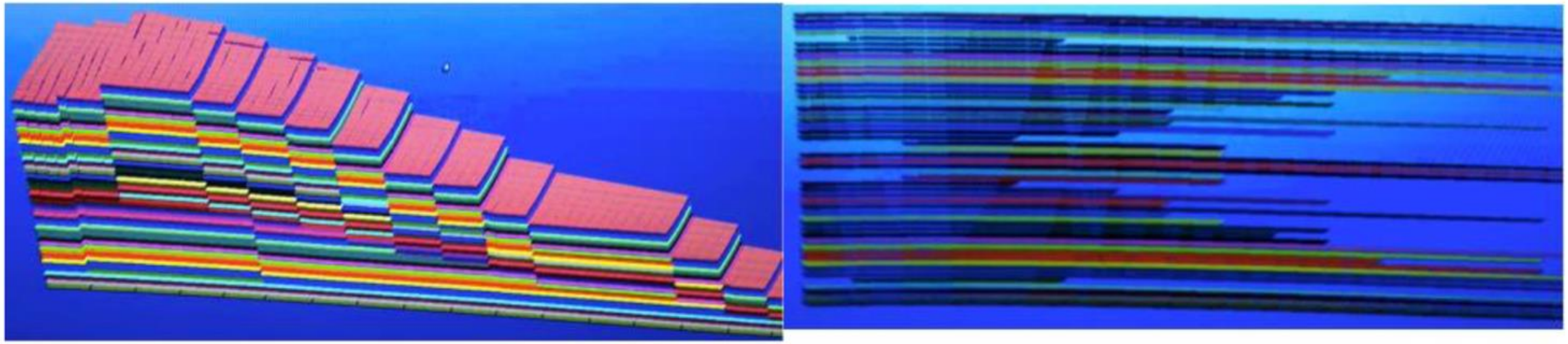
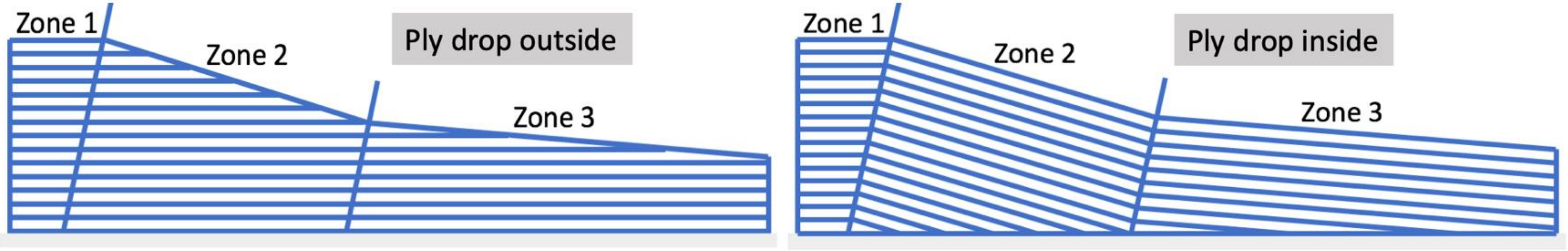
Wing profile
Sce : Hypersizer

Legacy quad

Thousands of discontinuities



DD



Performance by zone is achieved by thickness variation with a unique DD

DD High Performance tapering demonstrated

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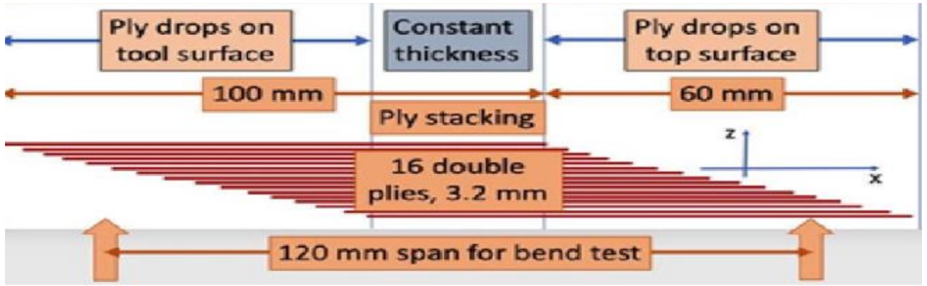
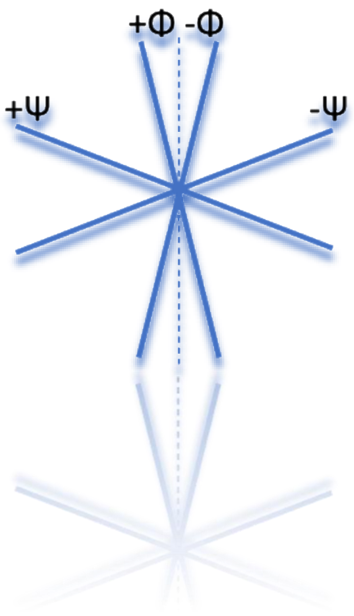


3 points bending test ASTM D7264 @NIAR (Waruna Seneviratne) Static and Fatigue

Results

- Failure : symmetric delamination appeared from both sides in the coupons (3rd to 5th layer)
- Coupons retain full strength after 500 000 cycles at 60% of the failure strength

Excellent static and fatigue properties of DD tapered beams



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Testing & Material Qualification

DD vs Legacy Quad

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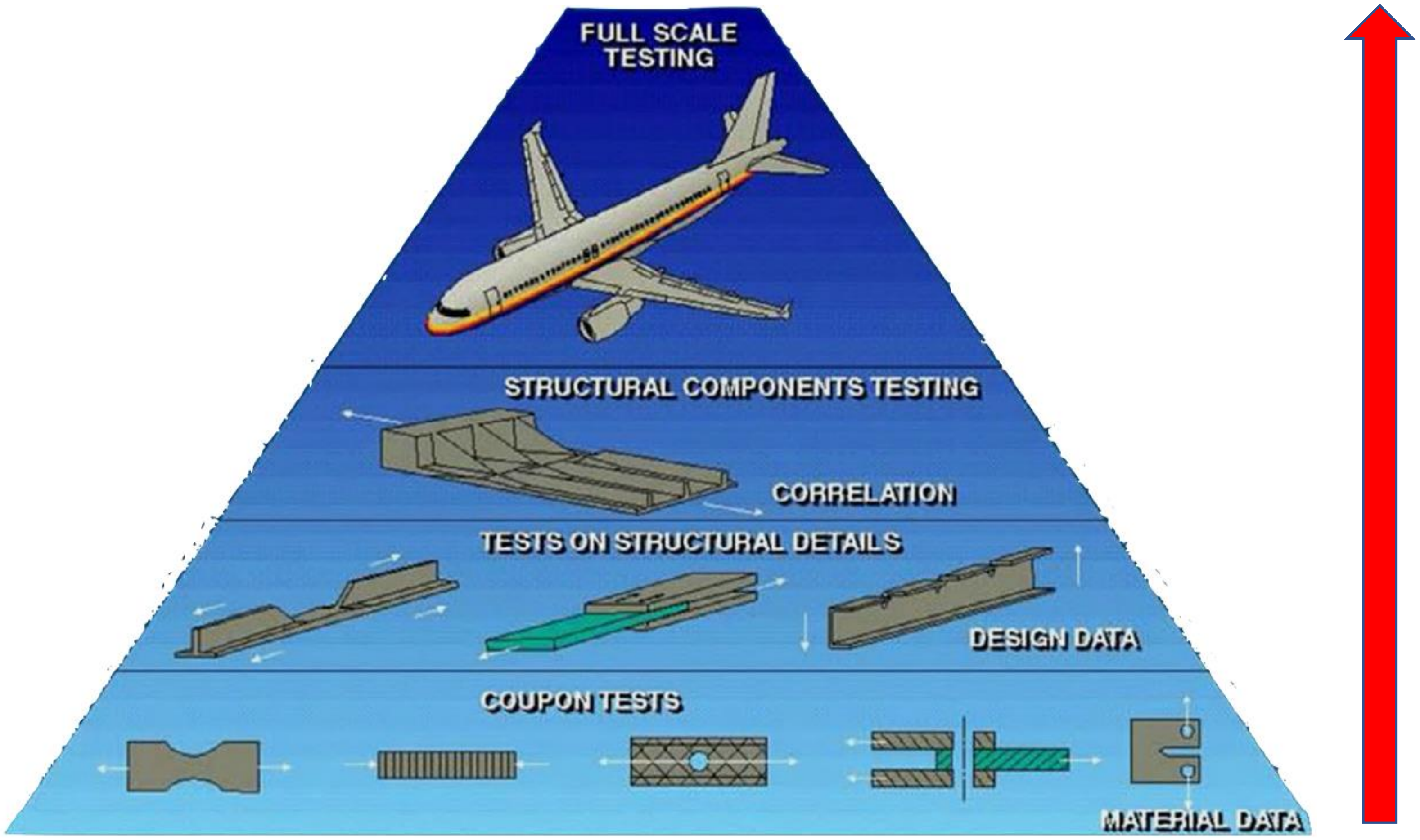
Sub Laminate	# Possible Laminates	# of possible Permutations
Quad 4	1	24
Quad 5	2	≃ 100
Quad 6	4	> 1 000
Quad 8	10	> 25 000
DOUBLE DOUBLE	**All**	**4**

DD always the same stacking – No stacking sequence permutation issues

Testing Pyramid for Quads

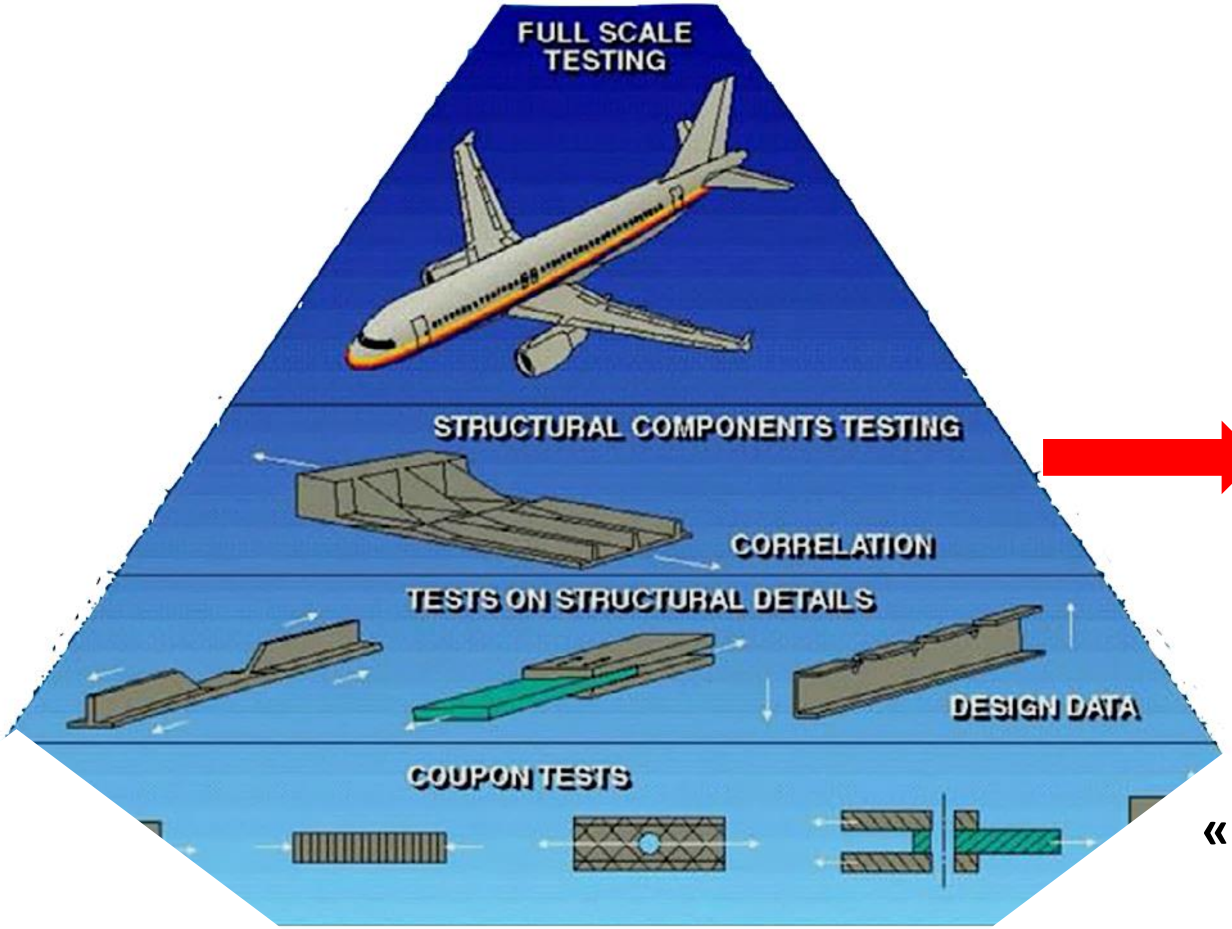
Stanford



High number of tests – Change in the material comes with huge cost

Proposed DD Testing

Stanford



Lamsearch from FEA design Provides Optimum DD

Test only those « as built » DD laminate

Using DD requires far less characterization tests

Proposed DD Material Qualification

Stanford

Stiffness

- Only ONE stiffness measurement is necessary
- All the other components of the stiffness matrix can be deducted using TRACE (see previous Steve Tsai Works)

Strength

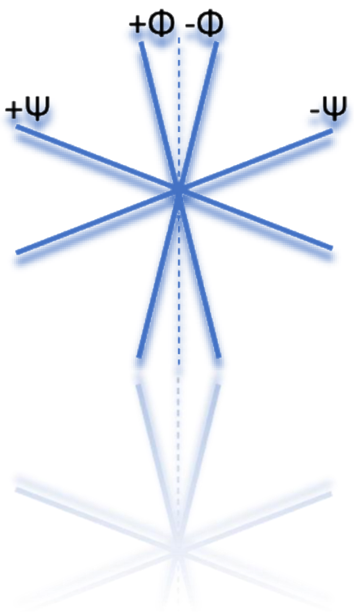
Strength data depends on the failure criteria used for design assessment

• Quadratic as TSAI-WU	5 measurements X , X', Y, Y', S,	For certification
• Nettles circle	One DD measurement (ε max)	For preliminary design

Damage material properties (as usual)

- Open-hole tension and compression
- Compression after impact
- Tension after impact

By using TRACE, DD material qualification requires far fewer tests



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Manufacturing

Manufacturing Focus

Stanford

Large areas with different loading case can be designed using the same DD

Faster and less prone to stacking error with no mid-plane symmetry and single ply drop

Much simpler transition from one zone to the other through thickness management

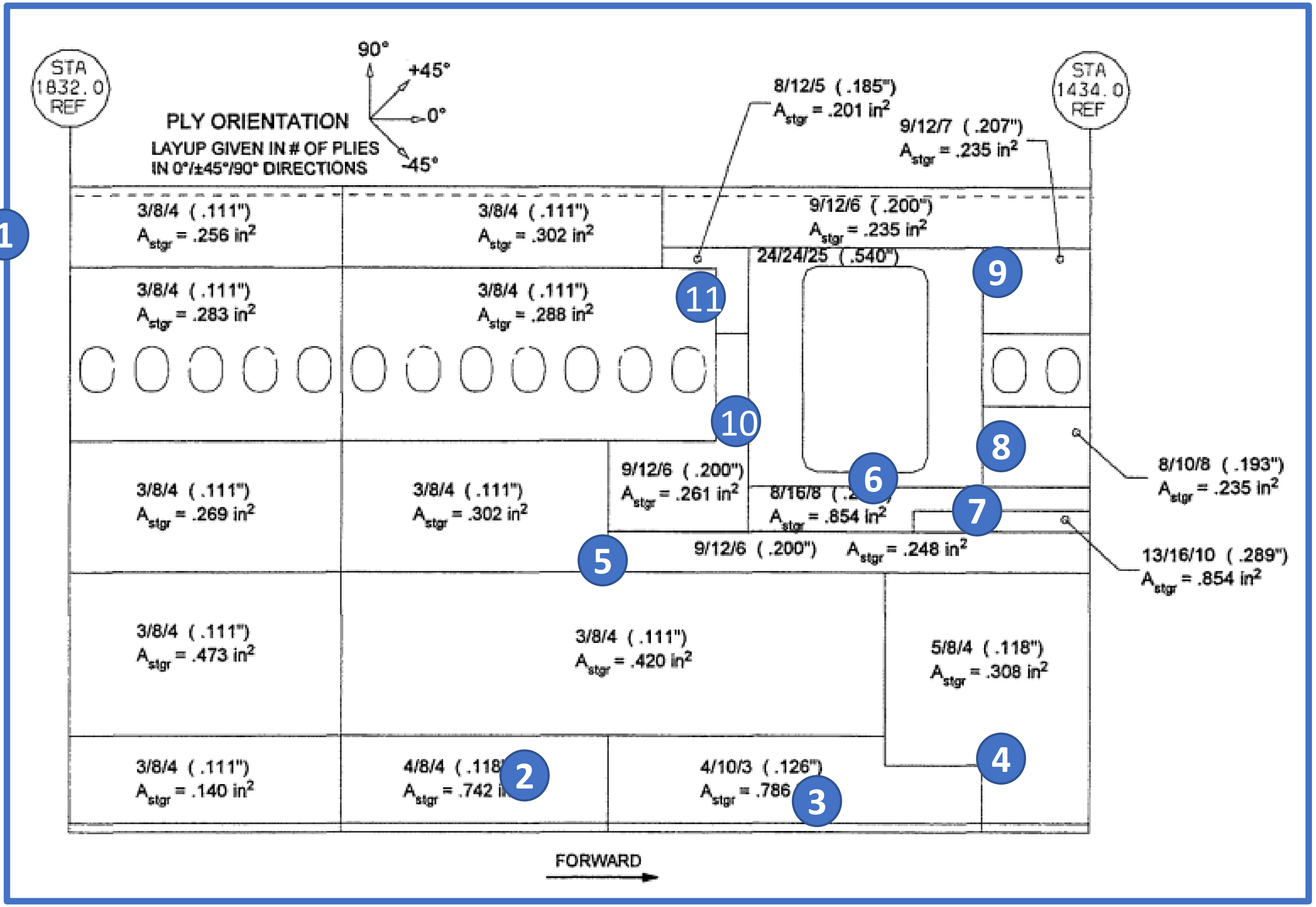
$\pm\Phi$ and $\pm\Psi$ can be prebuilt to speed up deposition rate using Non Crimp Fabrics

- Non Crimp Fabric allows Infusion processes even for large parts like aircraft wings.
- Combining DD laminates and Infusion processes offers great manufacturing improvement
- One-axis layup is at least 4X deposition rate

High Deposition Rate

Fuselage Design : 11 different Quads

Stanford

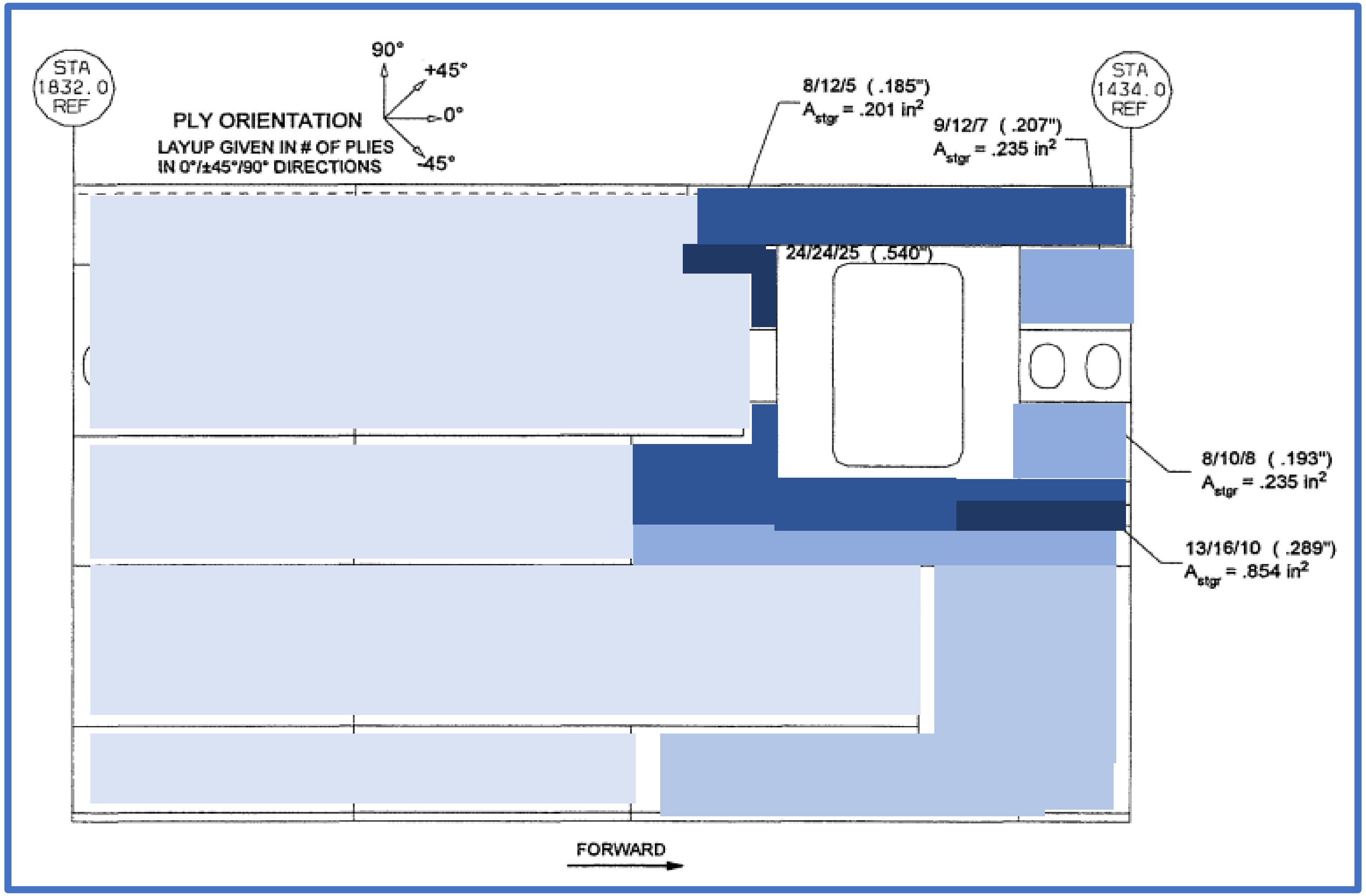


Zone #	n [0]	n[+/-45]	n [90]	total
1	3	8	4	15
2	4	8	4	16
3	4	10	3	17
4	5	8	4	17
5	9	12	6	27
6	8	16	8	32
7	13	16	10	39
8	8	10	8	26
9	9	12	7	28
10	24	24	25	73
11	8	12	5	25

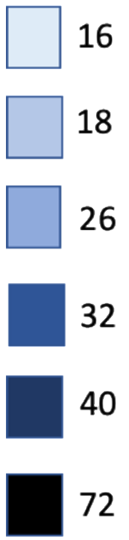
Patchwork of 11 different Quads
Complex continuity between zones

1 single DD matching 11 Quad Stiffness

Stanford



Best DD replacement
[± 20 / ± 66] for this example



By tapering between 6 zones

11 different Quads replaced by one DD laminate – Thickness management

Fuselage Design

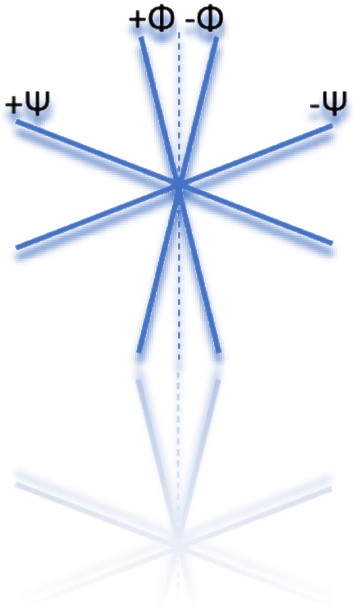
Stanford

The simple DD design allows large manufacturing cost savings

- High deposition rate with a single DD
- Manufacturing savings with no weight penalty
- Weight savings are possible taking full advantage of DD minimum gage
- Aggressive taper facilitated by single ply drop leading to weight reduction

Using a single Quad definition for the fuselage would increase weight by 20%.

DD offers tapering capability - Thickness variation as with metal



Conclusion & Next Steps

Double Double (DD) Next Steps

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Software improvement to optimize both strength and stiffness constraints

Failure criteria assessment and data acquisition

Damaged properties assessment and modeling

Buckling and micro buckling

Current case studies :

- Nasa cone adapter
- Campania University Italy Fuselage
- Otto Aviation DD for entire fuselage

Double Double (DD) Key Benefits

Stanford

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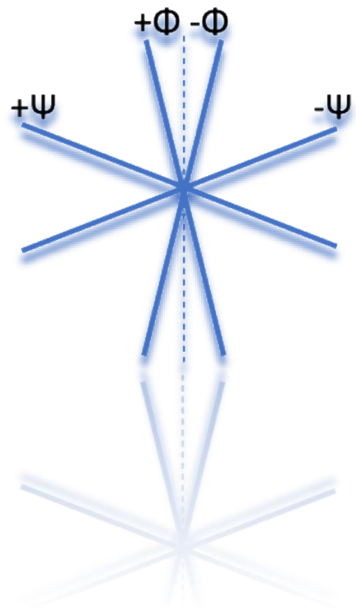
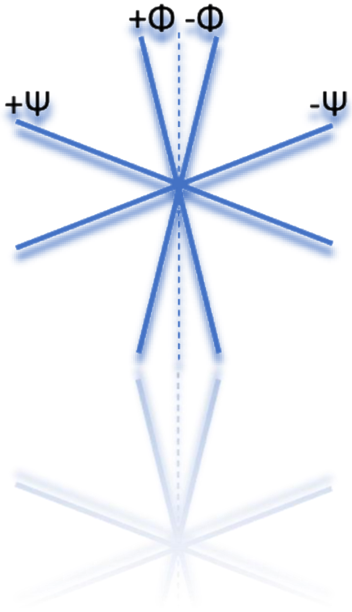
DD overcomes most of many current major composites limitations

Double Double (DD)

Opening the frontiers between manufacturing, materials and part performance for the optimal design of composite structures





Annex

Fuselage design 2/3

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Quads										
Zone #	n [0]	n[+/-45]	n [90]	total	% [0]	% [+/- 45]	% [90]	A11	A22	A66
1	3	8	4	15	20%	53%	27%	56,45	22,66	66,23
2	4	8	4	16	25%	50%	25%	62,33	21,67	62,32
3	4	10	3	17	24%	59%	18%	64,26	24,64	54,47
4	5	8	4	17	29%	47%	24%	66,81	20,68	59,82
5	9	12	6	27	33%	44%	22%	71,30	19,70	57,31
6	8	16	8	32	25%	50%	25%	62,33	21,67	62,32
7	13	16	10	39	33%	41%	26%	70,19	18,71	60,40
8	8	10	8	26	31%	38%	31%	66,28	17,72	66,28
9	9	12	7	28	32%	43%	25%	69,53	19,37	59,74
10	24	24	25	73	33%	33%	34%	67,23	16,07	68,62
Average					29%	46%	26%	65,67	20,29	61,75
CV					4%	6%	3%			

DD	Best DD replacement						
Zone #	±Φ	±Ψ	A11	A22	A66	n	n plies
1	26,0	69,0	56,45	22,66	66,23	4,00	16,00
2	22,0	63,0	62,33	21,67	62,32	4,00	16,00
3	22,0	62,0	64,42	24,76	54,07	4,25	18,00
4	19,0	66,0	66,79	20,54	60,13	4,25	18,00
5	20,0	71,0	71,50	19,21	58,07	7,00	28,00
6	22,0	63,0	62,33	21,67	62,32	8,00	32,00
7	19,0	70,0	69,98	19,16	59,69	10,00	40,00
8	18,0	66,0	65,65	17,97	66,40	6,50	26,00
9	19,5	69,5	69,98	19,16	59,69	7,00	28,00
10	16,0	67,0	67,26	16,05	68,65	18,00	72,00
Average	20,4	66,7	65,67	20,29	61,76		
CV	2,12	2,65	3,43	1,97	3,43		

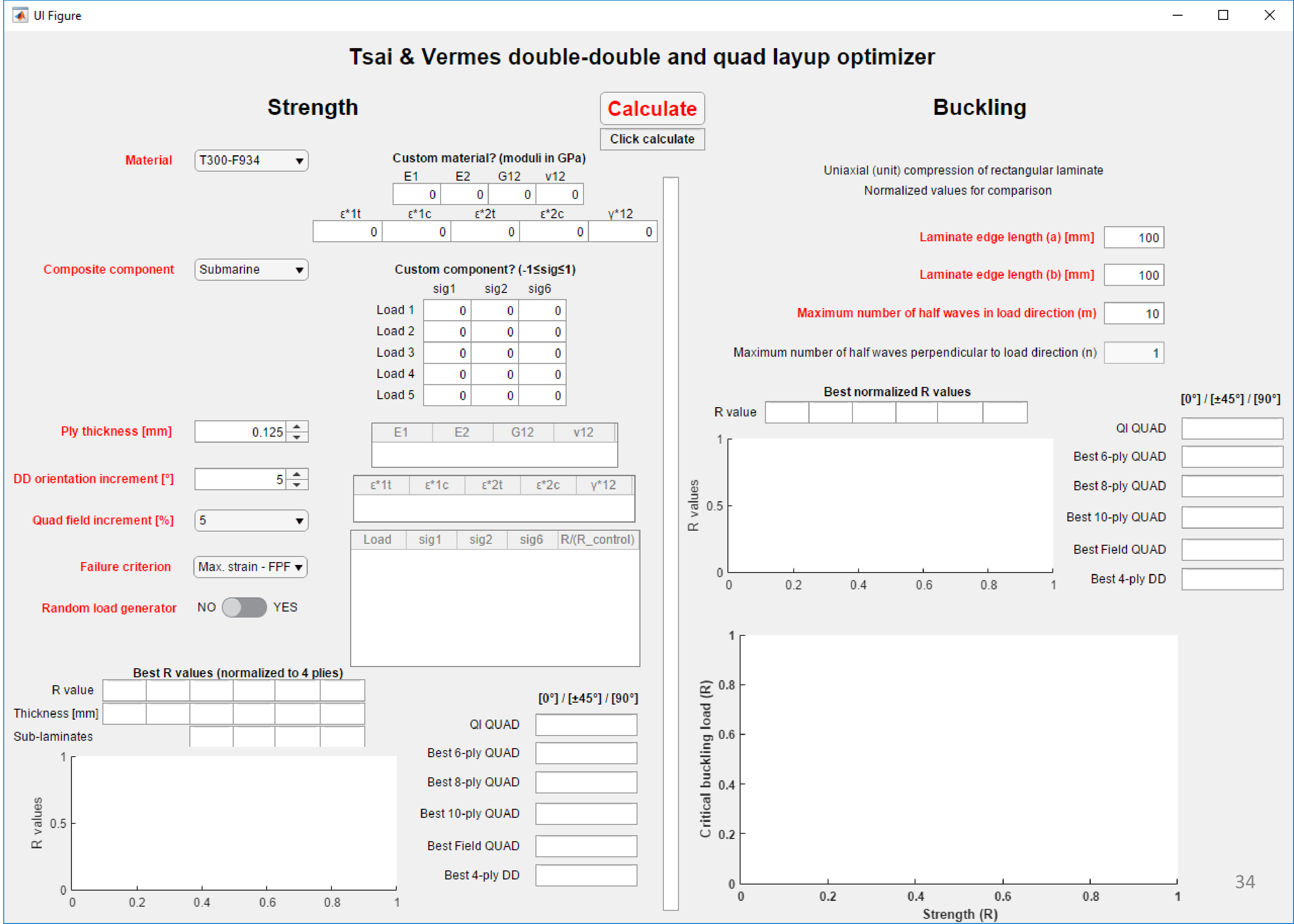
Material T800 / 3900

Matlab Lamsearch optimization tool

Stanford

- **Quad (QD)** ($[0_m/\pm 45_n/90_p]_{rS}$) **vs. double-double (DD)** ($[\pm\varphi/\pm\psi]_{rT}$)
- Based on classical laminate theory
- MATLAB script
- **Strength** comparison
- **Buckling** comparison
- Strength vs. buckling graph

- **Simple graphical interface**
- User defined custom inputs (red)
- Strength and buckling



- **Results**

- Comparing quad and double-double

- Strength *vs.* buckling for laminate selection