SAND2013-7360P

Investigating the use of a Higher Modulus Carbon Fiber in the Sandia 100m Carbon Wind Turbine Blade

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Overview

- Introduction
- Objectives
- Method
- Conclusions

Introduction

- Large blades
  - Produce more power
  - Produce rated power in lower wind speeds IEC-IIIB
  - Weight of blades
  - High performance materials
- Energy Surety
  - Expanded access to **sustainable** energy
  - Increases national **security** with "homemade energy"
  - Has the potential to reduce wind energy **cost** by reducing the overall cost of the turbine by using higher performing materials

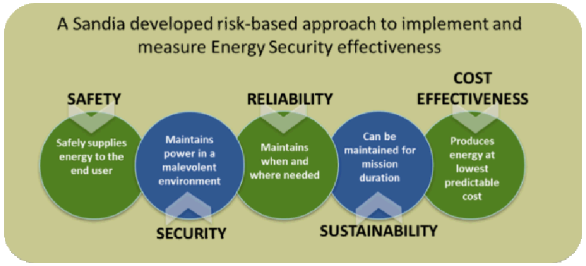


Figure 1. Points of Energy Surety.

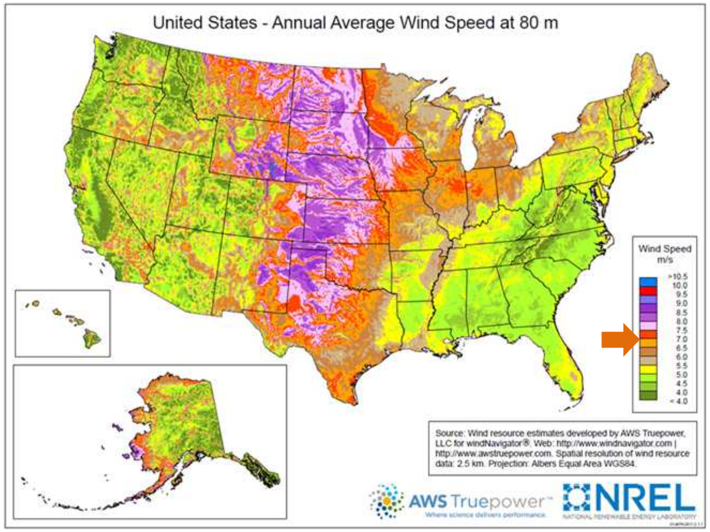


Figure 2. National Renewable Energy Lab. Wind Resource Map at 80m height [2].

Introduction

- Scale
  - Isotopes baseball stadium

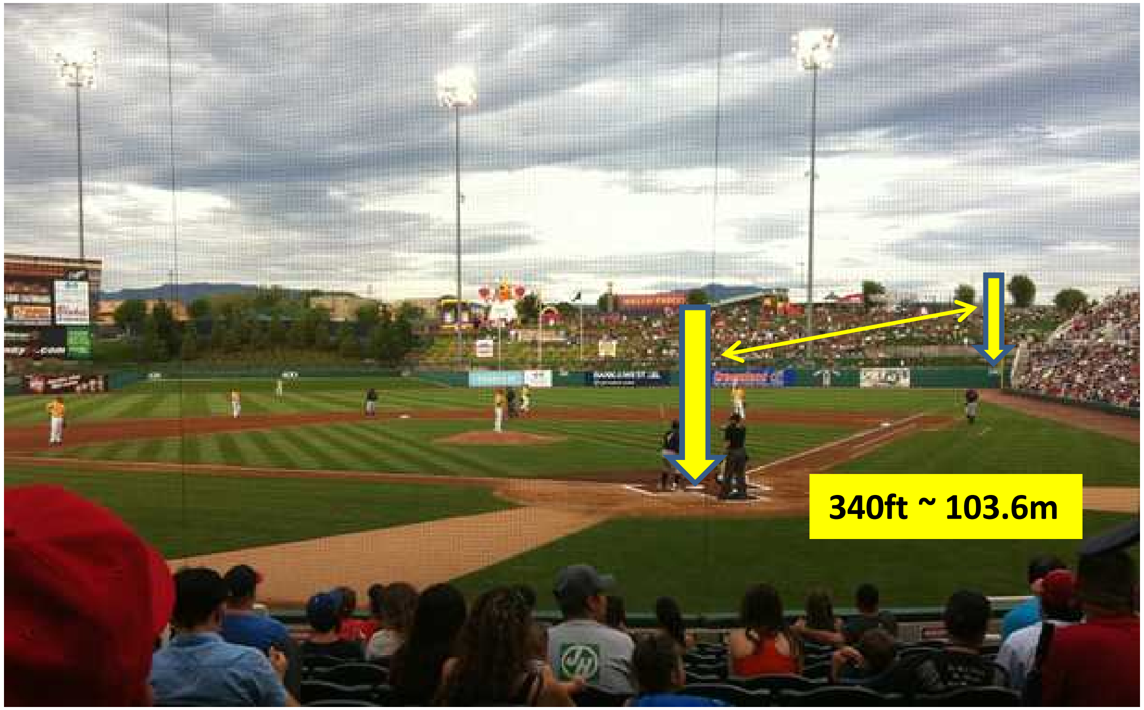


Figure 3. Blade length compared to Isotopes field

Objectives

- See if strategically used carbon fiber could reduce cost and improve performance over all glass blade for 100m length
- Improve upon baseline SNL 100-01 carbon blade model

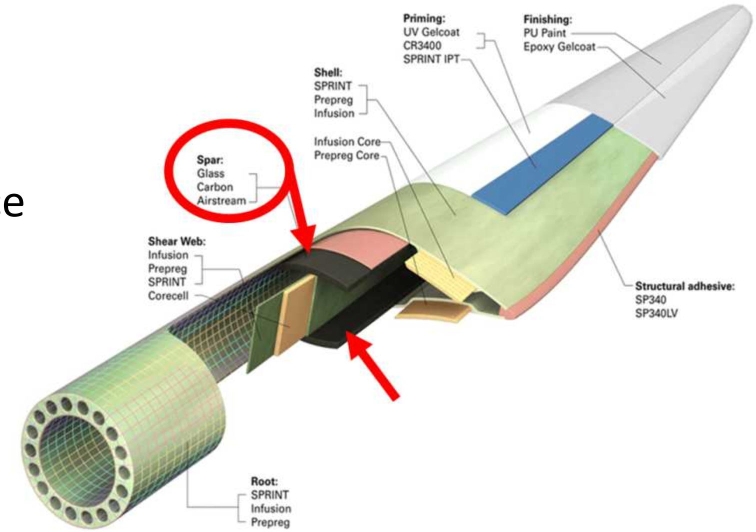


Figure 4. Wind turbine blade anatomy [3].

Design Margins

Analysis	Design Load Condition (DLC) designation	Metrics	Notes/method
Fatigue	Turbulent Inflow (NTM) (4 to 24 m/s)	202 years fatigue life at 50% span in spar 570 years fatigue life at 15% span in spar 1260 years fatigue life at 24% span in TE	MSU/DOE Database provided single cycle failure values and GL was referenced for slope values (10 for glass and 14 for carbon); Miner's Rule calculation
Ultimate	EWM50; 0 degree pitch with 15 degree yaw error	Max strain = 3525 micro-strain Allowable strain = 5139 micro-strain Max/allowable = 68.6%	At 2% span (near root); flap-wise; FAST
Deflection	ECD-R	Max (10.48 m) vs. allowable (13.67 m); Clearance = 3.19 m = 23.3%	FAST, NuMAD/ANSYS
Buckling	EWM50; 0 degree pitch with 15 degree yaw error	Min load factor (2.077) vs. allowable (2.042); near root to 10 meters span-wise)	Linear, ANSYS
Flutter	--	Flutter margin 1.84 (@ 13.7 RPM)	Sandia NuMAD-based Flutter Tool (BLAST); updated tool since SNL100-00 calculations

Strength

Stiffness

Figure 5. Blade design performance metric summary [4].

Objectives

- Stiffness critical parameter
  - Change geometry
  - Increasing volume fraction of fibers
  - Increasing modulus of constituents
- Less expense to increase modulus than strength
  - Can we reduce ply count used in the spar at a greater rate than the price increase for a higher modulus composite
  - Look at the possibility for predictive cost modeling for desired material properties
- Potential benefits
  - Design margins allow tradeoff of strength for stiffness
  - Potentially reduce amount of carbon fiber needed, which could reduce material cost

Objectives

- Current Accomplishments
  - Cost
    - Identify components of carbon fiber manufacturing process that increase the modulus
    - Obtain price increase estimation for modulus increase
  - Design Margins
    - Create 3 lamina with standard, intermediate, and high modulus fibers
    - Match stiffness distribution of baseline using higher modulus composites

Methods

- Overview for modifying ORNL cost model for SNL blade material cost input

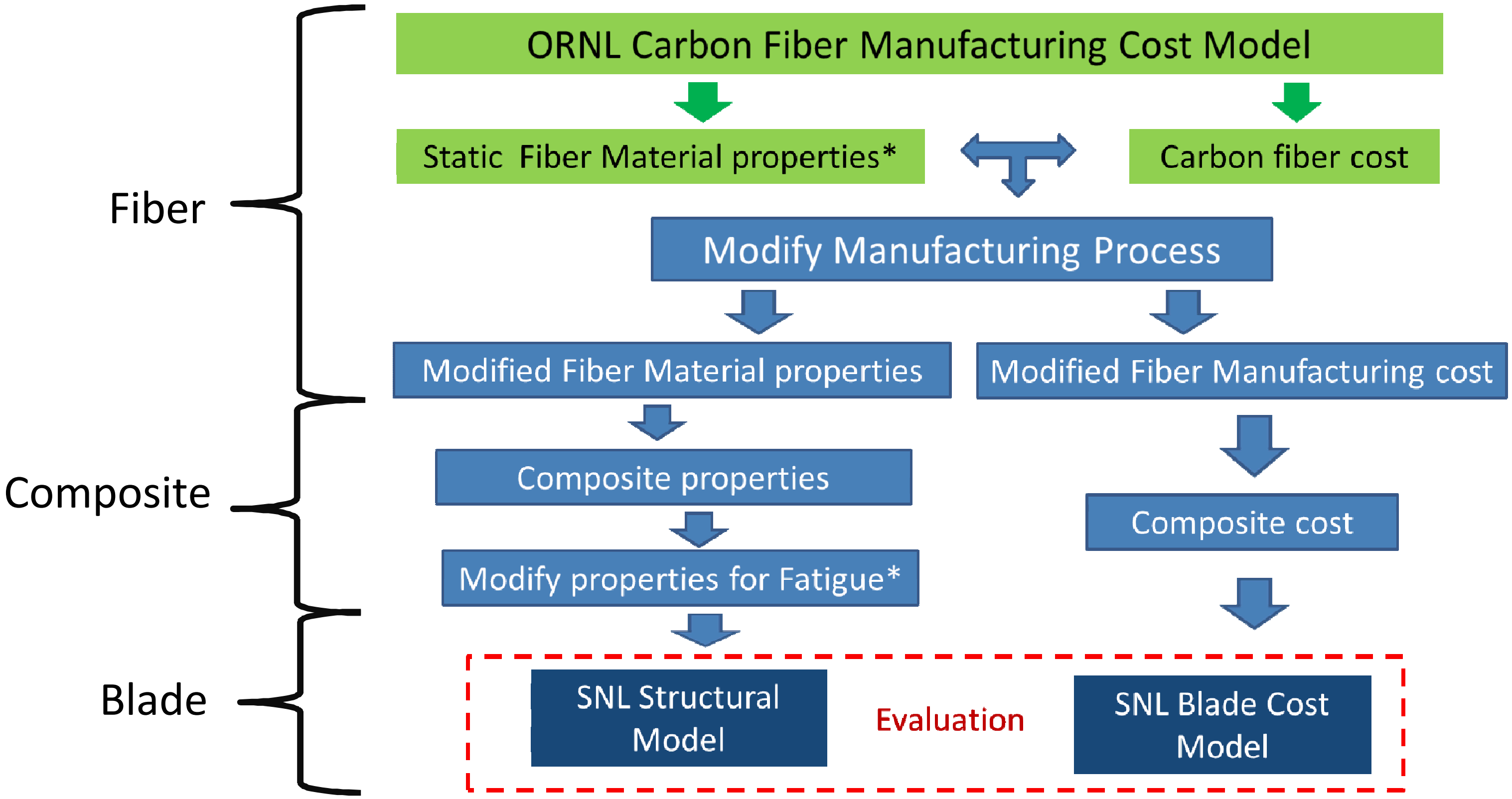


Figure 6. Feasibility evaluation model.

Cost

Methods

- Modifying manufacturing process
  - Changes
    - Precursor
    - Temperature profile

Original carbon fiber manufacturing process

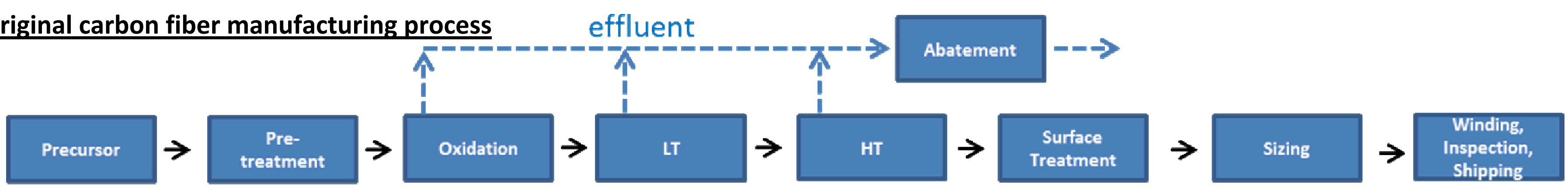


Figure 7. ORNL manufacturing cost model parameters[5].

increase from 30 Msi to 40 Msi using the model

Modified carbon fiber manufacturing process

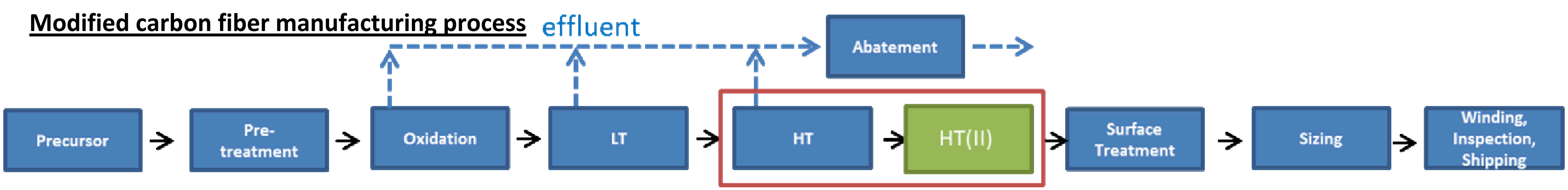


Figure 8. Modified manufacturing cost model parameters.

Methods

- First method required modifying a few manufacturing parameters :
  1. Doubled the floor space allocated to simulate space for a second HT oven
  2. Added 2 minutes to the HT residence time
  3. Applied an average temperature between the HT (1500C) and HT II (1800C)

Capacity of one CF line for the assumed plant availability and yields

2

Equipment width	3000	mm
Tow band width as proportion of equipment width	0.96	dimless
Tow band width	2880	mm
Tow spacing	20	mm
Strands/line	144	strands
Required line speed for entire plant	10.7647	m/min
Desired cxidation residence time	80	min
Required oxidation heated length for entire plant	861	m
Actual oxidation heated length for single CF line	862	m
Desired LT residence time	90	s
Required LT heated length for entire plant	16.1	m
Actual LT heated length for single CF line	16.2	m
Desired HT residence time	210	s
Required HT heated length for entire plant	37.7	m
Actual HT heated length for single CF line	16.2	m
Line speed imposed by oxidation equipment	10.78	m/min
Line speed imposed by LT equipment	10.80	m/min
Line speed imposed by HT equipment	4.63	m/min
Overall line speed imposed by equipment (min of Oxi, LT, HT)	4.63	m/min
Capacity of one CF line as defined by user	967,444	kg CF/yr
Number of CF lines required for desired production volume	3	CF lines
Collective utilization of all CF lines	0.7752	dimless
Hours equipment in operation per CF line	5,606	hours/CF line
Additional furnace hours for heatups (% of equipment hours)	10%	%
Total furnace hours per CF line	6,167	hours/CF line

HT furnace

3

kW installed	2715
HT Tmax (Celsius)	1,650
Steady state consumption (% of kW installed)	43%
Steady state kW consumption	1154
Number of CF lines in operation	3
kWh per year steady state	19,406,909
Warmup consumption (% of kW installed)	100%
Warmup kW consumption	2715
kWh per year warmup	4,565,741
Total kWh per year	23,972,650
Select process heating energy vector (1 = electrical, 2 = natural gas)	1
Cost per kWh	$0.0688
Total annual process heating energy cost	$1,649,318

1

Floor space allocation ft^2 per plant	
Pretreatment	30,000
Oxidation	30,000
LT	15,000
HT	30,000
Abatement	5,000
Surface Treatment	5,000
Sizing	5,000
Winding/Inspection/Shipping	30,000
	150,000

*HT oven was modified instead of adding a 3rd oven due to intricate equation referencing in model

Methods

- First method to simulate change in process that would increase fiber modulus from 30-40 Msi using textile PAN at a high volume production rate
  - The price increase was high, so a second method was also used

Standard Textile PAN process

$/lb CF Manufacturing Cost Matrix

	Materials	Capital	Labor	Energy	Total	
Precursor	$3.75	$0.00	$0.00	$0.00	**$3.75**	49.2%
Pretreatment	$0.00	$0.25	$0.13	$0.01	**$0.40**	5.2%
Oxidation	$0.00	$0.57	$0.13	$0.49	**$1.19**	15.6%
LT	$0.00	$0.26	$0.03	$0.10	**$0.39**	5.1%
HT	$0.00	$0.37	$0.03	$0.16	**$0.56**	7.4%
Abatement	$0.00	$0.12	$0.00	$0.12	**$0.24**	3.1%
Surface Treatment	$0.01	$0.19	$0.03	$0.08	**$0.31**	4.1%
Sizing	$0.01	$0.14	$0.03	$0.08	**$0.27**	3.5%
ng/Inspection/Shipping	$0.03	$0.20	$0.27	$0.02	**$0.51**	6.7%
Total	**$3.79**	**$2.09**	**$0.67**	**$1.05**	**$7.61**	
	49.8%	27.5%	8.8%	13.8%		

Modified Textile PAN process

...latrix

	Materials	Capital	Labor	Energy	Total	
Precursor	$3.75	$0.00	$0.00	$0.00	**$3.75**	27.6%
Pretreatment	$0.00	$0.55	$0.40	$0.03	**$0.98**	7.2%
Oxidation	$0.00	$1.54	$0.40	$1.13	**$3.08**	22.7%
LT	$0.00	$0.69	$0.10	$0.22	**$1.02**	7.5%
HT	$0.00	$1.14	$0.10	$0.39	**$1.63**	12.0%
Abatement	$0.00	$0.22	$0.00	$0.27	**$0.49**	3.6%
Surface Treatment	$0.01	$0.51	$0.10	$0.11	**$0.73**	5.4%
Sizing	$0.01	$0.38	$0.10	$0.12	**$0.60**	4.5%
ng/Inspection/Shipping	$0.03	$0.43	$0.81	$0.03	**$1.30**	9.6%
Total	**$3.79**	**$5.47**	**$2.02**	**$2.30**	**$13.58**	
	27.9%	40.3%	14.9%	16.9%		

78% increase in fiber cost using first method

Methods

- Second process change method
  - Add the price of the high temperature oven twice

$/lb CF Manufacturing Cost Matrix						
	Materials	Capital	Labor	Energy	Total	
Precursor	$3.75	$0.00	$0.00	$0.00	**$3.75**	49.2%
Pretreatment	$0.00	$0.25	$0.13	$0.01	**$0.40**	5.2%
Oxidation	$0.00	$0.57	$0.13	$0.49	**$1.19**	15.6%
LT	$0.00	$0.26	$0.03	$0.10	**$0.39**	5.1%
HT	$0.00	$0.37	$0.03	$0.16	**$0.56**	
Abatement	$0.00	$0.12	$0.00	$0.12	**$0.24**	3.1%
Surface Treatment	$0.01	$0.19	$0.03	$0.08	**$0.31**	4.1%
Sizing	$0.01	$0.14	$0.03	$0.08	**$0.27**	3.5%
ng/Inspection/Shipping	$0.03	$0.20	$0.27	$0.02	**$0.51**	6.7%
Total	**$3.79**	**$2.09**	**$0.67**	**$1.05**	**$7.61**	
	49.8%	27.5%	8.8%	13.8%		

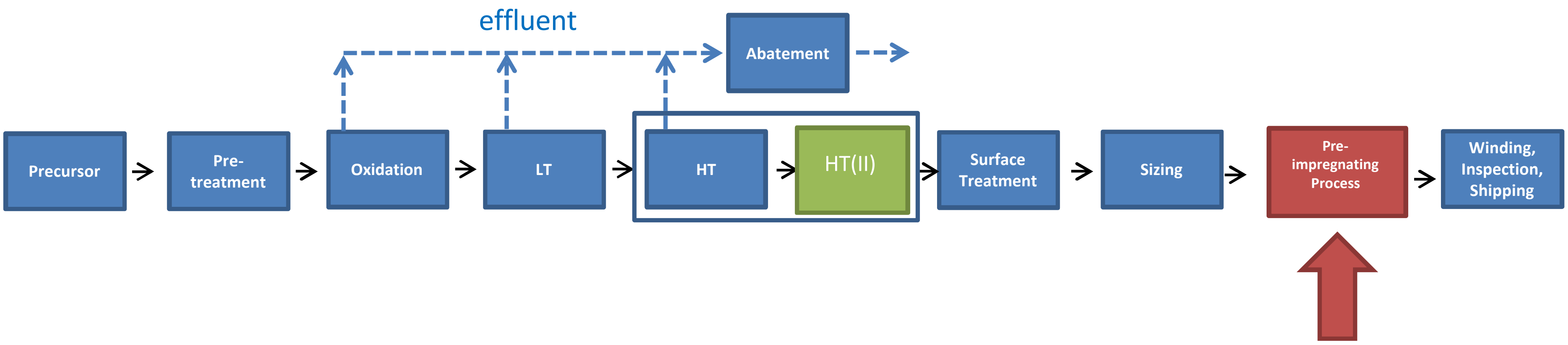
2x

$8.17

7.4% increase in fiber cost using the second method

Methods

- Additional factors that affect retail prepreg composite cost
  - Pre-impregnation process
  - Manufacturers mark-up



Methods

- Using the % increase in cost of fiber to improve modulus can be used to estimate the new price of composite with different properties
  - Example of how it could be used:

Retail price of uni-cf prepreg with a standard modulus - $26.40/lb

Standard mod fiber cost - $10.00 (assumption)

Remaining cost associated with prepreg - $16.40

Assuming 7.4% price increase to improve fibers properties from standard to intermediate modulus

Intermediate modulus fiber cost - $10.74

Estimated cost the intermediate modulus prepreg (assuming no change in matrix or other processes) - $27.14/lb

Use $27.14/lb for uni-cf prepreg input in SNL Blade cost model and correlate with structural analysis to evaluate whether using specific higher modulus is beneficial

Methods

- Cost Predicting using model
  - Has the potential to allow designers to correlate desired property with a price
  - Cost model correlates a change in process with a production price
  - Does not directly correlate mechanical props with price.
  - Additional information on how the process changes affect the properties is needed to make the connection
- Another method to predict prices associated with specific properties is to collaborate with industry who may be able to directly give a price for desired properties, but it’s difficult to get numbers from them

Design Margins

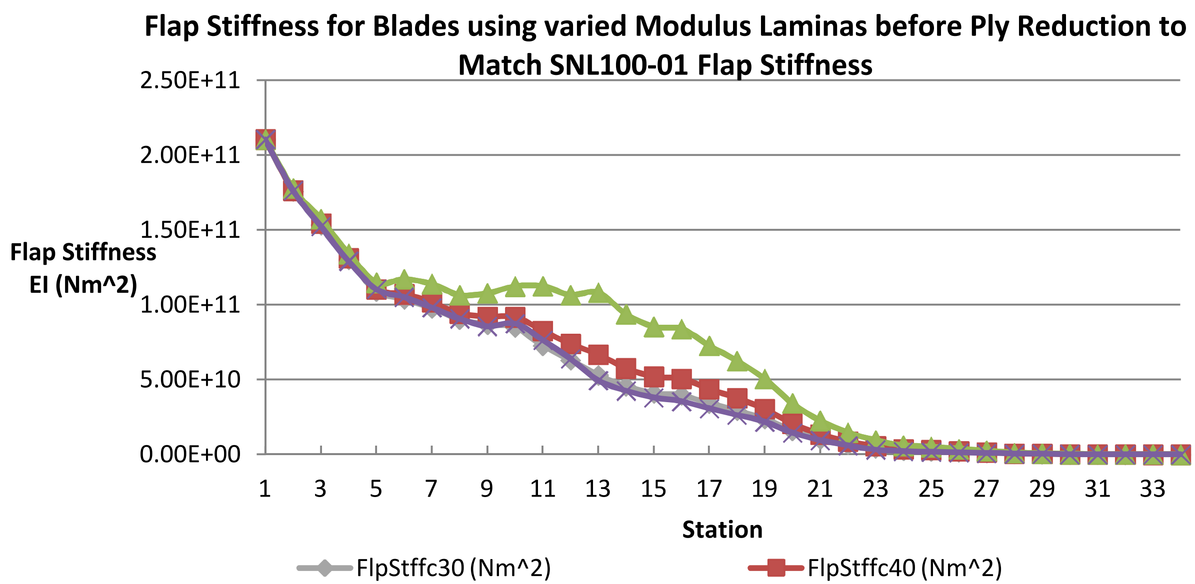
Methods

- Conceptual Lamina created to access how higher modulus fibers would reduce ply count in SNL100-01 blade
  - Standard, intermediate, and high modulus fibers
    - 30, 40, and 70 Msi
  - Hexcel 3501-6 epoxy matrix
    - 615 ksi

			Ex	Ey	Ez	Gxy	Gyz	Gxz	prxy	pryz	prxz	
	Type	Layer Thickness	E11	E22		G12						density
		[mm]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[-]	[-]	[-]	[kg/m3]
Carbon30ppreg	orthotropic	1	125802	20733		7594			0.266			1562
Carbon40ppreg	orthotropic	1	167170	21321		7810			0.266			1586
Carbon70ppreg	orthotropic	1	291276	22132		8107			0.266			1640

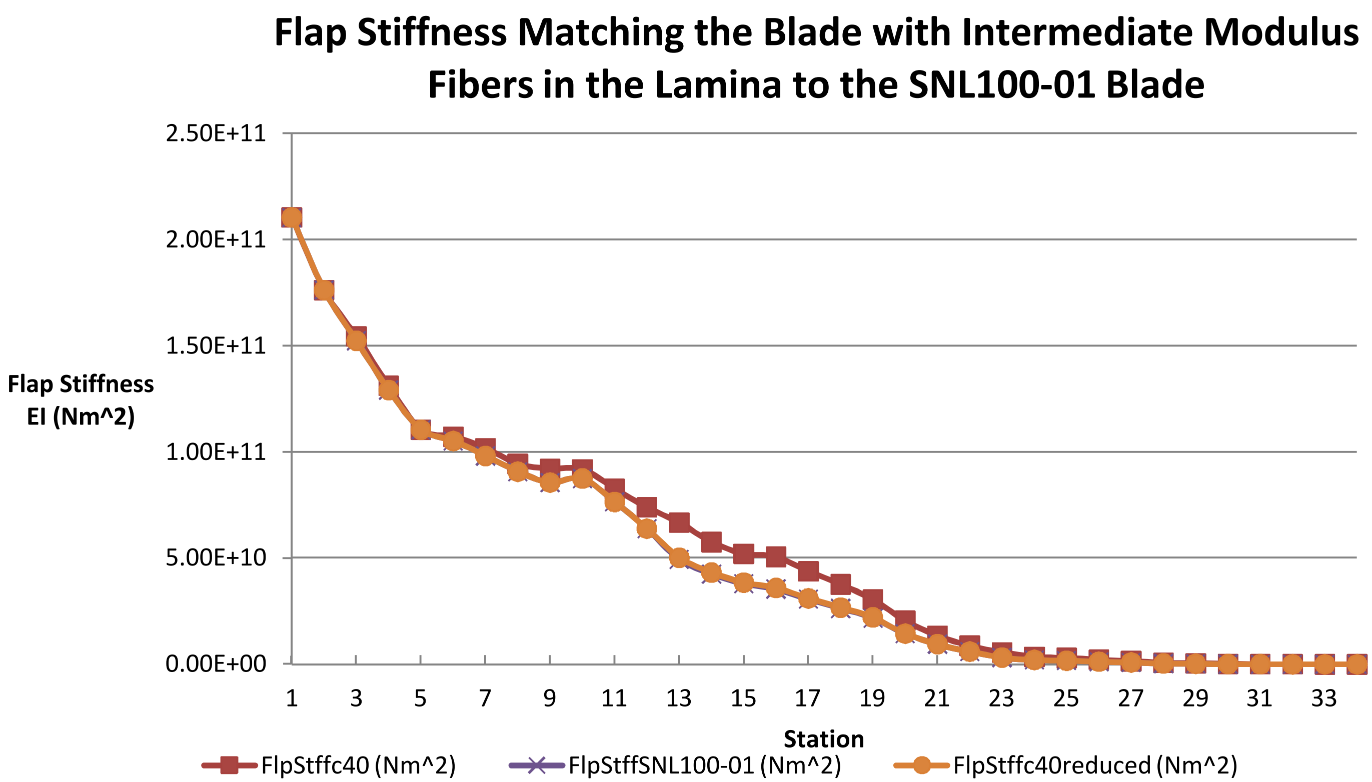
Methods

- Study conducted to reduce ply count of new lamina to match the stiffness distribution of SNL100-01 baseline
  - It allows us to assess the ply amount reduced by using the higher modulus prepregs
  - The ply amount reduced along with the $/lb allows us to assess the cost saved using that material
  - Only stiffness was observed because it is associated with tip deflection which is a critical design parameter



Methods

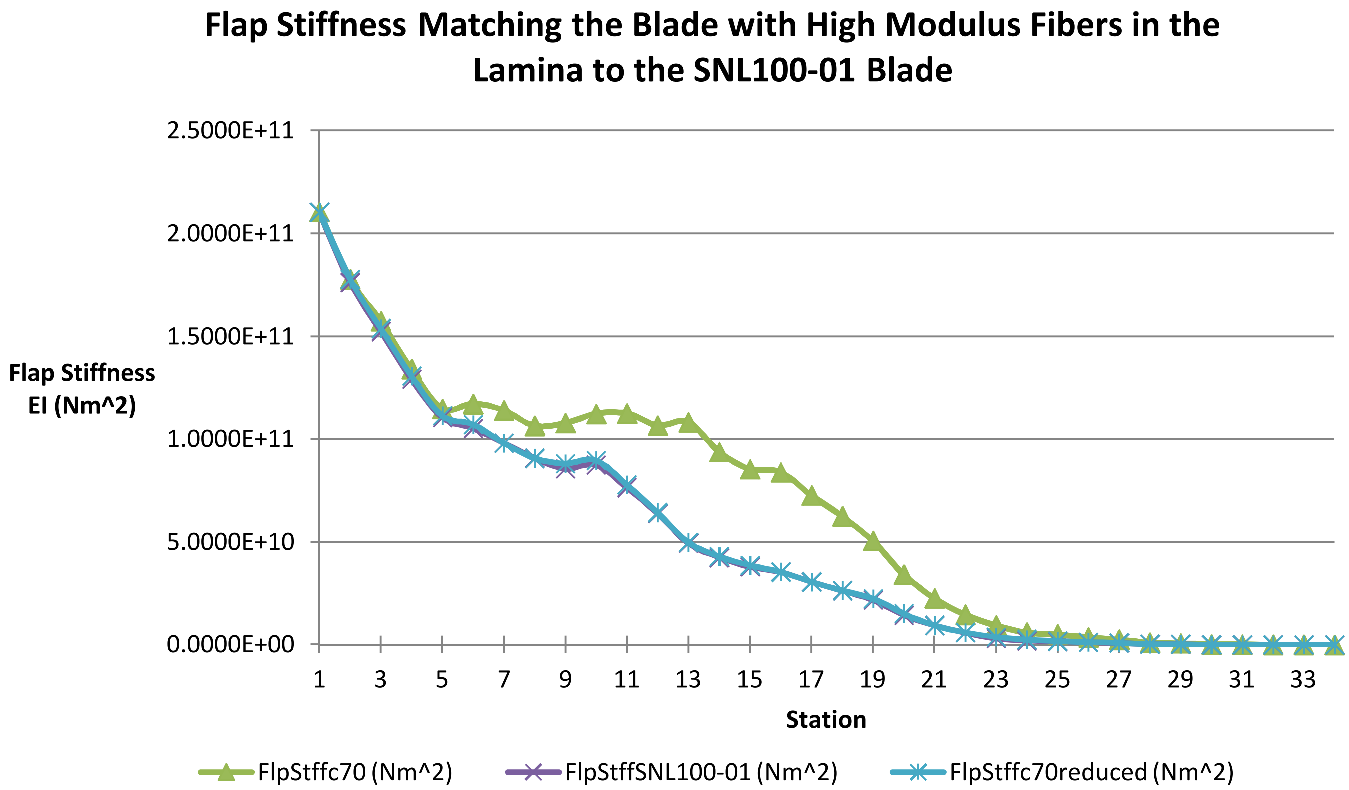
- Lamina using 40Msi fibers



SNL100-01 (baseline)	SNL100-01_rudd_c40
1	1
2	1
2	1
3	3
7	6
9	7
9	7
13	9
19	16
32	27
43	33
69	48
69	48
74	51
85	56
85	56
85	56
80	54
80	52
80	52
80	50
75	37
70	35
65	32
55	27
40	20
20	10
15	7
10	5
10	5
10	5
10	5
10	5

Methods

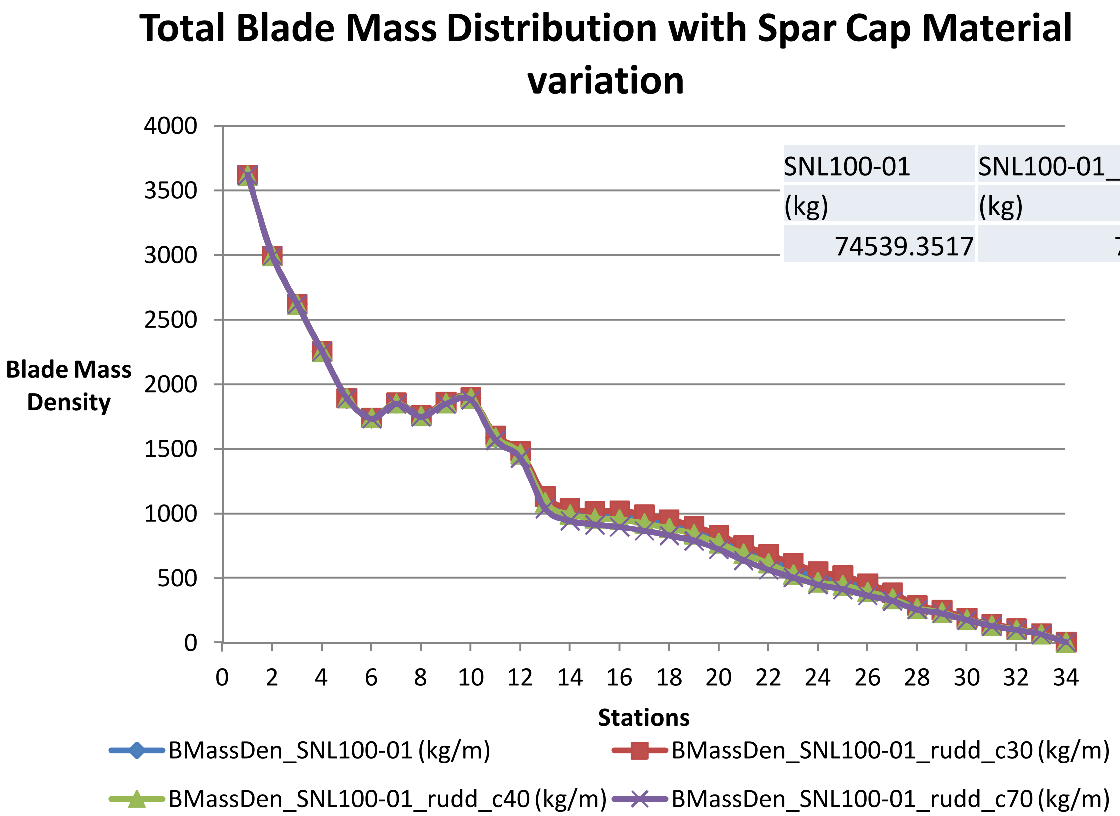
- Lamina using 70Msi fibers



SNL100-01 (baseline)	SNL100-01_rudd_c70
1	1
2	1
2	1
3	2
7	4
9	4
9	4
13	6
19	10
32	16
43	19
69	27
69	27
74	29
85	31
85	31
85	31
80	31
80	31
80	29
80	28
75	26
70	26
65	18
55	15
40	12
20	6
15	4
10	3
10	3
10	3
10	3
10	3

Methods

- Blade Mass



SNL100-01 (kg)	SNL100-01_rudd_c30 (kg)	SNL100-01_rudd_c40 (kg)	SNL100-01_rudd_c70 (kg)
74539.3517	77369.7941	72462.2271	69330.8591

Methods

- Fatigue effect on static properties
  - No data currently available, so literature is used to observe trends in uni-directional AS4/PEEK

Modulus

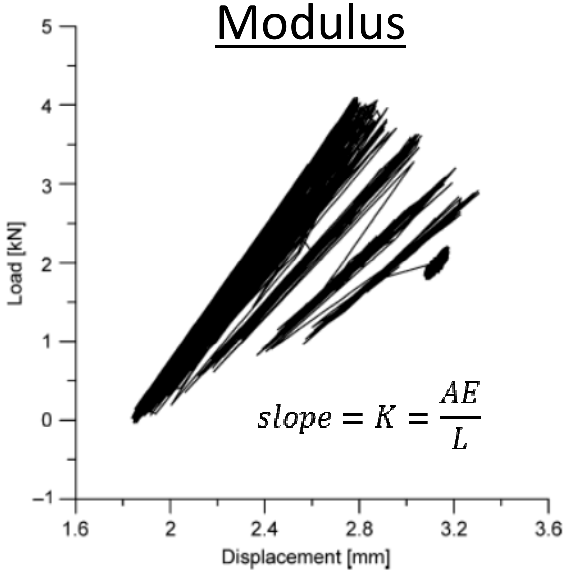


Figure 9. Load vs displacement data on unidirectional carbon specimen in low cycle fatigue tension test[6].

Strength

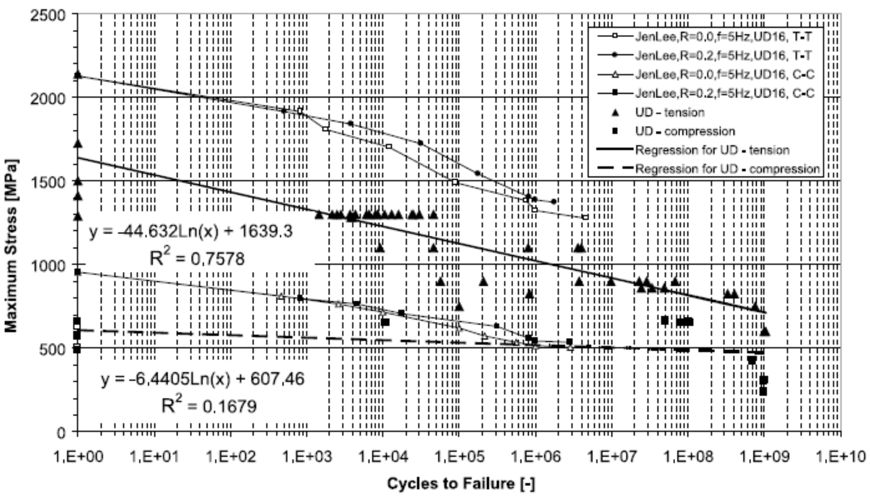


Figure 10. Fatigue data of unidirectional specimen [6].

Integrating the cost model into "pre-Numad"

- Making cost a function of the selected material properties

Pre-numad:
E, rho, v, G

Cost model

Material Properties >> manufacturing process
Manufacturing process >> production price

$/kg

NuMAD:
Ply amount

Cost estimation

Conclusion

- The cost model presents an opportunity to create an algorithm that approximates a price with desired properties, which will help assess the cost feasibility of using lamina with different grades of carbon fiber
- The simulations show that higher modulus can significantly reduce the amount of prepreg cf used in the blade, however, other design parameters like buckling and fatigue must be checked

Future work

- Look at the accuracy of correlating the cost model's manufacturing processes with desired properties
- Use manufacturer material information to get a precise price for specific properties for validation
- Investigating fatigue affect on stiffness and strength of lamina with higher modulus fibers

Acknowledgements

- David Warren

References

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