Recycling GFRP composite materials – a looming wind power sustainability problem?

Lawrence C. Bank, PhD, PE
Dist.M.ASCE, F.ACI, F.IIFC
Professor of Civil Engineering

The City College of New York

CUNY
The City University of New York

Acknowledgements

- CCNY Asst. Prof. Ardavan Yazdanbakhsh
- CCNY Students – Chen Chen, Franco Arias, Thomas Baez, Yuan Tian, Sandy Rampaul
- PowerBridgeNY – NYSERDA (New York State Energy Research and Development Authority)
- National Science Foundation (NSF)
- RAEng DVF

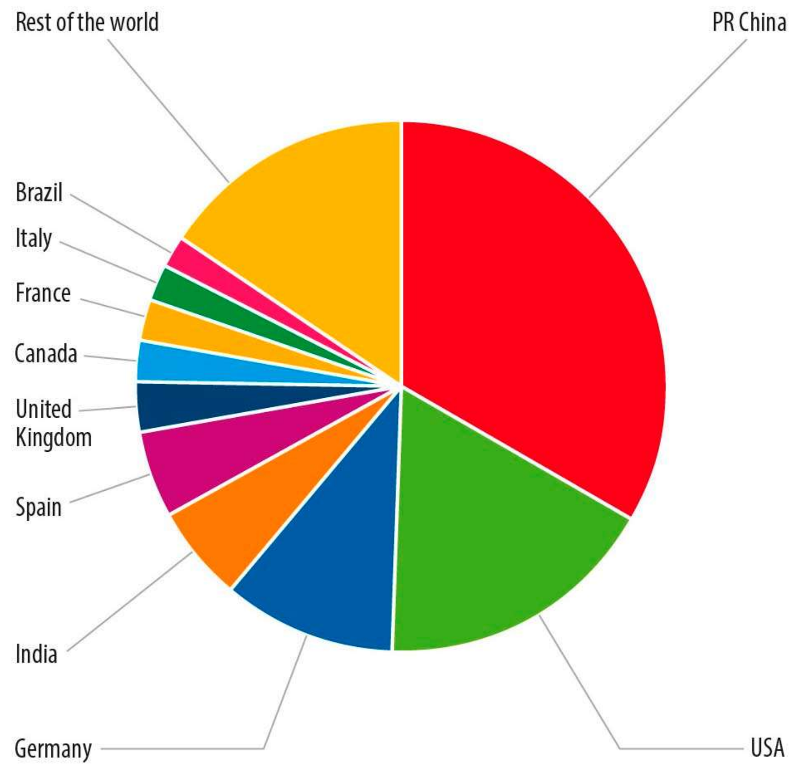
Outline

- Global wind energy overview
- FRP material recycling needs from wind power turbines
- Anatomy of a FRP turbine blade
- FRP-recycled aggregates in concrete
- Conclusions

VestasV82-1.65 MW 40.5m
Maple Ridge, New York

VestasV82-1.65 MW 40.5m
Maple Ridge, New York

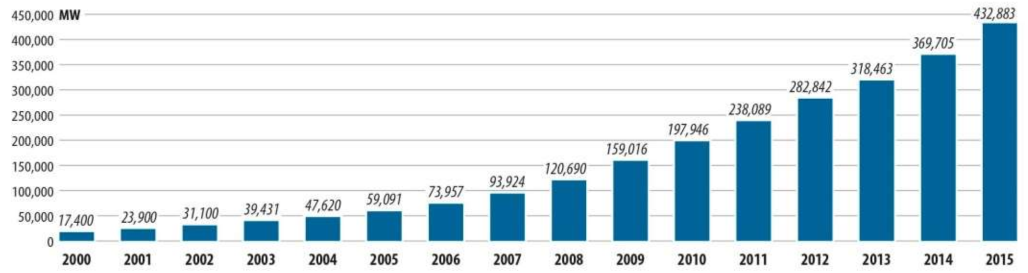
TOP 10 CUMULATIVE CAPACITY DEC 2015



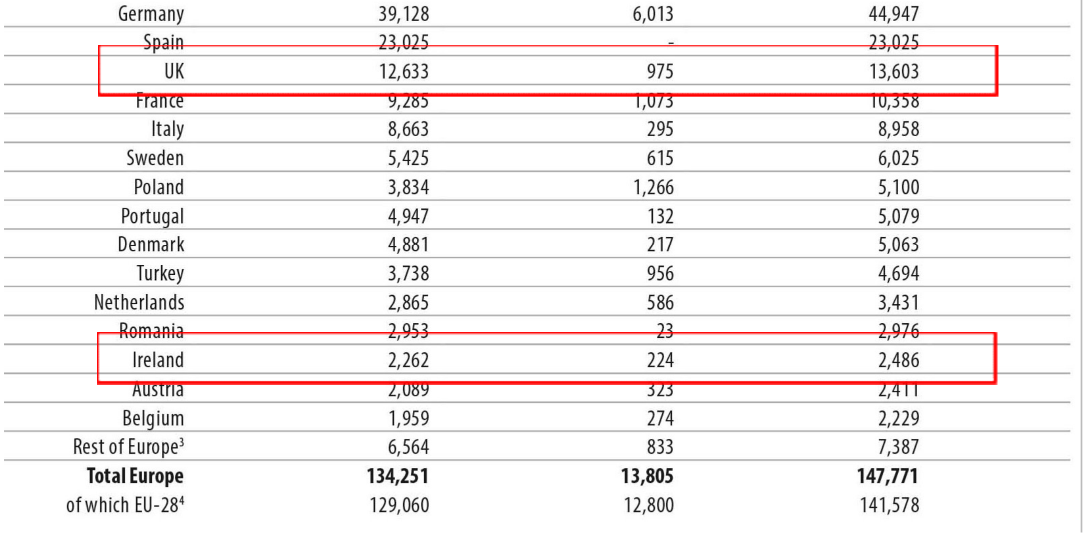
Country	MW	% Share
PR China	145,362	33.6
USA	74,471	17.2
Germany	44,947	10.4
India	25,088	5.8
Spain	23,025	5.3
United Kingdom	13,603	3.1
Canada	11,205	2.6
France	10,358	2.4
Italy	8,958	2.1
Brazil	8,715	2.0
Rest of the world	67,151	15.5
Total TOP 10	**365,731**	**84.5**
World Total	**432,883**	**100**

Source: GWEC

GLOBAL CUMULATIVE INSTALLED WIND CAPACITY 2000-2015



Source: GWEC

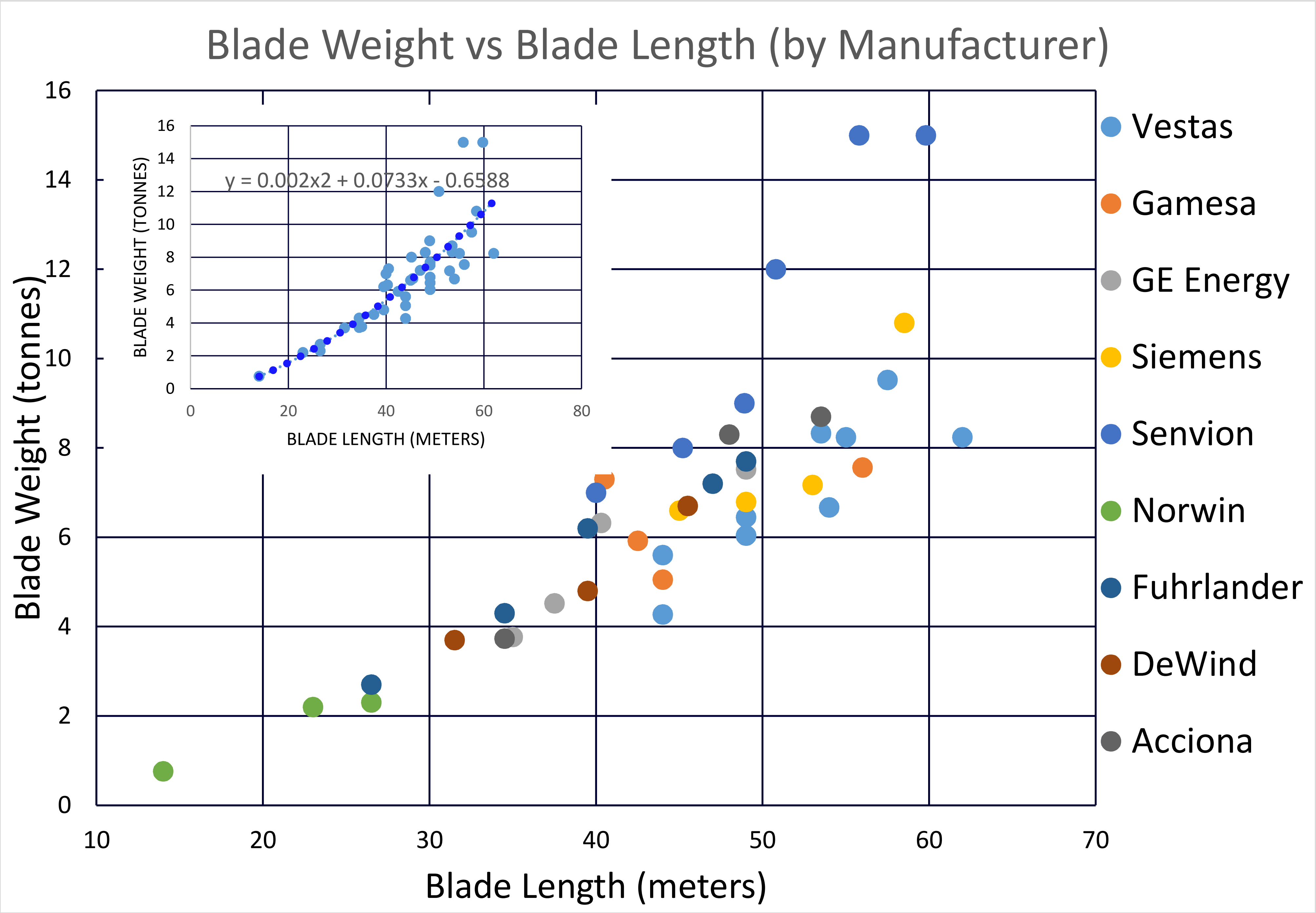


Germany	39,128	6,013	44,947
Spain	23,025	-	23,025
UK	12,633	975	13,603
France	9,285	1,073	10,358
Italy	8,663	295	8,958
Sweden	5,425	615	6,025
Poland	3,834	1,266	5,100
Portugal	4,947	132	5,079
Denmark	4,881	217	5,063
Turkey	3,738	956	4,694
Netherlands	2,865	586	3,431
Romania	2,953	23	2,976
Ireland	2,262	224	2,486
Austria	2,089	323	2,411
Belgium	1,959	274	2,229
Rest of Europe[3]	6,564	833	7,387
Total Europe	**134,251**	**13,805**	**147,771**
of which EU-28[4]	129,060	12,800	141,578

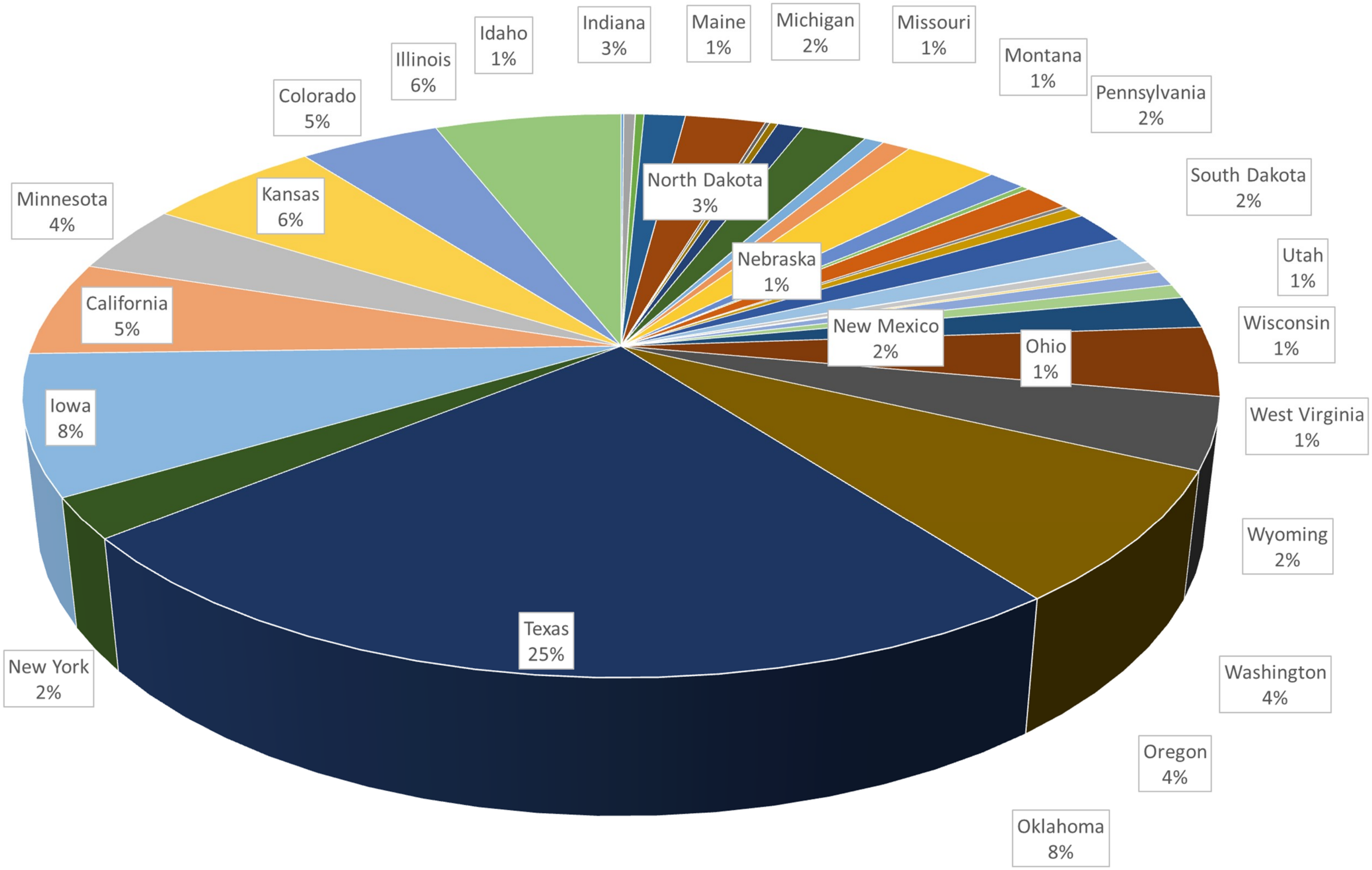
New York State

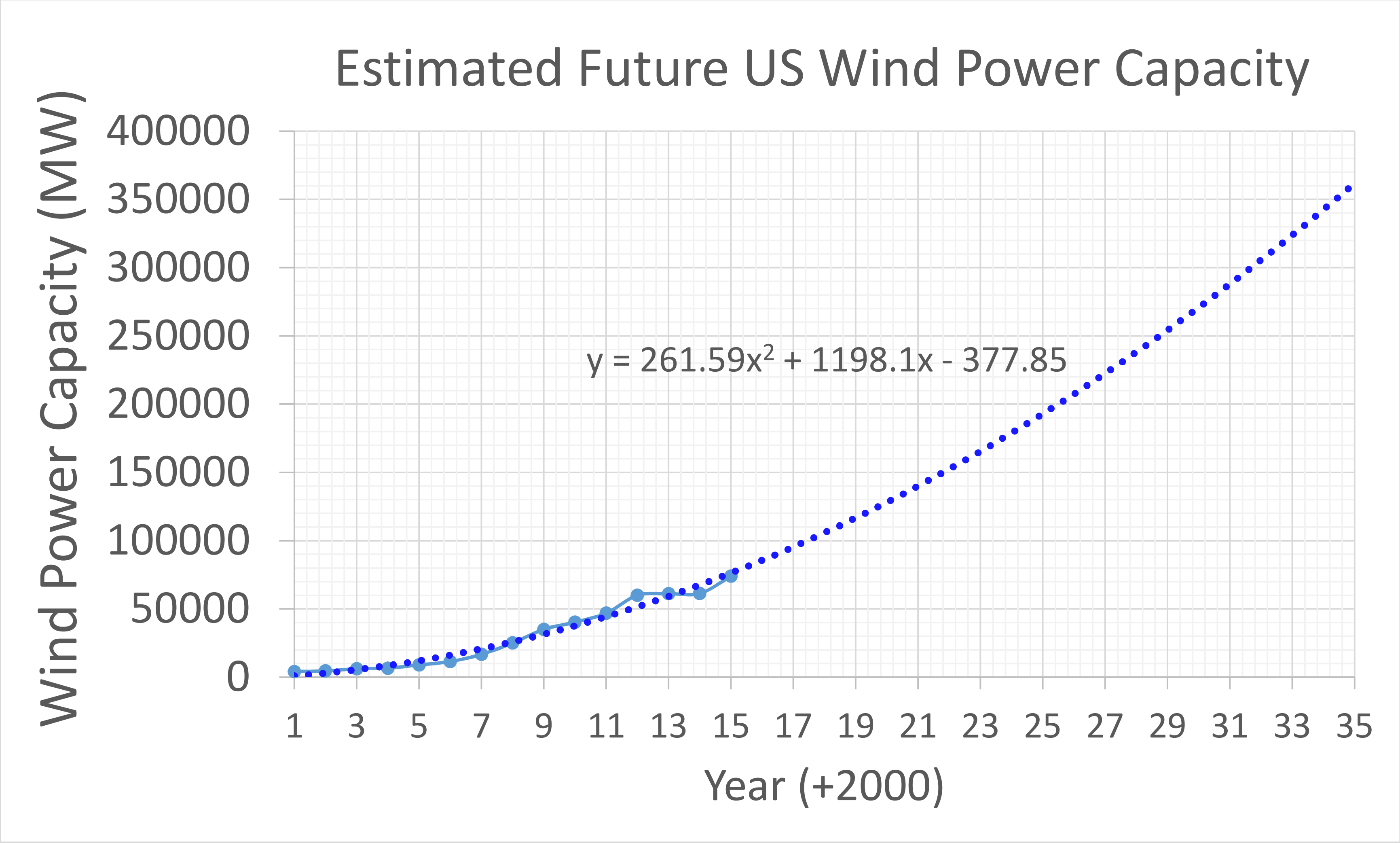
Manufacturer	Turbine Model	Blade Length (meters)	Weight Per WT (Tonnes)	Glass/Carbon Composites %	Total Composite Weight for 1 WT (Tonnes)
Vestas	V66-1.65 MW	32.5	190	6%	11.4
	V47-0.66 MW	23	95	7%	6.6
	V82-1.65 MW	40.5	205	8%	16.4
	V112-3.075 MW	55	353	8%	28.2
GE Energy	GE70.5-1.5 MW	35	149	8%	11.9
	GE77-1.5 MW	37.5	165.3	8%	13.2
	GE100-1.6 MW	49	285	8%	22.8
Clipper	C96-2.5 MW	47	305	7%	21.4
Gamesa	G90-2.0 MW	44	295.3	8%	23.6
	G58-0.85 MW	28.5	153	6%	9.2
Senvion	MM92-2.05 MW	45.2	287	8%	22.9
Hyundai	HQ82-1.65 MW	40.5	223	7%	16.4
Northern Power Systems	NPS100-0.1 MW	8	42	5%	2.1
Goldwind	GW82-1.5 MW	40.5	254	6%	15.3
Fuhrlander	F30-0.25 MW	14.5	86	3%	2.58
Vergnet	GEV29-0.275 MW	14	76	3%	2.28

Total Tonnes of Composite to recycle by 2025	1735.7
Total Tonnes of Composite to recycle by 2035	16707.8


Blade Weight vs Blade Length (by Manufacturer)
Blade Weight (tonnes)
16
14
12
10
8
6
4
2
0
10
20
30
40
50
60
70
Blade Length (meters)
Vestas
Gamesa
GE Energy
Siemens
Senvion
Norwin
Fuhrlander
DeWind
Acciona
y = 0.002x2 + 0.0733x - 0.6588
BLADE WEIGHT (TONNES)
16
14
12
10
8
6
4
2
0
0
20
40
60
80
BLADE LENGTH (METERS)

Decommissioned Turbine Count for 2020-2035	Online Capacity in 2000-2015 (MW)	Composite Weight to reycle in the US by 2035 (Tonnes)	Blade Weight to recycle by 2035 (Tonnes)
42,029	73,442	705,215	829,665

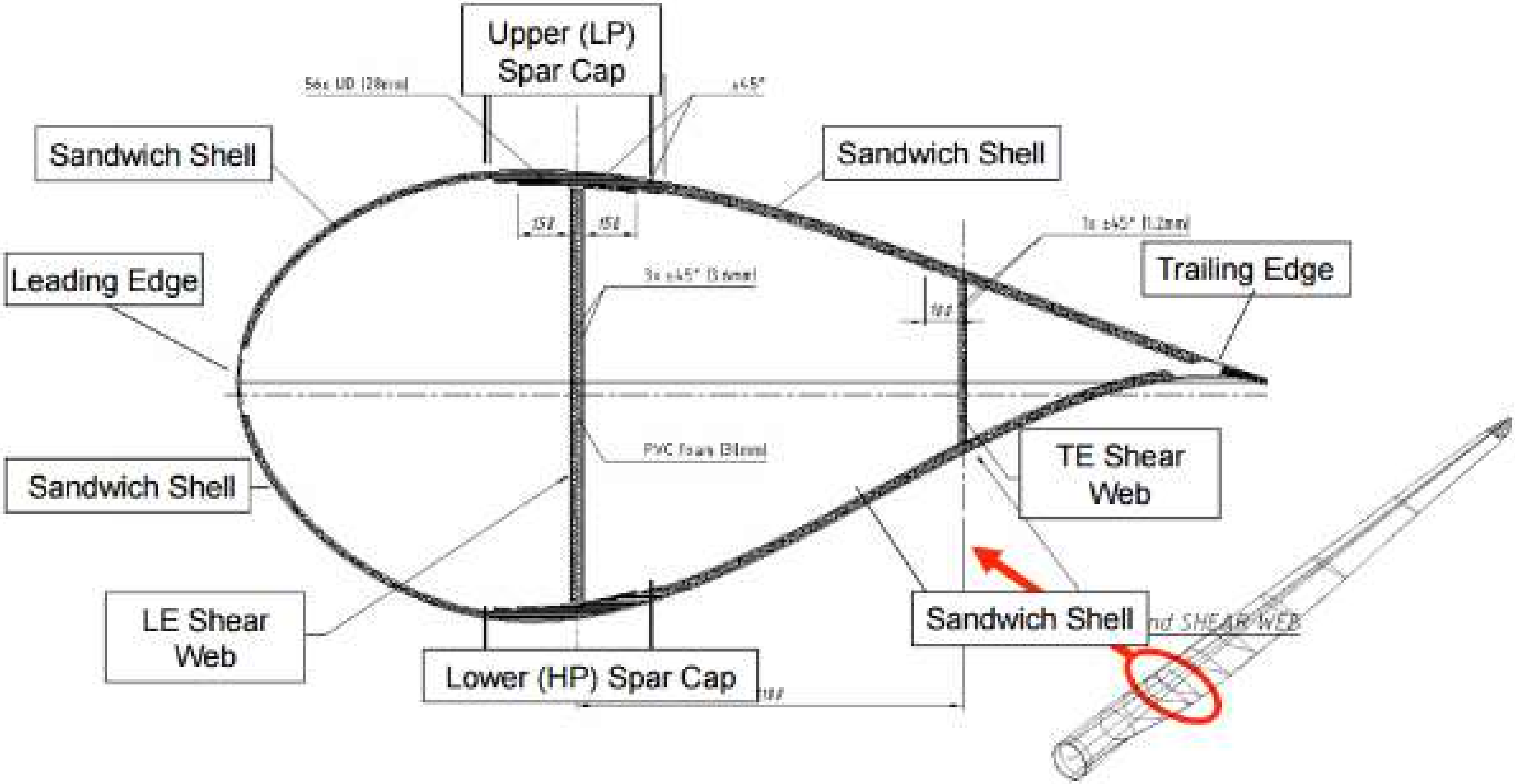




Cumulative Capacity (MW) in 2015	Cumulative Cpacity (MW) in 2035	Online Megawatt Capacity for 2015 to 2035	Averaged Composite Weight per Online Megawatt Installed (Tonnes/MW)	Total Composite Weight To Recycle by 2055 (Tonnes)	Total Blade Weight To Recycle by 2055 (Tonnes)
73,992	362,003	288,011	9.57	2,756,265	3,242,665

This equates to a global total of 4.2 million tonnes by 2055

Anatomy of a Wind Turbine Blade (near Max Chord)



Upper (LP) Spar Cap

Sandwich Shell

Sandwich Shell

Leading Edge

Trailing Edge

Sandwich Shell

TE Shear Web

LE Shear Web

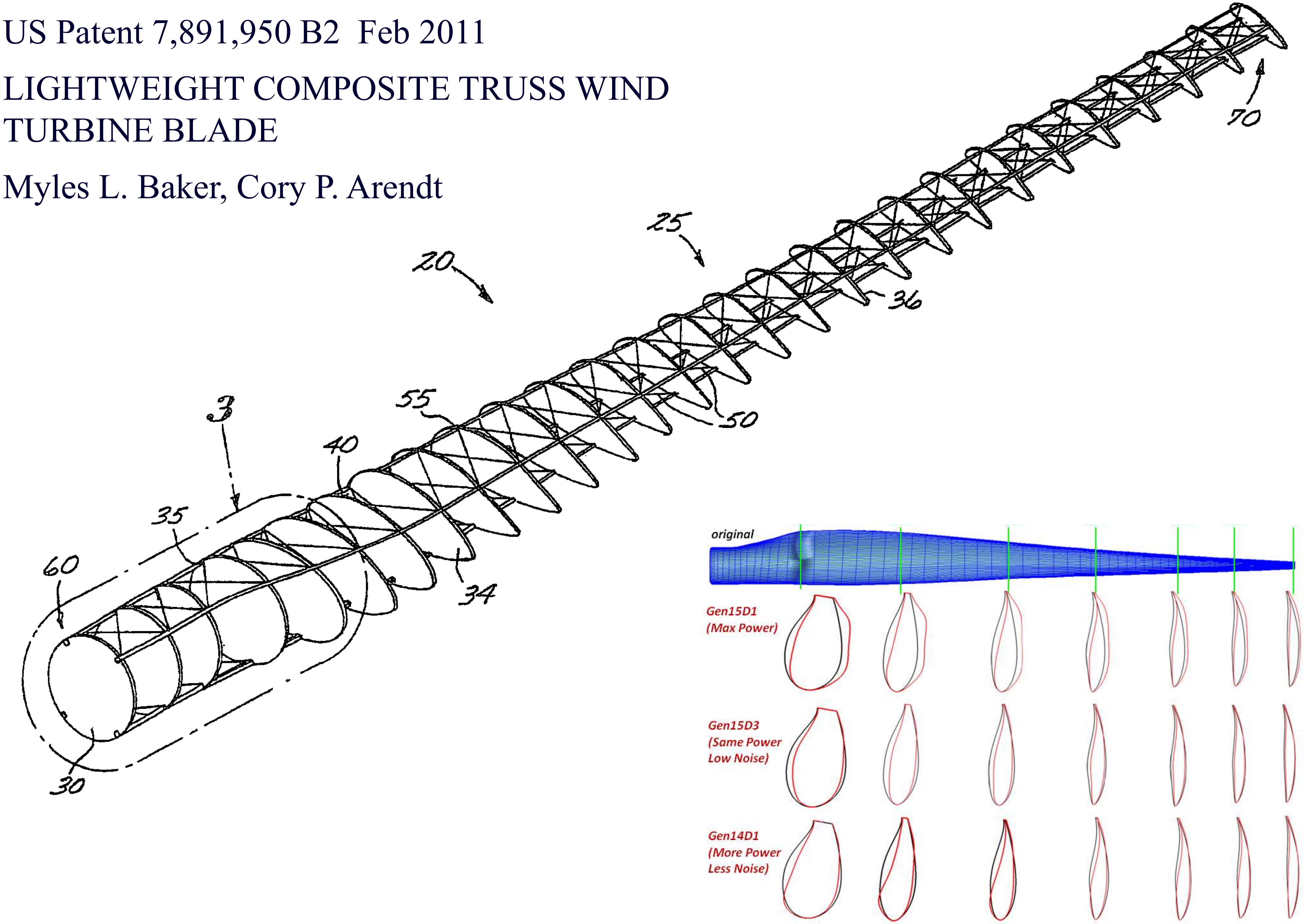
Sandwich Shell

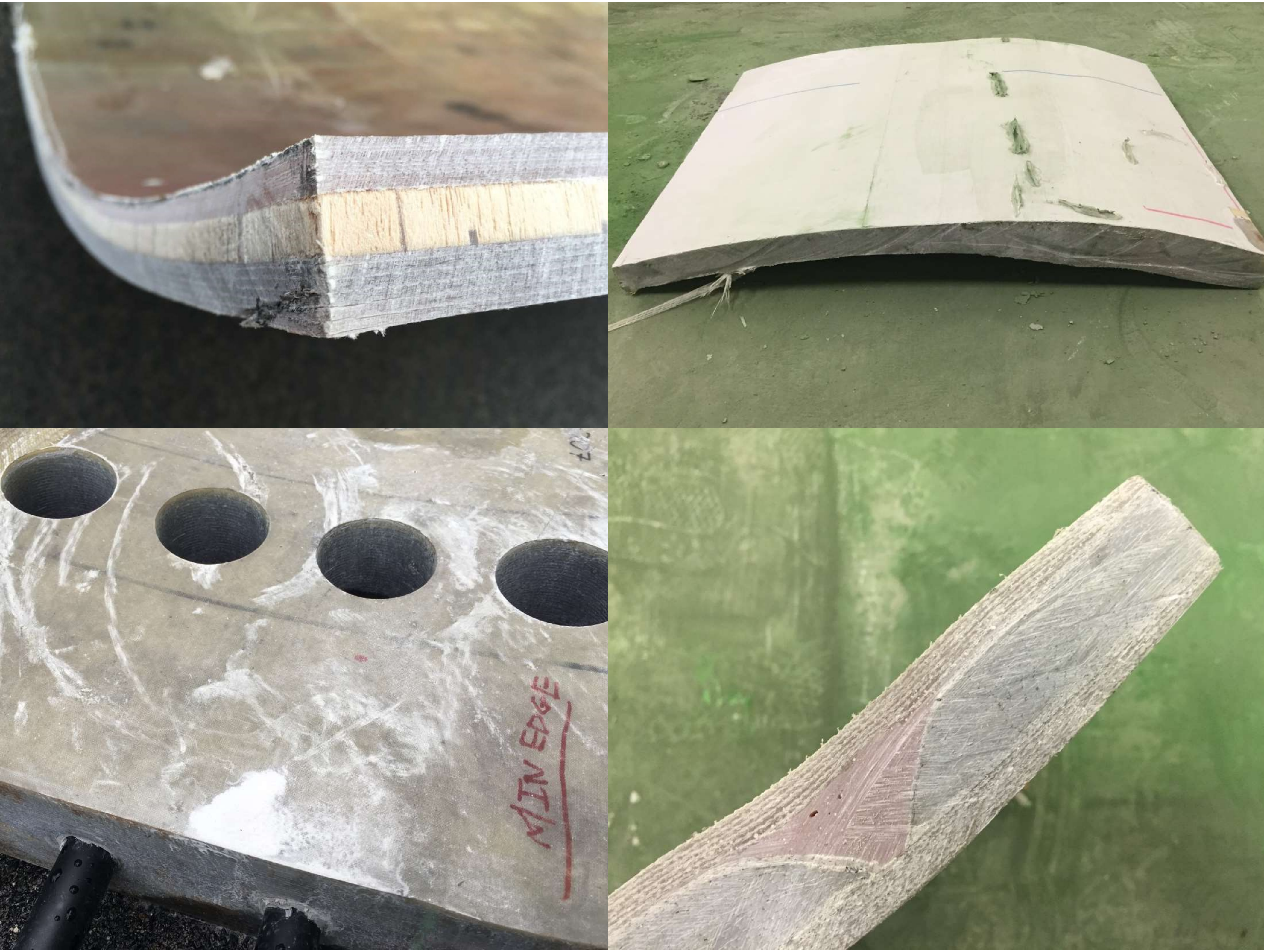
Lower (HP) Spar Cap

US Patent 7,891,950 B2 Feb 2011

LIGHTWEIGHT COMPOSITE TRUSS WIND TURBINE BLADE

Myles L. Baker, Cory P. Arendt



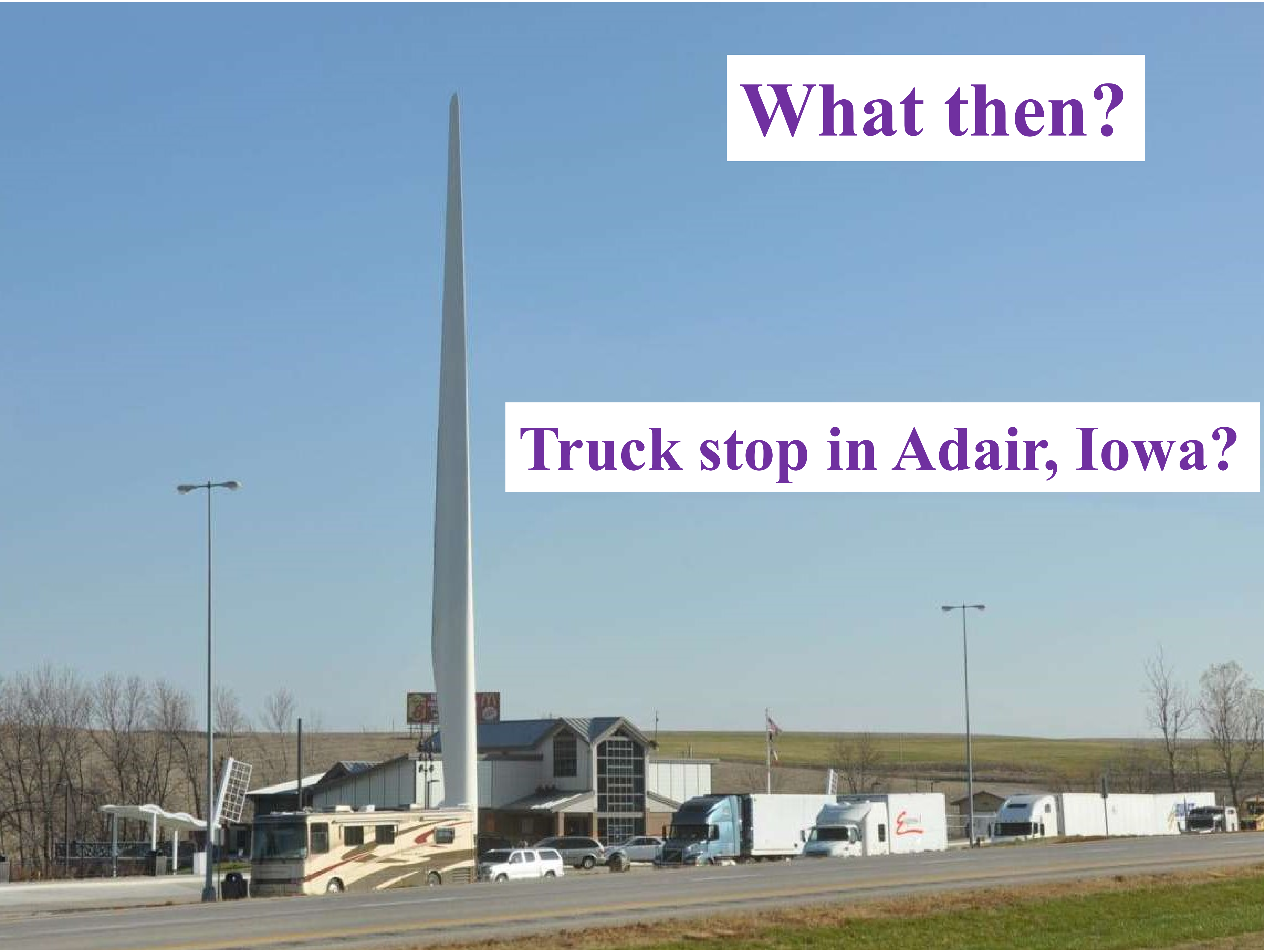

MAIN EDGE


1547
SARGENT-WELCH
SARGENT-WELCH SCIENTIFIC COMPANY


1547
SARGENT-WELCH
SARGENT-WELCH SCIENTIFIC COMPANY

Siemens B-75 6 MW 75 m

What then?



Truck stop in Adair, Iowa?

Motivation

- 8.8 million tonnes of worldwide composites production volume. European share about 2.3 million tonnes (JEC, 2014).
- Growth rate of FRP industry is expected to be 6% per year in volume for the next 6 years.
- Shift from North America and Europe (50% in 2015) to Asia (43% in 2015).
- 95% GRFP, of which 75% is thermosets.
- CFRP growth is also anticipated (mostly automotive).

Motivation

INSTITUTE FOR ADVANCED COMPOSITES MANUFACTURING INNOVATION

Institute for ADVANCED
Composites Manufacturing
INNOVATION

"Demonstrate >80% recyclability or reuse of FRP composites in 5 years into useful components with projected cost and quality at commercial scale competitive with virgin materials. (>95% in 10 years)."

Solutions

- Landfilling – legal or illegal.
- Incineration – w/wo energy recovery ("Cement-Kiln" process).
- Reuse
  - Part re-purposing: use in new products.
  - Constituent recovery: Pyrolysis, thermolysis, solvolysis to recover thermoplastic resins or fibers for reuse.
  - Downcycling: Shredding, grinding and milling for filler for FRP or concrete,

Concrete containing coarse aggregate recycled from scrap FRP rebars

- Concrete containing FRP-RA (Recycled Aggregate) from FRP rebars
- Compressive and Tensile (splitting) strength and stiffness measured
- Failure modes investigated
- Two series of tests completed

Ardavan Yazdanbakhsh, Lawrence C. Bank, and Chen Chen, “Use of recycled FRP reinforcing bar in concrete as coarse aggregate and its impact on the mechanical properties of concrete,” to appear in Construction and Building Materials, 2016.


0/690 6/46 RB6/19MM ASLAN100 W
G 105/724 6/46 RB5/16MM ASLAN10
G 110/758 6/46 RB4/13MM ASLAN
G 130/896 6/46 RB2/6MM ASLAN100 W
16FEET
5m
45°
60°

Cutting FRP bars

Concrete with FRP-RA – Mix proportions

Concrete mix	FRP-RA vol. replacement ratio, %	*w/c*	Total agg. (coarse and fine) /concrete vol. ratio	Coarse agg./total agg. vol. ratio	Coarse agg./ concrete vol. ratio
Series 1 (100 x 200 mm cylinders)					
NC1	0	0.57	0.70	0.55	0.39
N40	40*	0.57	0.70	0.55	0.39
N100	100**	0.57	0.70	0.55	0.39
H01	0	0.44	0.60	0.67	0.40
H40	40*	0.44	0.60	0.67	0.40
H100	100**	0.44	0.60	0.67	0.40
Series 2 (150 x 300 cylinders)					
NC2	0	0.45	0.606	0.58	0.35
N05	5***	0.45	0.606	0.58	0.35
N10	10***	0.45	0.606	0.58	0.35

NOTES: NS: Normal Strength. HS: High Strength

*only ¾” (19 mm) and 1” (25 mm) size aggregates replaced with FRP–RA

** ¼” (6 mm), 3/8” (10 mm), ½” (12 mm), 5/8” (16 mm), ¾”(19mm), and 1” (25mm) replaced with FRP-RA.

*** ¼”(6 mm), 3/8” (10 mm), ½” (12 mm) and ¾”(19mm) replaced with FRP-RA. 1” (25 mm) natural aggregate NOT used.


B4C3
B4C3
AIR BLEED


B4S2
B4S2
AIR BLEED


B4C3
AIR BLEED


B4S2
AIR BLEED

Results – Strengths and Code comparisons

Mix	f'_c (MPa)	% decrease from NC	COV (f'_c)	f_{ct} (MPa)	% decrease from NC	COV f_{ct}	$f_{ct,ACI}$ (MPa)	$f_{ct,EC2}$ (MPa)
Series 1 (100 x 200 mm cylinders)								
NC1	37.5	-	3.8	4.0	-	6.4	3.43	3.19
N40	32.8	–13	1.0	3.0	–25	10.2	3.21	2.83
N100	29.5	–21	2.4	2.6	–35	5.4	3.04	2.58
HC1	46.3	-	5.5	4.5	-	5.3	3.81	3.79
H40	40.4	–13	4.9	4.0	–11	5.2	3.56	3.39
H100	36.6	–21	6.1	3.6	–20	5.3	3.39	3.12
Series 2 (150 x 300 cylinders)								
NC2	40.2	–	2.2	3.4	–	4.7	3.55	3.92
N05	37.9	–6	2.6	3.1	–9	3.9	3.45	3.77
N10	38.9	–3	2.2	3.4	0	2.1	3.49	3.84

$$f_{ct,ACI} = 0.56 f_{cm}^{0.5} \quad \text{(MPa)}$$

$$f_{ct,EU2} = 0.33 f_{cm}^{0.67} \quad \text{(MPa)}$$

Series 1

B1wc57NA	1	B1A1	
	2	B1A2	NC1
	3	B1A3	
B2hsNA	4	B2A1	
	5	B2A2	HC1
	6	B2A3	
B3wc57bar	7	B3A1	
	8	B3A2	N100
	9	B3A3	
B4hsBar	10	B4A1	
	11	B4A2	H100
	12	B4A3	
B5wc57barNA	13	B5A1	
	14	B5A2	N40
	15	B5A3	
B6hsBarNA	16	B6A1	
	17	B6A2	H40
	18	B6A3	

Series 2

NA(control)		B1S1	NC2
		B1S2	
		B1S3	
FRP-fib-5		B3S1	N05fib
		B3S2	
		B3S3	
FRP-fib-10		B2S1	N10fib
		B2S2	
		B2S3	
FRP-RA-5		B5S1	
		B5S2	N05
		B5S3	
FRP-RA-10		B4S1	
		B4S2	N10
		B4S3	

Compression S1 - Normal Strength mix

NC1

N40

N100

Compression S1 – High Strength mix

HC1

H40

H100

Compression S2 - Normal Strength mix

NC2

N10

N05

Splitting S1- Normal Strength mix

NC1

N40

N100

Splitting S1- High Strength mix

HC1

H40

H100

Splitting S2- Normal Strength mix

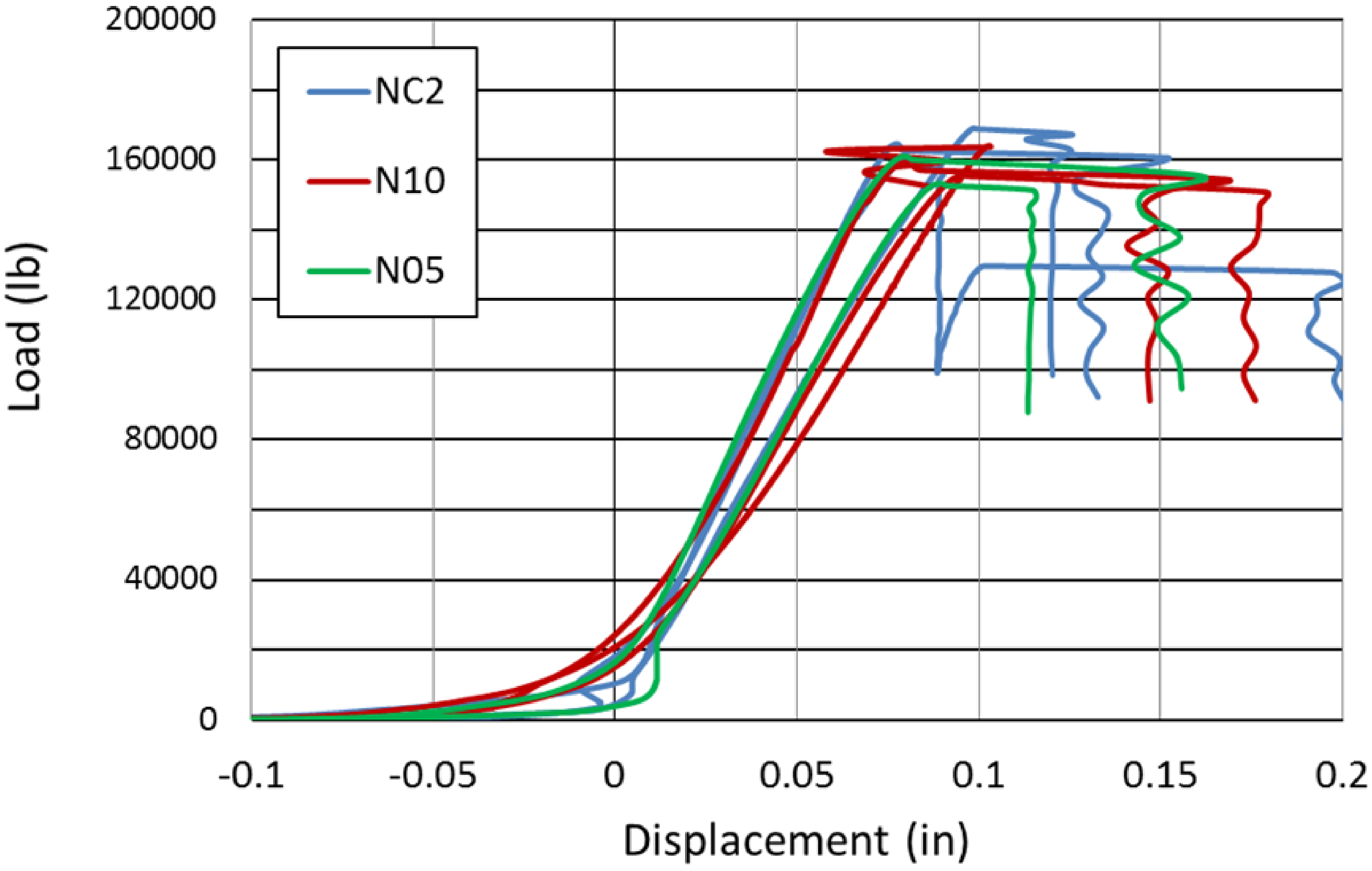
NC2

N10

N05

Stiffness – Series 2

Stiffness from Compression Test (Strain gage measurement ASTM 469)			
	E (GPa)	E_{ACI} (GPa)	% diff
NC2	26.6	30.0	–11
N05***	29.5	28.7	+2.8
N10***	33.4	29.5	+13.2



Observations

- For high % replacement (40, 100%) FRP-RA leads to strength reductions compared to NA.
- For low % replacement (5, 10%) little effect was observed.
- The strength reduction is higher for tensile (splitting) than for compression strength in normal strength mixes.
- The Interfacial Transition Zone (ITZ) between the FRP-RA and the cement paste is the cause of the reduced strength.
- For high strength concrete the strength reductions are less due to better ITZ.

Conclusions

- Innovative solutions are needed for recycling non-biodegradable FRP materials, especially wind blades.
- Even though high % replacement led to reduced strengths they are still in above 30 MPa and adequate for design of structural members.
- Low % replacement levels can be considered as a viable means of recycling FRP perhaps in conjunction with RCA for non-critical structures.
- Detailed Life Cycle Assessment (LCA) is needed to make a stronger case to the wind power industry.

The rapid growth in wind energy technology in the last 15 years has led to a commensurate rapid growth in the amount of FRP materials used in this industry. One wind blade of a typical 2.5 MW turbine is 50 m long blade, contains approximately 8 tonnes of FRP material, and costs about $150,000. Unlike FRP materials used in other industries, such as, marine, construction and transportation, turbine blades have a well–defined lifespan. They are expected to be taken out of service after approximately 20 years due to fatigue life limits; and may even be replaced before that time. By 2035, 705,200 tonnes of blades will need to be disposed in the US from the turbines installed between 2000 and 2015. This translates to a global total of 4.2 million tonnes. It is clear that innovative concepts at all scales, from materials, to parts, to whole structures need to be developed to recycle these GFRP blades that do not include landfilling or incineration and contain very little material of value. Work at CCNY is currently addressing a number of these different scales.

On the materials level, the use of production waste FRP parts is being studied as a replacement for coarse aggregates in concrete. As a precursor to obtaining materials from wind blades, recent experimental investigations have used waste pultruded GFRP reinforcing bars. Rebars ranging from 6 mm to 25 mm in diameter were cut into cylindrical aggregate–sized pieces and used as a replacement for the natural coarse aggregate at percentages of 5, 10, 40 and 100%. Test cylinders were cast and tested for compressive strength and tensile (splitting) strength. Strength data are presented and compared with ACI and EU predictions. An analysis of failure modes and failure surfaces as a function of the replacement percentages is provided. In addition, the electricity consumed (in kWh) to cut of the FRP aggregate pieces is discussed and a brief discussion of life–cycle assessment (LCA) needed to address the economic and environmental trade–offs with this down–cycling method is provided. The significance of these results on the possible use of aggregate pieces from waste wind blade pieces is discussed, as well as needs for future research in this area.