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University College Cork, Ireland Coláiste na hOllscoile Corcaigh

1	STRUCTURAL ANALYSIS OF A ROOF EXTRACTED FROM A WIND TURBINE
2	BLADE
3	
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6	
7	Abstract
8	
9	The objective of this research is to demonstrate that parts of decommissioned wind turbine
10	blades can be repurposed for infrastructure applications for a sustainable future of the wind
11	power industry. The purpose of this paper was to develop a methodology to conduct detailed
12	structural engineering design of composite material parts extracted from wind turbine blades. A
13	large section extracted from a 100 meter long blade was repurposed as a roof for a small
14	(approximately 40 m ²) single-story masonry house. Geometric and material properties were
15	taken from the blade design documents. A 3-D graphical model was created from the exterior
16	surface and material layups. The roof was designed using the Load and Resistance Factor

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17	(LRFD) method familiar to civil engineers. Analysis of stresses and defections was conducted
18	using hand calculations and the finite element method (FEM). The results of the analyses show
19	that the roof is within code mandated stress and deflection limits. The methodology developed
20	can be applied to other wind blade repurposing concepts.
21	
22	Keywords: Recycling, Repurposing, Design, Finite element analysis, Wind turbine blades,
23	
24	Introduction
25	
26	Fiber Reinforced Polymer (FRP) composite materials are not biodegradable and present unique
27	problems for waste management and their End-of-Life (EOL). The impact of polymers on the
28	environment and society has become a major concern in many countries. In response to the
29	European Waste Directive (DIRECTIVE 2008/98/EC, 2008), the option of disposing of end-of-
30	life FRP blades in landfills is now restricted by landfill taxes and reuse, recycling and recovery
31	targets. Since the 1990s, there has been a developing body of research that has studied the issues
32	of recycling and EOL of FRP composites, in general, and composite wind blades, in particular.
33	Recent analyses of the key issues related to the EOL of wind turbine blades can be found in Liu
34	and Barlow (2017), Jensen and Skelton (2018) and Bank et al. (2018). For example, a typical 2.0
35	MW turbine with three 50 m blades has approximately 20 tonnes of FRP material and an 8 MW
36	turbine has approximately 80 tonnes of FRP material (based on a conservative 1 MW ≈ 10
37	tonnes of FRP conversion). Based on a predicted "moderate growth scenario" from the Global
38	Wind Energy Council (GWEC), waste blades from future wind power installations will total of
39	16.8 million tonnes by 2030 and 39.8 million tonnes by 2050 if no action is taken in the interim

40	(G	WEC, 2016). At the present time numerous large (40 to 60 meter) composite material wind
41	tur	bine blades are coming out of service due to their original 20-year design life or due to
42	rep	placement by more efficient turbines and/or blades (referred to as repowering).
43		
44	M	anaging Composite Material "Waste"
45		
46	Th	ere are various methods to manage waste composites (either production waste or EOL waste
47	pro	oducts) at the present time (Oliveux et al., 2015, Job et al, 2016) – some of which are referred
48	to	as "recycling". Unfortunately, the term "recycling" has many different meanings in this field
49	an	d the term "second-life" is preferred so there is a clear understanding of their position in a
50	wa	ste processing hierarchy. Following Skelton (2017) and Jensen and Skelton (2018) we
51	pro	opose the following categorization of second-life options for FRP wind blades;
52		
53	1.	Reuse: In this scenario the entire blade is reused. The blade is used as a turbine blade in its
54		second life but has its lifetime extended by refurbishment or remanufacturing or is sold on
55		the second-hand market.
56	2.	Repurpose: In this scenario the structural properties and the material properties of the
57		composite are repurposed. The blade is used whole or sectioned into parts and repurposed for
58		other products such as parts of temporary or inexpensive housing, office and home furniture,
59		benches and playgrounds, pedestrian bridges and powerline structures (Bank et al., 2018;
60		Adamcio, 2019; Bladesign, 2019,:SuperuseStudios, 2012; Speksnijder, 2018; Suhail et al.,
61		2019; Anmet, 2019; Bank et al, 2019; Alshannaq et al, 2019).
62	3.	Recycle

63	a. F	ully-Recycle: In this scenario the material properties of the composite are recycled.
64	Т	he blade is cut, shred or ground into small pieces or granular material as filler for
65	u	se in concrete or other composites (Beauson et al, 2016; Mamanpush et al, 2018;
66	Y	'azdanbakhsh et al, 2018; Rodin et al., 2018).
67	b. P	artially-Recycle: In this scenario the glass fiber constituent of the composite is
68	u	sed. This includes thermo-chemical methods such as pyrolysis, solvolysis,
69	th	nermolysis (fluidized bed) (Oliveux et al 2015) that are used to reclaim the glass
70	fi	ber. Or the glass fiber is used as a feedstock for cement clinker by co-processing the
71	sl	hredded composite material in a cement kiln (Ramesh et al 2018).
72		
73	Waste dispos	sal methods such as landfilling or incineration, with or without energy recovery, or
74	syngas produ	action are not considered to be second-life methods since no material is reused in a
75	new product.	. Clearly, all the second-life methods listed above will need "third-life" or other
76	disposal met	hods in the future. In most of the world landfilling is the predominant method of
77	disposing of	FRP scrap and EOL waste costing in the range of \$45 to \$200 per ton. With the
78	increased aw	vareness of the environmental impacts of climate change, decreased and more
79	expensive na	tural resources, and greater global concerns for health, the barriers to FRP
80	production a	nd waste disposal are likely to increase.
81		
82	In what follo	ows the repurposing of a part extracted from a 100 m long FRP blade as a roof
83	structure is d	liscussed. Fig. 1 shows conceptual designs for platform foundations, doors and
84	window shut	ters, roof panels and roof for small (approx. 40 m ²) masonry block houses (Bank et

al, 2018.) Such buildings are ubiquitous in the developing world. Of the different possible uses

86 of the blade parts shown in Fig. 1, the roof was chosen for further detailed structural analysis 87 because of its large size and complex geometry and materials. The study follows and expands a 88 prior conceptual study of a similar roof structure with different geometry and calculations (Bank 89 et al, 2019.) 90 91 Wind Blade Geometry 92 The wind blade selected for the current work was a 100 m long prototype wind blade designed 93 94 by Sandia National Laboratories (SNL) identified as SNL-100-01 (Griffith, 2013). This blade is 95 similar in size to a 107-meter turbine blades currently being manufactured for a 12 MW turbine (General Electric, 2019). The geometry is defined by 25 different airfoils at specific stations 96 97 along the blade length from the root end, where the blade is connected to the turbine hub, to the 98 tip. The materials are defined by 393 different solid and sandwich composite material lay-ups. 99 The SNL-100-01 model of the blade is a two-dimensional wire frame (surface) model built using 100 the Numerical Manufacturing and Design Tool (NuMAD) (Berg and Resor, 2012, Arias, 2016). 101 A three-dimensional architectural model of the blade including thickness and material types at all 102 locations is required for architectural and structural calculations and detailing. Fig. 2. shows the 103 three-dimensional model of the 100-meter blade which was built from the stack lavups and 104 material types provided in Griffith (2013) using Rhino 3D (Rhino, 2017, Arias, 2017)

105

The blade has a maximum chord (i.e., the distance between the leading edge and trailing edge) of
7.628 m at a distance of 19.5 m from the root end. The blade has a foam core shell, three internal
foam core webs (identified as SW1, SW2 and SW3 from left to right in Fig. 2(b)) and a carbon

109	fiber spar cap (shown in black above and below the webs SW1 and SW2). The part of the 100
110	meter blade that was extracted from the three-dimensional blade model to create the roof region
111	was extracted from Station 19 to Station 20 (27.6 m to 35.8 m) and is shown schematically in
112	Fig. 3.
113	
114	A schematic rendering of the part used for the roof is shown on the masonry block walls of the
115	approximately 40 m ² house in Fig. 4. Fig. 4 also shows schematics of the connection details
116	using Simpson Strong-Tie $^{\ensuremath{\mathbb{R}}}$ straps between the blade roof and the masonry walls. Fig.4 also
117	shows schematics of louvre type window shades to enclose the open ends of the blade roof.
118	Louvre type windows and shades are commonly used in informal housing in developing
119	countries where high humidity and temperatures are common (Bank et al 2018)
120	
121	Structural Analysis of the Roof
122	
123	Dimensions
124	
125	The center-line dimensions of the roof used in the calculations that follow are shown in Fig. 5.
126	
127	Materials
128	The mechanical and physical properties of the materials as well as their layups in different
129	locations around the cross-section and along the length of the SNL-100-01 blade are given in
130	Griffith (2013). These are based on the MSU material test database (Mandell et al 1997, SNL

131 2019). In cases where properties were not provided in Griffith (2013) they were obtained from132 the literature as noted in Table 1.

133

134 The geometric and material properties of the roof were determined for the laminates and 135 sandwich panels for the region from Station 19 to Station 20 (27.6 m to 35.8 m). These were used in both hand calculations and in the LS-DYNA finite element method (FEM) analysis in 136 137 what follows. The as-reported properties given in Griffith were used in the analysis. Any changes 138 in material properties or dimensions due to the expected 20-year in-service operation of the blade 139 were not considered at this time. The estimation of residual properties in wind blades after 20 140 years of service (known as remining-life) is an active research field (Post et al 2008). 141 142 Design Philosophy 143 For civil engineering structural analysis of composite material structures the Load and Resistance 144 145 Factor Design (LRFD) (or its equivalent called Limit States Design (LSD) in the EU) methods or 146 Allowable Stress Design (ASD) methods are used (Bank, 2006). The two primary limits sates 147 analyzed are the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS). In the 148 ultimate limit state (strength, stability) analysis, nominal service loads are typically increased 149 using prescribed load factors and the structural or material capacities are typically reduced using 150 prescribed resistance or materials safety factors. In the serviceability limit state (deflections,

vibrations etc.), neither the nominal service loads nor the material properties are typically

152 factored. The loads for the ULS and SLS are referred to as the factored loads or the service loads,

153 respectively.

154

Nominal service live loads and load combinations (load cases) are used for a civil engineering
structural design and are stipulated in ASCE 7-16 (2016) or Eurocode EN 1991: Actions on
structures (1991). Load combinations are factored amounts of nominal dead load, live load, roof
live load, wind load, snow load, and others (ASCE 7-16).

159

160 The resistance or material factors depend on the type of materials used and are given in separate 161 material specific design codes (e.g., for concrete, the ACI 318-19 or EN 1992: Design of 162 concrete structures; CEN 1992) At the time of writing (2019) an approved design code does not 163 exist for composite materials for civil engineering structures. An ASCE Standard and a Eurocode are currently under development. In the absence of a code the material factors for the FRP 164 165 materials used in this analysis are taken from EUR (2016), the precursor document to the 166 Eurocode. The Material Partial Factor, γ_M , for ultimate strength was calculated to be $\gamma_M = (1.15)$ $\times 1.35 \times 1.2$ = 1.86, assuming (1) the material properties were obtained by test (γ_{M1} = 1.15), (2) 167 168 the production processes and properties of the materials have a standard deviation ≤ 0.10 ($\gamma_{M2} =$ 169 1.35), and, (3) be the material was not post-cured (γ_{M3} =1.2).

170

171 For the serviceability analysis the nominal service loads are used and the Material Partial Factor, 172 $\gamma_M = 1.0$. For most structures the serviceability requirements are set by building codes (e.g., 173 International Building Code (IBC 2018)). For roof structures the requirement is typically that the 174 deflection, δ , (displacement downwards due to gravity) be $\delta < L/240$ (i.e., the member span 175 divided by 240)

It is also of interest to note that design codes for composite wind blades themselves are not yet
available. Technical Committee TC 88, working group PT 61400-5 of the International
Electrotechnical Commission (IEC) is currently working on IEC 61400 - Part 5: Rotor blades.
However, even when these codes are published, they will not be suitable for structural design for
civil structures since local authorities provide construction permits for projects based on building
codes such as the International Building Code (ICC, 2018) which incorporate the model material
design codes (e.g., ACI-318).

185 <u>Loads for roof design</u>

186

For the purposes of the proof-of-principle analysis presented in this paper only one load 187 188 combination was considered: Dead Load + Roof Live Load ($D + L_r$). Only a uniform dead load 189 was considered. Concentrated live load, wind, snow or ice load on the roof load were not 190 considered at this time. This was done to demonstrate the methodology needed for such 191 calculations. It is important to note that other load cases especially those related to wind loads 192 also need to be analyzed. Wind load can create uplift on a roof system which could affect not 193 only the design of the roof itself but, perhaps more significantly, the design of the connection 194 details and louvres shown in Fig. 4.

195

The dead load was determined by uniformly distributing the entire 24.32 kN weight of the roof (determined from the material densities and volumes) over the entire projected roof area of 42.9 m^2 . This gave a uniformly distributed dead load, $D = 0.566 \text{ kN/m}^2$. The code stipulated roof live

199 load, $L_r = 0.96 \text{ kN/m}^2$ was used. This gives an unfactored service load of 1.52 kN/m² and a

200 factored load of $1.2(0.566) + 1.6(0.96) = 2.212 \text{ kN/m}^2$ (ASCE 7-16 LRFD load combination 3).

201

- 202 Preliminary Analysis Hand calculations
- 203

204 Hand calculations using one-dimensional mechanics of materials models were used to determine stresses in individual elements of the roof – Case (1) the shell panel between the 2^{nd} shear web 205 206 and the trailing edge, and Case (2) the third shear web of the roof section. These two cases were 207 chosen for the hand calculations since they were found to be those that gave the largest local 208 deflections and stresses in the roof structure based on a prior approximate analysis conducted 209 (Bank et al 2019). Simplifying assumptions were made relative to the boundary conditions of the 210 shell and web sandwich panels in order to obtain a rough order of magnitude (ROM) estimate of 211 the stresses prior to conducting the detailed FEM analysis described in the following section. 212 Such analyses are routinely made in the early conceptual design stages by structural engineers 213 and architects. 214

- 215 (1) <u>Out-of-Plane Bending of the Shell Panel</u>
- 216

The sandwich panel at the chosen location in the blade consists of a 60 mm thick thermoplastic foam core and two 5 mm composite material face skins of SNLTriax (see Table 1). Since this shell panel is in the transverse (contour) orientation relative to the blade (and roof) longitudinal axis the transverse stiffness and strength properties of the materials are used: $E_{22(Triax)} = 13.65$

221 GPa, $E_{\text{foam}} = 0.256 \text{ GPa}$, $\sigma_{22(\text{Triax})} = +144 \text{ MPa}$, $\sigma_{22(\text{Triax})} = -213 \text{ MPa}$, $\sigma_{\text{tens(foam)}} = +3.1 \text{ MPa}$,

222 $\sigma_{\text{comp(foam)}} = -3.8 \text{ MPa}$, and $\tau_{\text{ult(foam)}} = 2.0 \text{ MPa}$ (see Table 1).

223

The shear web sandwich panels consist of a 60 mm thick thermoplastic foam core and two 3 mm composite material face skins of SNLBiax (see Table 1). Since the shear web sandwich panels are parallel to the blade (and roof) longitudinal axis the longitudinal stiffness and strength properties of the materials are used: $E_{11(biax)} = 13.60$ GPa, $E_{foam} = 0.256$ GPa, $\sigma_{11(Biax)} = +144$ MPa and $\sigma_{11(Biax)} = -213$ MPa.

229

The critical shell panel for analysis was assumed to span between the second web and the trailing edge over the third web as shown in Fig 6. It was analyzed as a flat continuous beam of unit width (1 m) over three supports: S1 second web (0.9 m); S2 third web (0.6m); and S3 the trailing edge. The end supports at the trailing edge and the second web (0.90 m deep) were assumed to be pinned while the middle support (0.60 m web) was assumed to be an elastic spring support with a stiffness equal to the in-plane stiffness of the web. The spans were 1.81 m and 1.94 m respectively.

237

Using the transformed section method the SNLtriax skins were transformed into the properties of the core ($n_1 = 13.65/0.256 = 53.3$) to give a transformed second moment of the 70 mm thick shell panel of $I_{t(shell)} = 5.82 \times 10^8 \text{ mm}^4$. For the 600 mm deep shear web 3 the SNLBiax skins were transformed to the properties of the core ($n_2 = 13.60/0.256 = 53.1$) to give a transformed second moment of the 600 mm deep web of $I_{t(web)} = 6.84 \times 10^9 \text{ mm}^4$. The flexural stiffness of the shell is calculated as, $E_c I_{t(shell)} = 1.49 \times 10^{11} \text{ N.mm}^2$ and that of the web $E_c I_{t(web)} = 1.75 \times 10^{12} \text{ N.mm}^2$.

244	Solving the indeterminate structure in Fig. 6 for the contact force, R_2 , between the shell and the
245	web gives the support reactions due to factored loads, $R_1 = R_3 = 2694$ N, $R_2 = 2876$ N. The
246	maximum moment occurs at $x = 1223$ mm from S1 and is equal to $M_{max} = 1.64 \times 10^8$ N-mm.
247	The maximum shear force is $V_{max} = 2694$ N. The maximum tensile and compressive stresses in
248	the top shell skin is $\sigma_{Triax_skin} = \pm 5.26$ MPa and the core of $\sigma_{foam} = \pm 0.085$ MPa. The shear stress
249	in the core is $\tau_{foam} = 2694/(60)(1000) = 0.045$ MPa. The downward deflection of shell due to
250	service loads at R_2 was $\delta = 12.08$ mm.
251	

- 252 (2) <u>In-plane Bending of the Shear Web</u>
- 253

The 600 mm deep by 8000 mm long web is loaded by a tributary area of half the distance (1.81 254 m) to SW2 on the left side and half the distance (1.94 m) to the trailing edge on the right side as 255 256 shown in Fig. 7. The web is assumed to be simply-supported at its two ends (spanning between 257 the short-end walls of the house) and connected to the shell at its top edge. It is analyzed as a Tbeam. The effective width of the T-beam flange is taken as $b_{eff} = b_{web} + 16(t_{shell}) = 66 + 16(70) =$ 258 259 1186 mm which is less than L/4 = 2000 mm or the web spacing, S = 1810 mm (ACI 318-19). 260 For this configuration the SNLTriax skin is in its longitudinal direction and the longitudinal 261 stiffnesses and strength properties are used: $E_{11(Triax)} = 27.7 \text{ GPa}, \sigma_{11\text{tens}(Triax)} = +972 \text{ MPa},$ $\sigma_{11\text{comp}(\text{Triax})} = -702$ MPa. Properties of the shear web and the foam are as in Case (1) above. 262 263 264 Using the transformed section method the SNLtriax and SNLtriax skins were transformed into the properties of the core $(n_1 = 27.7/0.256 = 108.2, n_2 = 13.60/0.256 = 53.1)$ above giving $\bar{Y} =$ 265 589 mm from the bottom of the web and $I_t = 2.90 \times 10^{10} \text{ mm}^4$. The uniform line load (factored) 266

267	on the top of the web was calculated to be 4.16 N/mm. The maximum bending moment at
268	midspan assuming simple supports at the 8-m ends was $M_{max} = 3.31 \times 10^7$ N-mm and the
269	maximum shear force at the supports was $V_{max} = 16,640$ N. The maximum positive and negative
270	flexural stresses at midspan were $\sigma_{Triax_top} = -10.06 \text{ MPa}, \sigma_{Biax_bot} = +36.06 \text{ MPa}, \sigma_{foam_shell} = -10.06 \text{ MPa}, $
271	0.087 MPa, σ_{foam_web} = -0.680 MPa, τ_{foam_web} = 0.462 MPa (assuming the web foam core carries
272	all the shear force). The maximum displacement (deflection) under service loads at midspan was
273	29.9 mm. (span/268).
274	
275	If the T-beam web is assumed to be fixed-fixed at its ends the maximum deflection is 5.98 mm
276	(span/1338) and the maximum stresses at midspan (positive moment) are: In the panel Triax skin
277	$\sigma_{Triax_top} = -3.35$ MPa and in the web Biax skin $\sigma_{Biax_bot} = +12.01$ MPa, and the maximum stresses
278	at the fixed support (negative moment) in the panel Triax skin $\sigma_{Triax_top} = +6.71$ MPa and in the
279	web Biax skins σ_{Biax_bot} = -24.02 MPa (all four stresses need to be determined since the section is
280	unsymmetric and both positive and negative moment regions exist.)
281	
282	Overdesign Factor – Hand Calculations
283	
284	Comparing the calculated stresses and displacements to the material strengths and the code
285	specified deflection limits (L/240 in this case) indicates the amount of overdesign. It is important
286	to note that this not the safety factor which is accounted for in the load and material factors used.
287	Ideally the structural designer attempts to get the overdesign factor (ODF) as close as possible to
288	1.0. In the current repurposing design the structure and its properties are predetermined by the
289	original design (as a wind blade) and the stresses and deflections are checked with allowable

values. The properties of the section cannot be changed as in a typical design iteration (although they can be modified with local stiffeners and strengtheners). The architectural design is performed at the conceptual stage where the repurposing concept is developed for different sizes of blades. Hence the structural analysis is done to verify the acceptability of stresses, deflections and overdesign factors as opposed to the safety factors that need to be reported. The level of overdesign for the two cases considered above is presented separately for purposes of discussion but, in reality, the lowest number obtained is the actual overdesign factor for the entire structure.

The calculated stresses and displacements and their relevant allowable values and overdesign factors for Case 1 are shown in Table 2. The critical stress for the shell panel is the tensile stress in the transverse direction SNLTriax material in the top layer; but the ODF = 14.7 is high which indicates low utilization of the material capacity. However, the deflection is closer to the code requirement with an ODF = 1.29. Since all overdesign factors are > 1.0 the shell panel has sufficient strength and stiffness under this loading condition. For large glass fiber composite material structures, it is common that serviceability conditions control the design (Bank, 2006).

The calculated stresses and displacements and their relevant allowable values and overdesign factors for Case 2 are shown in Table 3. The critical stress for the shell panel is the tensile stress in the longitudinal direction of the SNLBiax material in the web skins, with an ODF = 2.1. The foam core critical shear stress in the web has an ODF = 2.4. Again, the serviceability condition controls the design with an ODF = 1.1. Nevertheless, all ODFs are > 1.0 for these handcalculations and the structure is safe and serviceable. Note that the results shown in Table 3 for the shear web are for the less conservative analysis that assumes that the shear web is pin-roller

supported (as opposed to fixed-fixed) at its ends. ODFs will be higher if the fixed-fixedconditions are used.

315

316 Detailed analysis – finite element method

317

318 The finite element modeling of the roof was conducted using the implicit version of the LS-319 DYNA software code (LS-DYNA, 2018). LS-DYNA implicit was chosen because the authors 320 have detailed knowledge and many years of experience working with this code (both the implicit 321 and explicit forms (e.g., Bank and Gentry (2001)). Unfortunately, finite-element codes of this 322 type are not ideally suited to structural engineering analysis since they do not allow "automatic" 323 evaluations of standard ASCE 7 load cases. This means that the load cases must be input 324 manually which is not trivial. Equally unfortunate is that standard structural engineering design 325 codes (e.g., ETABS, STAAD, ROBOT) do not permit arbitrary laminated composite plate and 326 shell elements.

327

The FEM mesh, global (X, Y, Z) and local (x, y, z) coordinate systems for the shell and the webs, and the boundary conditions are shown in Fig. 8. In Fig. 8 triangles represent pinned supports and circles roller supports and grey circles indicate support hidden from view in this orientation. The colors in the model represent different layups in segments of the blade that were used in the roof. The foreshortened perspective shown in Fig. 8 is drawn looking from the 35.8 m station towards the 27.6 m station (i.e., tip to root of the blade).

335	The yellow region is the Carbon Fiber Reinforced Polymer (CFRP) / Glass Fiber Reinforced
336	Polymer (GFRP) spar cap between webs 1 and 2 (5 mm SNLTriax/80 mm SNLCarbon/5 mm
337	SNLTriax), the green regions are the GFRP/foam shell sandwich panel (5 mm SNLTriax/60 mm
338	foam/5 mm SNLTriax), the brown region is the trailing edge panel (TE) (5 mm SNLTriax/15
339	mm Glass UD/40 mm Foam/5 mm SNLTriax), and the blue regions are the SNLBiax/foam web
340	panels (3 mm SNLBiax/50 mm foam/3 mm SNLBiax) (Griffith, 2013). A fully-integrated
341	laminated shell element (LSDYNA ELFORM=16) was used. The total model consisted of 3115
342	nodes and 1813 elements. The major 11-axis of the materials (see Table 1) is aligned with the
343	global Y-direction and the local x-direction for the shell and web segments (see Fig. 8).
344	
345	Results of Finite Element Analysis
346	
346 347	Selected results from the finite element analyses are presented to illustrate the stress distributions
346 347 348	Selected results from the finite element analyses are presented to illustrate the stress distributions and displacements in key locations. As in the hand calculations the factored load in the global Z-
346 347 348 349	Selected results from the finite element analyses are presented to illustrate the stress distributions and displacements in key locations. As in the hand calculations the factored load in the global Z-direction was 2.212 kN/m^2 . This was uniformly distributed over the 3115 nodes in the model.
346 347 348 349 350	Selected results from the finite element analyses are presented to illustrate the stress distributions and displacements in key locations. As in the hand calculations the factored load in the global Z- direction was 2.212 kN/m ² . This was uniformly distributed over the 3115 nodes in the model. Fig. 9 shows the vertical displacement (deflection) of the roof in the negative Z-direction. The
 346 347 348 349 350 351 	Selected results from the finite element analyses are presented to illustrate the stress distributions and displacements in key locations. As in the hand calculations the factored load in the global Z- direction was 2.212 kN/m ² . This was uniformly distributed over the 3115 nodes in the model. Fig. 9 shows the vertical displacement (deflection) of the roof in the negative Z-direction. The maximum displacement of 7.1 mm (downwards) occurs over the 3 rd shear web near the center of
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 346 347 348 349 350 351 352 353 	Selected results from the finite element analyses are presented to illustrate the stress distributions and displacements in key locations. As in the hand calculations the factored load in the global Z- direction was 2.212 kN/m ² . This was uniformly distributed over the 3115 nodes in the model. Fig. 9 shows the vertical displacement (deflection) of the roof in the negative Z-direction. The maximum displacement of 7.1 mm (downwards) occurs over the 3 rd shear web near the center of the large panel between the trailing edge support and the 2 nd shear web.
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transverse direction of -5.0 MPa occurs in the two panels on either side of the 3^{rd} shear web. It

be can be seen that the 3rd shear web provides a flexible intermediate support and the
compressive stress decreases along this line giving the butterfly shaped stress contours. The light
blue shading over the 2nd shear web indicates a tensile stress and a negative curvature (and
moment) over the support. Regions of high tensile stress in the shell top skin are also seen at the
upper ends of the 3rd shear web indicating negative curvature at the end of the flexible
intermediate support and some fixity at the ends provided by shell action.

364

365 The stress at the midplane of the top surface in the SNLTriax layer in the skin of the shell 366 sandwich panel in the local x-direction is shown in Fig. 11. (In this figure the stress along the blade axis is shown, σ_x , while in Fig. 10 the stress transverse to the blade axis is shown, σ_y . Due 367 to two-way bending of the panel these stresses are different.) As with the y-direction the central 368 369 portion is in compression (green) with a maximum longitudinal compressive stress in this region 370 of -5.0 MPa. Similar to the *y*-direction tensile stresses are seen in the *x*-direction at the ends of 371 the 3rd shear web indicating a negative curvature in this direction as well. However, this is not as 372 significant as in the x-direction due to the higher stiffness of the shell skin laminate in the x-373 direction.

374

The displacements and stress in the shear webs are shown next. To help with visualization the shell panels are only shown in outline in these contour plots. Downwards displacement of the shear webs in shown in Fig. 12. The maximum deflection in the Z-direction is 7.1 mm (downwards) and occurs under the 3rd shear web which is equal to the deflection of the top shell at this location shown in Fig. 9. This to be expected as the in-plane deformation of the shear

webs in the Z-direction is negligible. The maximum displacement under the 2nd shear web is 380 significantly less and is 2.4 mm at its center. This explains the restrain provided by the 2nd shear 381 web and the negative curvature over the webs seen in Fig. 10. The 1st shear web which is fully 382 383 supported at its bottom along the wall shows no downward displacement, as expected. 384 385 The stresses in the x-direction in the shear webs are shown in Fig.13. The maximum tensile stress occurs in the SNLBiax skin in the 3rd shear web at the bottom of the web and is equal to 386 10.9 MPa. Tensile stresses at the bottom of the 2^{nd} shear web are less, with a maximum at the 387 388 center of 5.7 MPa. It is interesting to note the relatively large compressive stresses of -25.0 MPa at the pinned supports of the shear webs. This implies a localized outward thrust due to a global 389 restraint provided by the shell. It is important to note the shear webs are supported by roller 390 391 supports (no restraint in the longitudinal X-direction) at their far ends (see Fig. 8) so ideally there 392 should be no thrust at the pinned supports at the near ends. However, the shear webs do not 393 behave as simple beams and are restrained at their ends by the global two-way action of the shell. 394 395 The stresses in the local *y*-direction of the shear webs are shown in Fig. 14. Compressive 396 stresses are noted at the supports which are larger at the near ends due to the pinned support as 397 noted previously. 398 Finally, elastic buckling analysis was conducted to check for overall instability of the roof 399 400 structure. The buckling occurs at a load magnification factor of 31 (i.e., 31 times the factored load of 2.212 kN/m².) Buckling occurs in the 3^{rd} shear web as is shown in Fig. 15. This is logical 401 given the large compressive stresses seen in this location in both the local x and y directions. 402

403	However, the buckling load is much larger than would be required to cause material failure in
404	these locations and elastic instability will be precluded. Nevertheless, local stiffening will be
405	needed at the supports of the 2 nd and 3 rd webs to prevent both local bearing failure and local
406	buckling at these locations (Borowicz and Bank 2013).
407	
408	Overdesign Factor – 3-D FEM Calculations
409	
410	The finite element analysis gives results for the entire structure unlike the hand-calculations
411	where the shell and web were analyzed separately. The results for the 3-D FEM calculations are
412	given in Table 4.
413	
414	The critical stress for the roof as a whole is the compressive stress in the longitudinal direction in
415	the SNLBiax layer in the shear web with an $ODF = 4.6$. All ODFs are all greater than 1.0 for
416	this FEM analysis and the structure is safe. The critical displacement is in the shell panel with an
417	ODF of 2.2 which satisfies serviceability requirements.
418	
419	Discussion
420	
421	The results obtained from the one-dimensional mechanics-of-materials hand calculations and the
422	full three-dimensional finite element method analyses are in reasonably good agreement.
423	Generally, the stresses and deflections obtained from the FEM analysis are less than those
424	obtained in the hand-calculations. This is to be expected as the roof shell has a two-way action
425	that distributes loads in both the transverse and longitudinal directions. It is encouraging to know

426 that provided good modeling assumptions are made for hand-calculations, these calculations can 427 be used in preliminary design stages to assess the feasibility of repurposing designs. In addition, 428 the FEM analysis uncovers local multi-directional stresses, especially at the supports, which 429 provides important input for structural detailing such as local stiffening and strengthening. 430 431 Conclusions 432 433 A methodology for structural analysis of EOL wind turbine blade sections has been developed 434 and demonstrated. This is essential for repurposing wind turbine blades. The methodology can be 435 applied to other structural applications for decommissioned wind turbine blades. This will 436 contribute to improved sustainability of the wind energy sector. As indicated in the paper both 437 hand-calculations and finite element methods can be used for analysis. Nevertheless, this is not 438 trivial as a wind blade tapers and twists and its material properties change along its length. In 439 either case the analysis results will only be as good as the assumptions made in building the 440 analytical models. Over-simplification of hand-calculation models is not advised. When FEM 441 analysis is used laminated shell elements must be used and care must be taken to correctly orient 442 the orthotropic materials in the laminate with respect to the global coordinate system. 443 For structural analysis and architectural detailing a full 3-D model showing the individual 444 445 material layers of the blade is needed. However, most blade models used for aerodynamic and 446 structural analysis are wire frame surface models. In addition, for infrastructure applications governing building codes will need to be used since local jurisdictions permit construction based 447 on these codes. These codes are not typically familiar to composite material designers. At the 448

449	current time a code does not exit to obtain probabilistically based material partial factors or
450	element resistance factors for design of FRP structures. But, code like documents can be and are
451	used in lieu of these codes.
452	
453	Acknowledgement
454	
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457	16/US/3334 and by Science Foundation Ireland (SFI) under grant USI-116 (US-Ireland Tripartite
458	program).
459	
460	Data Availability Statement
461	
462	Some or all data, models, or code that support the findings of this study are available from the
463	corresponding author upon reasonable request.
464	
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621 622	List of Figures
623 624 625	Fig. 1 Repurposing concepts for housing from 100 m long blade parts
626 627 628	Figure 2. a.) Entire 100-m long blade, b.) Cross-sectional view at Station 19 (27.6-m from the root end)
629 630	Fig. 3 Location of roof section extracted from blade (along the length)
631 632	Fig. 4 Schematic of roof
633 634	Fig. 5 Dimensions of the roof (perspective drawing)
635 636	Fig. 6 Analytical model of the shell panel and supports
637 638	Fig. 7 Analytical model of the shear web and supports
639 640	Fig. 8. FEM mesh and boundary conditions
641 642	Fig. 9. Z-displacement of the roof
643 644	Fig. 10. Stresses in top skin layer in <i>y</i> -direction (blade transverse or contour direction)
645 646	Fig. 11. Stresses in top skin layer in x-direction (blade longitudinal direction)
647 648	Fig. 12 Displacement of the shear webs in the Z-direction
649 650	Fig 13 Stresses in the shear webs in the <i>x</i> -direction (longitudinal direction of the web)
651 652	Fig 14 Stresses in the shear webs in the y-direction (vertical direction in the web)
653 654 655 656	Fig. 15 Buckled shape of the 3 rd shear web

657 List of Tables

658 659

- 660 Table 1. Material properties of laminates in the SNL-100-01
- 661 Table 2. Hand-Calculation Overdesign Factors (ODFs) for Case 1 Shell Panel
- 662 Table 3. Hand Calculation Overdesign Factors (ODFs) for Case 2 Shear Web (T-Beam)
- 663 Table 4. 3-D FEM Calculation Overdesign Factors (ODFs) for entire roof

665 Figure 1.



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668 Figure 2



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671 Figure 3



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674 Figure 4



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677 Figure 5



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680 Figure 6



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683 Figure 7



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Final published version: https://doi.org/10.1061/(ASCE)AE.1943-5568.0000440

686 Figure 8



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689 Figure 9



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Final published version: https://doi.org/10.1061/(ASCE)AE.1943-5568.0000440

692 Figure 10



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695 Figure 11



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Final published version: https://doi.org/10.1061/(ASCE)AE.1943-5568.0000440

698 Figure 12



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701 Figure 13



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Final published version: https://doi.org/10.1061/(ASCE)AE.1943-5568.0000440

704 Figure 14



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Final published version: https://doi.org/10.1061/(ASCE)AE.1943-5568.0000440

707 Figure 15



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710 711

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- 713

Table 1. Material properties of laminates in the SNL-100-01

714			1								1
715	Material	F.,	Eas	Gua	1/10	0	σ_{11}	σ_{11}	σ_{22}	σ_{22}	au
716	Туре	$(\mathbf{C}\mathbf{P}_{\mathbf{a}})$	$(\mathbf{C}\mathbf{P}_{\mathbf{a}})$	$(\mathbf{GP}_{\mathbf{a}})$	v 12	$(k\alpha/m^3)$	(tens)	(comp)	(tens)	(comp)	
717		(Ora)	(UFa)	(Ora)		(kg/m)	(MPa)	(MPa)	(MPa)	(MPa)	(IVIF a)
718							× /	× ,	× ,	、 /	
719	Foam	0 2 5 6	0 2 5 6	0.022	03	200	3 1 [#]	-3.8#	3 1 [#]	-3.8#	$2.0^{\#}$
720	i ouili	0.200	0.200	0.022	0.5	200	5.1	5.0	5.1	5.0	2.0
721	C1										
722	Glass	41.80	14.00	2.63	0.28	1920	972	-702	31*	-118*	72^{*}
723	$UD [0]_2$		1		0.20	1720	<i>, , _</i>	, •=	01	110	. –
724											
725	SINLBIAX	13.60	13.30	11.80	0.51	1780	144	-213	144	-213	
726	[±45]4	$[\pm 45]_4$ 1000 1000 1000 1000 110 210 110 210									
727											
728	SNLTriax	27.70	13.65	7.20	0.39	1850	972	-702	144 [§]	-213 [§]	
729	$[\pm 45]_4[0]_2$ 27.76 15.65 7.26 0.57 1050 772 702 144 -215 -1										
730											
731	SNLCarbon	114 50	e 20	5.00	0.27	1220	1546	1047	52*	206*	02*
732	(UD)	114.30	0.39	5.99	0.27	1220	1340	-104/	52	-200	95
733											
734	Notes: # from AIREX® T92.200 (2018)										
735	* from Agarwal et al (2006)										
736	$^{\$}$ assumes that ±45plies control strength in transverse direction										
737	not determined (not used in analysis)										
738											
739											

	7	4	2
--	---	---	---

Stress or	Hand-	Relevant	Ultimate	Partial	Code	ODF =
Displacement	Calculated	Design	Value	Safety	Allowable	Allowable/Calculated
Component	Value	Property	(MPa or	Factor	(MPa or	Values
Analyzed	(MPa or		mm)	(γ_M)	mm)	
	mm)					
σ_{Triax_top}	+5.26	$\sigma_{22tens(Triax)}$	+144	1.86	+77.4	14.7
σ_{Triax_bottom}	-5.26	$\sigma_{22comp(Triax)}$	-213	1.86	-114.5	21.7
σ_{foam}	+0.085	$\sigma_{tens(foam)}$	+3.1	1.86	+1.7	19.6
σ_{foam}	-0.085	$\sigma_{comp(foam)}$	-3.8	1.86	-2.0	24.0
$ au_{\mathrm{foam}}$	+0.045	$\tau_{ult(foam)}$	+2.0	1.86	+1.1	23.9
$\delta_{ m midspan}$	12.08	L(3650)/240	15.6	1.0	15.6	1.29

743

745

- 746 747
 - Table 3. Hand Calculation Overdesign Factors (ODFs) for Case 2 Shear Web (T-Beam)

748

Stress or	Hand-	Relevant	Ultimate	Partial	Code	ODF =
Displacement	Calculated	Design	Value	Safety	Allowable	Allowable/Calculated
Component	Value	Property	(MPa or	Factor	(MPa or	Values
Analyzed	(MPa or		mm)	$(\gamma_{\rm M})$	mm)	
	mm)					
σ_{Triax_top}	-10.06	$\sigma_{11comp(Triax)}$	-702	1.86	-377.4	37.5
σ_{Biax_skin}	+36.06	$\sigma_{11tens(Biax)}$	+144	1.86	+77.4	2.1
σ_{foam_shell}	-0.087	$\sigma_{comp(foam)}$	-3.8	1.86	-2.0	23.0
σ_{foam_web}	-0.680	$\sigma_{comp(foam)}$	-3.8	1.86	-2.0	2.9
$ au_{foam_web}$	+0.462	$\tau_{ult(foam)}$	+2.0	1.86	+1.1	2.4
$\delta_{midspan}$	29.9	L(8000)/240	33.3	1.0	33.3	1.1

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751

Table 4. 3-D FEM Calculation Overdesign Factors (ODFs) for entire roof

752

Stress or	Hand-	Relevant	Ultimate	Partial	Code	ODF =
Displacement	Calculated	Design	Value	Safety	Allowable	Allowable/Calculated
Component	Value	Property	(MPa or	Factor	(MPa or	Values
Analyzed	(MPa or		mm)	(γ_M)	mm)	
	mm)					
σ_{yTriax_top}	-5.0	$\sigma_{11comp(Triax)}$	-702	1.86	-377.4	75.5
σ_{yTriax_top}	+4.8	$\sigma_{11tens(Triax)}$	+972	1.86	+552.6	108.9
σ_{xTriax_top}	-5.0	$\sigma_{22comp(Triax)}$	-213	1.86	-114.5	22.9
σ_{xTriax_top}	+5.0	$\sigma_{22tens(Triax)}$	+144	1.86	+77.4	15.5
σ_{xBiax_bottom}	+10.9	$\sigma_{11tens(Biax)}$	+144	1.86	+77.4	7.3
σ_{xBiax_bottom}	-25.0	$\sigma_{11comp(Biax)}$	-213	1.86	-114.5	4.6
σ_{yBiax_bottom}	-14.6	σ _{22comp(Biax)}	-213	1.86	-114.5	7.8
δ_{shell}	7.1	3750/240	15.6	1.0	15.6	2.2
δ_{web}	7.1	8000/240	33.3	1.0	33.3	4.7