SAND2022-3804C

Accurate Modeling of Material Nonlinearities in a Wind Turbine Spar Cap

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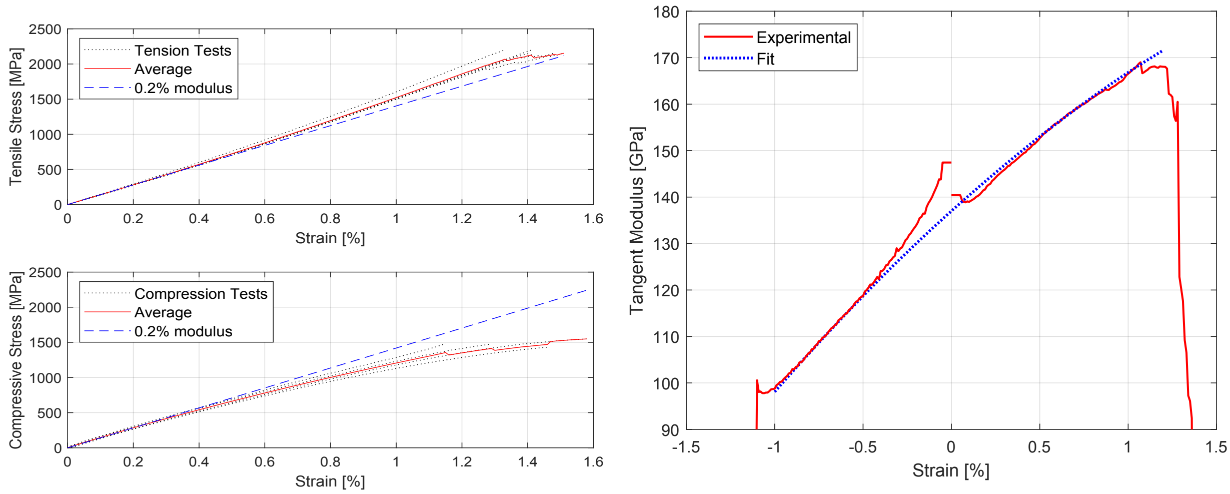
Abstract. This study presents component-level testing of carbon fiber sandwich beams and the effect of carbon fiber material nonlinearity in its strain response in bending. A simple material model is presented and validated that accurately captures the carbon fiber longitudinal nonlinearity in both the tensile and compressive response. This material model is implemented in a finite element model of the BAR-DRC reference wind blade, a downwind 100-meter rotor blade, and the effects of the nonlinearity on ultimate limit states of the blade are analyzed. The material nonlinearity has negligible effect on the deflection, and material failure predictions. The buckling analysis revealed significant reductions in buckling load factor in the controlling flap direction caused by the material nonlinearity, revealing the importance of including this material model for buckling analyses of wind blade with carbon fiber reinforced spar caps.

1. Introduction

As wind blades continue to increase in length, stiffer structural materials like carbon fiber are becoming necessary to continue to decrease the costs of wind energy. Carbon fiber has superior mechanical properties over glass fiber and has been shown to have significant benefits for modern wind blade design [1]. However, carbon fiber composites have been shown to exhibit nonlinear elastic performance [2, 3]. Nonlinear material behavior is typically not modeled in standard structural analyses which assume linear elastic behavior of the wind blade material in design simulations [4]. Recent testing of pultruded Zoltek PX-35 carbon fiber composites has shown non-linearity in both tensile and compressive stress-strain behavior of the carbon fiber composite before failure [5]. While the nonlinear effect seems insignificant through visual observation of the stress-strain diagram in Figure 1a, the tangent modulus is observed to vary approximately (-30%, +20%) up to failure. The instantaneous stiffness of a material is related to the tangent modulus at a given strain level which is shown from coupon test data in Figure 1b. While other materials commonly used in wind blades are known to have a more pronounced nonlinear response than the carbon fiber analyzed in this study, such as biaxial laminates in tension [6], this was deemed important to analyze due to the high criticality of carbon spars in the structural integrity and response of the wind blade structure.

This work presents component-level test data from carbon fiber sandwich beams and the effect that the carbon fiber elastic nonlinearity has on the structural response in bending. Additionally, Finite Element (FE) modeling is performed to accurately model the carbon fiber nonlinearity and implemented into a FE model of a modern wind blade design [7]. The FE wind blade model with carbon spar cap nonlinearity is then analyzed using a critical set of static design load cases representing the extreme loads, and compared to predictions using a standard linear elastic wind blade model.



(a) Coupon tension and compression test data.

(b) Tangent modulus computed from averaged test data.

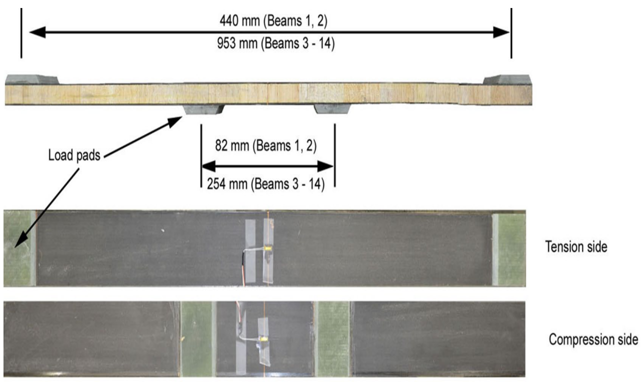
Figure 1: Coupon test data showing carbon fiber nonlinear elasticity [5].

2. Component Testing

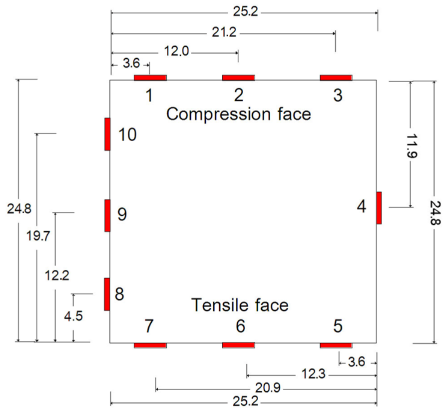
Composite materials are traditionally tested using either small coupon samples or in full structures. Coupon-level tests produce idealized results that provide insight into the mechanical properties, and enables the generation of statistically representative data sets. Full composite structures provide less fundamental insight into material mechanical performance, but include the effects of geometry and manufacturing to get a truly representative performance prediction. Component-level tests have been performed to test fundamental mechanical performance while also including geometrical effects experienced in realistic structures.

2.1. Experimental Setup

Fifteen composite sandwich beams were fabricated using pultruded Zoltek PX-35 carbon fiber epoxy face sheets. Initially, balsa was used as the core material in the first eight iterations of the tested carbon fiber sandwich beams, however, it was determined that standard balsa or foams do not have the shear or compressive strength necessary to work with the testing geometry without producing premature core failures. To reach representative face sheet strains without premature core failure, a biaxial glass fiber epoxy composite oriented with the +/-45° plies being in the beam height direction was used as the sandwich core for beams 9-15. The composite sandwich beams were tested in four-point bending with a major span of 953 mm and a minor span of 254 mm, shown in Figure 2a. Load pads were used in all configurations to reduce stress concentrations caused by the loading of the beams. The final beam configuration (beam 15) was additionally instrumented with ten strain gauges applied at mid-span in a configuration shown in Figure 2b to measure the tensile and compressive faces of the beam as well as mid-thickness strains to track the shifting of the neutral axis. The nonlinear elastic performance of the carbon fiber pultrusions results in asymmetric strain in the tensile and compressive face sheets as shown for beams 12-14 in Figure 3.



(a) Sandwich panel beam test components.



(b) Diagram of strain gauge layout at mid-span of beam 15.

Figure 2: Dimensions and specifications of tested carbon fiber sandwich beams [8].

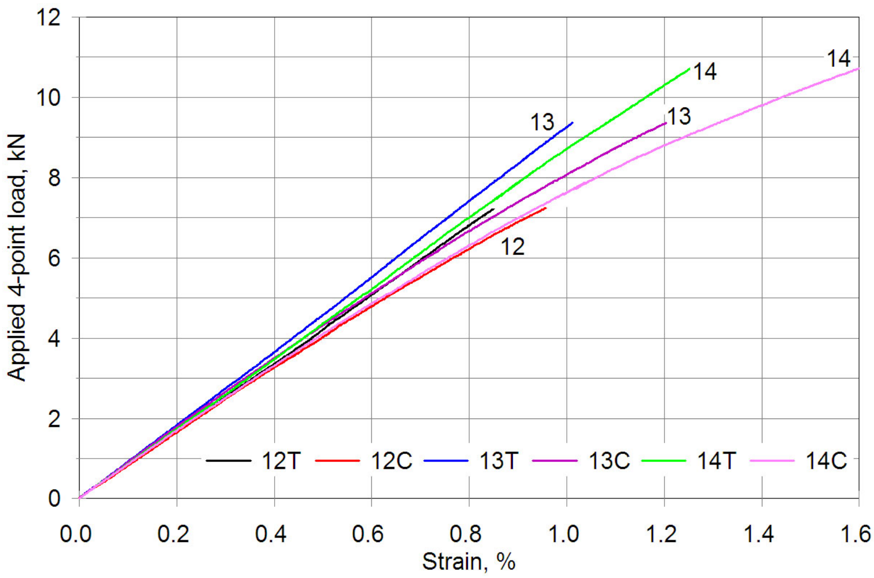


Figure 3: Bending load vs. mid-span carbon fiber face sheet strains for Beams 12-14 [8].

2.2. Characterization of asymmetric strain in beams

The nonlinearities in the tensile and compressive moduli of the carbon fiber face sheets causes a shifting of the neutral axis in the sandwich beam as load is applied, moving towards the stiffer tensile side of the beam. The shift of the neutral axis away from the geometric center observed as a non-zero strain response in the mid-thickness strain gauges on composite sandwich beam 15, Figure 4. Since material strain is linearly related to the distance to the neutral axis, a standard linear elastic wind turbine blade analysis that does not capture this effect would over-predict the tensile strain and under-predict the compressive strain in this beam. The underprediction of compressive strain means the industry standard approaches are non-conservative as compressive strain often drives the spar cap material usage in a wind turbine blade.

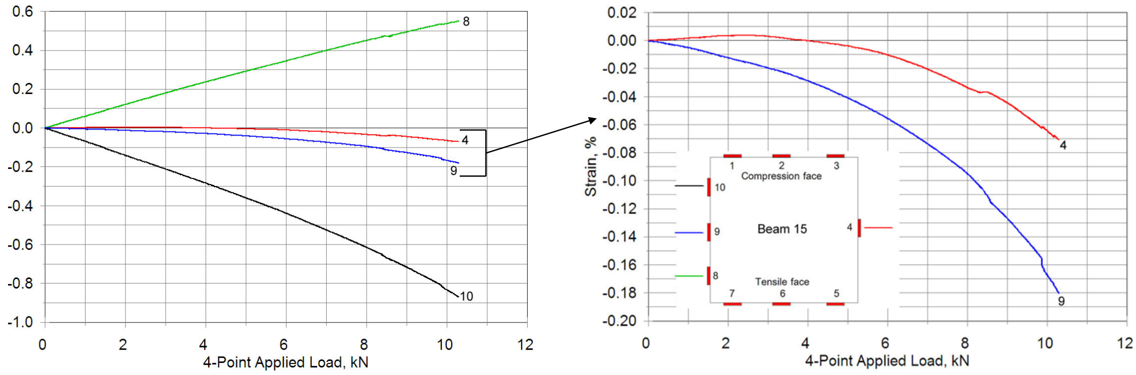


Figure 4: Strain load diagram of mid-thickness strain gauges show non-zero compressive strain indicating a shifting of the neutral axis towards the tensile (stiffer) side [8].

3. FE modeling of composite nonlinearity

3.1. Material model definition

To accurately model the nonlinearity of carbon fiber an ANSYS® USERMAT was created using Equation 1 to model the tension stiffening and compressive softening behavior, where E_1^0 is the initial Young's modulus in the fiber direction, ε_{11} is the normal strain in the fiber direction, and K is a calibration parameter. The ANSYS USERMAT was calibrated using a one element test with the averaged coupon test data of the Zoltek PX-35 pultruded carbon fiber plates as seen in Figure 5. To better fit the nonlinearity, different K values were fitted to the data depending on if it was in compression (K_c) or tension (K_t). The values for K_c and K_t along with the other composite properties used in the pultruded carbon fiber material model are shown in Table 1.

$$E_1 = E_1^0(1 + K\varepsilon_{11}) \tag{1}$$

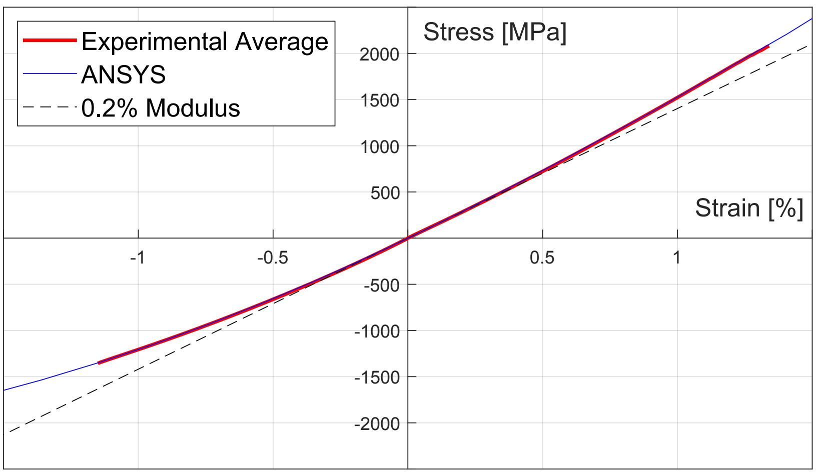


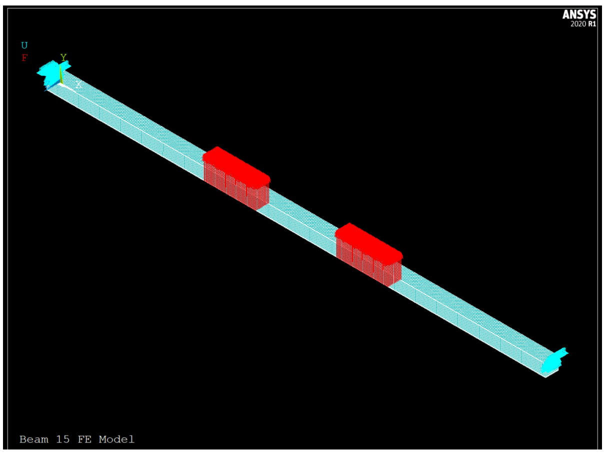
Figure 5: One element test results of nonlinear carbon fiber ANSYS USERMAT compared to averaged coupon test data.

Table 1: Mechanical properties used in the pultruded carbon fiber composite model.

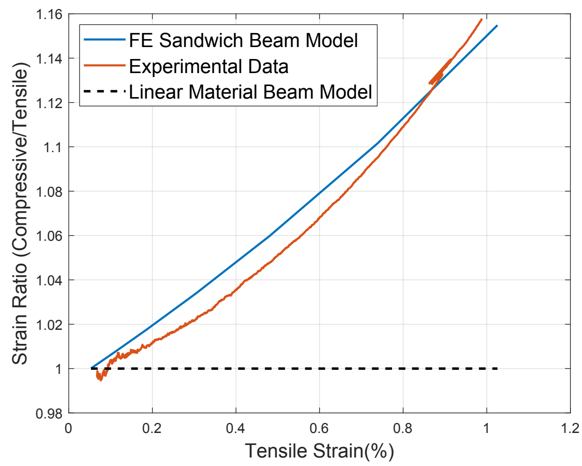
E_1^0[GPa]	E_2[GPa]	ν_{12}	G_{12}[GPa]	G_{23}[GPa]	K_t	K_c
142	9.1	0.32	4.0	2.689	8	15

3.2. Material model verification

To verify the performance of the nonlinear carbon fiber material model in representative structures, an FE model of the tested beam geometry in four point bending is developed, shown in Figure 6a. The FE model of the beam was meshed with 20-node SOLID186 brick elements. Material property values for the biaxial glass core were taken from Camarena [7] with properties for the carbon fiber USERMAT from Table 1. Nodes corresponding to the major span of the beam had their Y and Z translational degrees of freedom fixed while the X degrees of freedom corresponding to the span direction were allowed to move. Loading was applied via forces applied to the nodes corresponding to the minor span load pads using actuator load readings taken from the testing of beam 15 to simulate the four-point bend test. The model was then verified by comparing the strain ratio (SR) of compressive to tensile strain at mid-span of beam 15's face sheets to that of the element strains in the FE model as seen in Figure 6b. The slight discrepancy between the FE SR and experimental SR is caused by unmodeled nonlinearities in the core material. The data and FE results are compared with a linear beam model where the strain ratio is equal to one, for reference.



(a) Meshed Beam 15 FE Model showing boundary conditions and loads.



(b) Compressive-side/Tensile-side strain ratio comparison between FE model, sandwich beam test data from 4-point bending tests, and a linear material beam model.

Figure 6: Model and results of carbon fiber material nonlinearity in component level tests

4. Wind blade comparison study

To investigate the effect the carbon fiber nonlinearity has in a wind turbine blade, a comparison study is performed between a conventional linear elastic wind blade FE model and a wind blade model with the developed carbon fiber nonlinearity model. BAR-DRC, a downwind, rail transportable 100 meter blade with carbon fiber spar caps was chosen for the comparison [7]. Both FE models are identical except for the material models used in their respective spar caps. Both models are meshed using linear SHELL 181 elements with a mesh size of 0.1 meters. Model creation was automated using NuMAD 3.0 [7]. BAR-DRC was designed using pultruded Zoltek carbon fiber in it's spar caps with a volume fraction of 68%. The material tested in this paper had a fiber volume fraction of 62%, so elastic properties for the 68% volume fraction spar cap were used from Camarena [7]. The scale factor in the nonlinear model is dependent on strain and not the Young's modulus, and it is assumed that the calibrated values for K would not change. All other material properties, and safety factor values used in the analysis were defined by Camarena [7]. The FE models have been evaluated for factors critical to safe design such as max tip deflection, material strain limits, and buckling using NuMAD. The BAR-DRC reference blade was designed under a mid-fidelity optimization scheme which required the use of linear finite element analysis for speed. However, because material nonlinearity effects cannot occur in a linear analysis, nonlinear finite element analyses are used in the design studies in this paper. Note, safety factors for material rupture, buckling, and deflection were applied prior to the analysis.

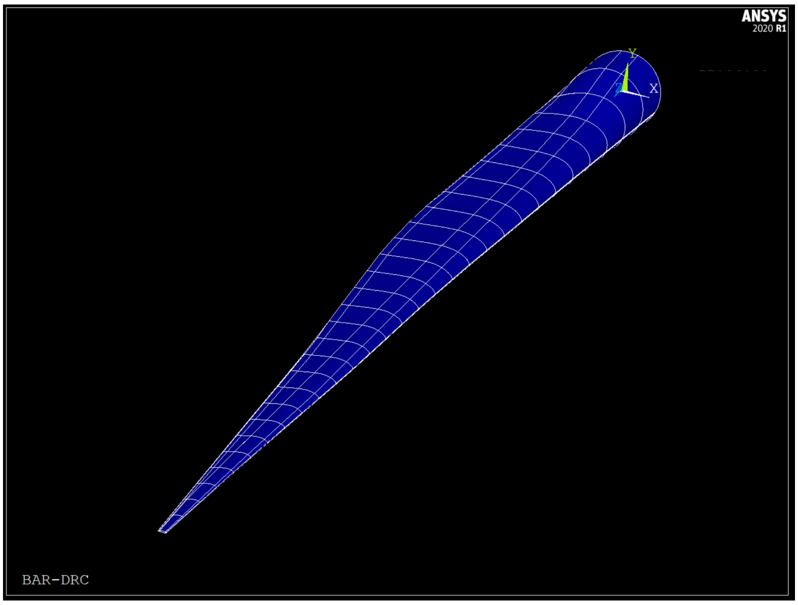


Figure 7: FE model of wind blade BAR-DRC.

4.1. Deflection analysis

To evaluate the maximum deflection constraint, OpenFAST [9] has been used to simulate operational design load cases (DLCs) 1.1, 1.3, 1.4, and 1.5 to identify the load distribution at the time of the out-of-plane max deflection [4]. The spanwise load distribution determined in OpenFAST was then transferred to the 3D FE shell model using the process outlined by Berg [10]. A more detailed explanation of the loading scheme and how load equivalency was determined between OpenFAST and the ANSYS shell model is described by Camarena [7].

Even though BAR-DRC is a down wind rotor design and does not need to adhere to the traditional deflection constraint brought on by the potential for tower strikes, the analysis is performed to illustrate any potential effects that the carbon fiber nonlinearity might have. BAR-DRC was initially designed using a linear finite element analysis and the blade was not able to reach the full deflection loading without structural buckling using nonlinear analysis (for either material models). To perform a comparison of the blade deflection, the loading was reduced to 64% of it's original magnitude, which is the level just below where global buckling had occurred. This load reduction is considered acceptable for this study since it is a comparative analysis of the effects of material nonlinearity and not a full design study of a wind blade. The load reduction meant the spar cap strain levels only reached a max of 0.3% and 0.35% for the pressure and suction sides of the blade respectively.

The FE analysis shows only a minor impact on the predicted maximum tip deflection from material nonlinearities. The maximum tip deflection for the linear spar material model was 15.56 meters while the maximum tip deflection of the nonlinear spar material model was 15.68 meters, a difference of only 0.74%. The difference in tip deflection between the linear and nonlinear spar cap material models for the BAR-DRC model is insignificant at the reduced load and is easily accounted for with the IEC partial safety factors. However, the observed carbon fiber nonlinearity becomes more prominent with larger material strains and it could produce a meaningful difference in tip deflection had the blade had been able to reach it's full designed deflection state.

4.2. Buckling analysis

A geometrically nonlinear buckling analysis has been performed where the FE wind blade model was incrementally loaded until non-convergence occurred. Wind blade design standards that specify nonlinear finite element analysis as part of the design process do so with a requirement of accounting for sensitivities to imperfections through superimposing the scaled results of an linear bifurcation analysis onto the structure to initiate buckling[11]. This was not done for this study because the material nonlinearity introduced in the spar cap changes the structural characteristics of wind blade model that a linear bifurcation analysis cannot account for. Using a linear bifurcation analysis on a nonlinear material may yield unrealistic buckling modes and therefore unrealistic critical imperfection shapes. Wind blades are inherently eccentrically loaded structures with internal moments and therefore do not necessarily need a starting imperfection to initiate global buckling. The blade loading profile for the buckling analyses was constructed using the maximum loads experienced at each individual blade span from the set of simulated IEC DLCs and thus is an artificial load distribution meant for design use and evaluation. The IEC design standard allows for less conservative design and lower safety factors if multiple load directions are considered[4]. Eight load directions are analyzed from 0° to 360° in increments of 45°, with 0° corresponding to a moment profile with a primary deflection in the leading edge direction and the angles continuing in a counter-clockwise fashion through the blades cross-section. A more detailed explanation of the design loading for blade failure can be found in Camarena [7].

Results of the nonlinear buckling analysis are shown in Table 2, where load factors less than unity indicate a buckling failure is predicted prior to the applied load. Several of the load factors, even for the linear spar cap material are below unity meaning the blade buckles prior to reaching the design load in that direction. These premature failures can be expected considering BAR-DRC was designed using a linear analysis. Even though the blade appears to not be adequately designed for buckling under nonlinear analysis it is still valid for comparison purposes. Despite material nonlinearities not significantly affecting the tip deflection for the BAR-DRC, the buckling analysis does reveal non-negligible differences. The largest effect the nonlinear material has for buckling in BAR-DRC occurs in the 90°, and 135° load directions, corresponding to positive deflection in the downstream flap and the downstream flap-trailing edge directions, respectively. This makes sense as flap loading produces the largest longitudinal strain in the spar cap material and associated deviation from the linear modulus. The flap-trailing edge ultimate load profile with accurate modeling of the carbon fiber nonlinearity results

Table 2: Results of geometrically nonlinear buckling analysis using the two material models.

Load direction[°]	Linear material load factor	Nonlinear material load factor	Difference[%]
0	13.96	13.84	-0.86
45	0.94	0.99	5.32
90	0.66	0.52	-21.21
135	1.02	0.59	-42.16
180	6.67	6.72	0.75
225	2.09	2.03	-2.87
270	0.80	0.80	0
315	1.34	1.34	0

in a premature buckling failure at a 40% lower load than the applied design loads. For reference, the simulated characteristic loads from OpenFAST have a 35% safety factor which means that this load direction would fail at 80% of the simulated characteristic loads. It is important to note that buckling itself is a highly nonlinear process and a 40% reduction in load carrying capacity does not necessarily equate to needing 40% more material for a safe design.

4.3. Material failure analysis

Wind turbine blades can also fail through an ultimate failure in the blade material itself, resulting in either a catastrophic failure or in a crack that can grow through fatigue loading. a material failure analysis has been performed using the same loading scheme as described in Section 4.2. Since many of the analysis directions buckled before reaching the full design load in nonlinear analysis the failure index was evaluated for each direction just before buckling using the lower of the linear or nonlinear material model buckling predictions. The Tsai-Wu failure criterion was used to evaluate the failure index with the default value of -1 for the 3 shear coupling coefficients. Material strength values for all the materials used in BAR-DRC and required for the Tsai-Wu criterion can be found in Camarena [7]. To fairly compare the effect carbon fiber nonlinearity has on the material failure analysis of BAR-DRC, the effective maximum failure index of all elements in the blade ()Table 3) was chosen to compare between the two models. The effective maximum was computed as the 99th percentile of the failure indexes in the blade model. This was done instead of using the true maximum failure index to remove any non-physical stress concentrations caused by inaccuracies in the NuMAD shell model representation of the blade.

The material nonlinearity seems to have very little effect on the material failure characteristics of BAR-DRC blade, where values of unity and above indicate material failure. The maximum failure index predictions reveal that overall the blade material is far from failure with the exception of the 45° loading direction. It is noteworthy that this critical load direction has the largest increase in maximum failure index of 7.55% due to modeling the spar cap material nonlinearities. It should also be considered that several of the critical downstream load directions considered (90° and 135°) could only be loaded to 50-60% of the true design load as to not have the blade buckle. Therefore the material nonlinearities in these critical flap-wise load directions did not have a chance to develop.

Table 3: Effective maximum failure index for each analyzed load direction.

Load direction[°]	Linear material model	Nonlinear material model	Difference[%]
0	0.224	0.224	0
45	2.490	2.678	7.55
90	0.505	0.506	0.2
135	0.187	0.187	0
180	0.131	0.130	-0.76
225	0.196	0.195	-0.51
270	0.125	0.128	2.40
315	0.146	0.146	0

5. Conclusions

This work presents component-level testing of carbon fiber sandwich beams and how carbon fiber material nonlinearity affects its strain response in bending. A simple validated material model accurately captures the carbon fiber longitudinal nonlinearity in both the tensile and compressive response. This material model is implemented in an FE model of the BAR-DRC reference wind blade and the effects of the nonlinearity on the ultimate limit states of the blade are analyzed. The BAR-DRC model was designed under linear finite element analysis assumptions and therefore did not pass many of the ultimate limit state analyses for the nonlinear FE analyses required to assess material nonlinearities. Design load levels had to be reduced 40-50% in some critical cases which makes it hard to generalize some of the findings of the comparative analysis with and without material nonlinearities modeled. Since the material nonlinearity increases with the load profile (and resulting strain state), the presented differences when modeling the material nonlinearities would only increase for the cases where the load profile had to be reduced.

The comparative analyses quantified the effect of carbon fiber nonlinearity on the blade design responses of maximum tip deflection, global buckling, and material failure. The effect of material nonlinearity was inconsequential on the maximum tip deflection, although at a reduced load profile to 64% of the design load. The buckling analysis revealed the most significant deviation when modeling the material nonlinearity where a failure buckling load factor was reduced by 42% for the moment profile with deflection in the downstream-trailing edge direction. For this load direction, an otherwise predicted safe design with a buckling load factor of unity is seen to have a buckling failure that is purely a result of modeling the carbon fiber material nonlinearity. This result merits further investigation as nonlinear finite element buckling analyses are known to be sensitive to a variety of factors. Material failure was calculated using the Tsai-Wu composite failure criterion. An increase of 7.5% is observed in the failure index when modeling the carbon spar material nonlinearity. Other critical downstream load directions had a more minor change in the maximum failure index predicted, however, the load profiles had to be reduced to 50-60% to resist global buckling occurring as a result of the nonlinear FE analysis. These additional directions did have low maximum failure indices and the increased loads would not necessarily result in material failure predictions.

Other than a few buckling load cases, modeling the nonlinearity of carbon fiber spar caps was observed to have a relatively minor effect on the ultimate limit states of BAR-DRC. It appears that the buckling constraint and inclusion of various safety factors means that the spar cap material does not experience high enough strains for the carbon fiber nonlinearity to occur at a significant level (see Figure 1b). The most significant impact observed comes from modeling the geometric effects using nonlinear FE analyses. Previous literature has also shown the necessity for nonlinear analysis for robust blade design [12]. Finally, it is important to note that fatigue was not accounted for in this analysis. Fatigue damage predictions can be highly sensitive to relatively minor changes in the operational strains in a material and warrants further investigation.

The carbon fiber nonlinearity model simulations showed comparable run speeds to the linear material model. Including the nonlinear material model affected the buckling predictions of the wind blade analysis, which may not change the material usage in the wind blade significantly, but will potentially drive the design from a safe design to a failed one (as seen in this analysis). In conclusion, the significant effects material nonlinearity has on buckling design predictions (while also being relatively inconsequential to analysis speed) merits the inclusion of carbon fiber material nonlinearity in wind blade design.

Acknowledgments

This work has been funded by the US Department of Energy, Wind Energy Technologies Office as part of the Optimized Carbon Fiber task within the Big Adaptive Rotor project.

The authors gratefully acknowledge Ernesto Camarena, Evan Anderson, and Josh Paquette at Sandia National Laboratories for their help and advice with the analysis.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

References

[1] Ennis B L, Kelley C L, Naughton B T, Norris R E, Das S, Lee D and Miller D A 2019 Optimized carbon fiber composites in wind turbine blade design. Sandia National Laboratories Report, Albuquerque, NM

[2] Kumar R, Mikklesen L P, Lilholt H and Madsen B 2020 Understanding the mechanical response of glass and carbon fibres: stress-strain analysis and modulus determination. *IOP Conf. Ser.: Mater. Sci. Eng.* **942** 012033

[3] Stecenko T B and Stevanovic M M 1990 Variation of elastic moduli with strain in carbon epoxy laminates. *J. Comp. Mat.* **24** 1152-8

[4] International Electrotechnical Commission IEC 2005 61400-1. Wind turbines-Part 1: Design requirements.

[5] Miller D A, Samborsky D D and Ennis B L 2019 Mechanical testing summary: optimized carbon fiber composites in wind turbine blade design. Sandia National Laboratories Report, Albuquerque, NM

[6] Amijima S and Adachi T 1979 Nonlinear stress-strain response of laminated composites. *J. Comp. Mat.* **13** 206-18

[7] Camarena E, Anderson E, Paquette J, Bortolotti P, Feil R and Johnson N 2022 Land-based wind turbines with flexible rail-transportable blades - Part 2: 3D finite element design optimization of the rotor blades. *Wind Energ. Sci.* **7** 19-35

[8] Ennis, B.L., Clarke, R.J., Paquette, J.A., Norris, R.E., Das, S., Miller, D.A. and Samborsky, D.D., "Optimized Carbon Fiber Composites in Wind Turbine Blade Design: Follow-On Studies," Tech. Rep., Sandia National Laboratories, forthcoming 2022.

[9] Bortolotti P, Johnson N, Abbas N J, Anderson E, Camarena E and Paquette J 2021 Land-based wind turbines with flexible rail transportable blades - Part 1: Conceptual design and aeroservoelastic performance. *Wind Energ. Sci.* **6** 1277-90

[10] Berg J C, Paquette J A and Resor B R 2011 Mapping 1D Beam Loads to the 3D Wind Blade for Buckling Analysis. *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference* April 2011, Denver, CO.

[11] DNV GL A/S 2015 DNVGL-ST-0376 - Rotor Blades for wind turbines.

[12] Rosemeier M, Berring P, and Branner K 2016 Non-linear ultimate strength and stability limit state analysis of a wind turbine blade. *Wind Energ.* **19** 825-46