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Development of Validated Blade Structural Models[‡]

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The focus of this paper is on the development of validated models for wind turbine blades. Validation of these models is a comprehensive undertaking which requires carefully designing and executing experiments, proposing appropriate physics-based models, and applying correlation techniques to improve these models based on the test data. This paper will cover each of these three aspects of model validation, although the focus is on the third – model calibration. The result of the validation process is an understanding of the credibility of the model when used to make analytical predictions. These general ideas will be applied to a wind turbine blade designed, tested, and modeled at Sandia National Laboratories. The key points of the paper include discussions of the tests which are needed, the required level of detail in these tests to validate models of varying detail, and mathematical techniques for improving blade models. Results from investigations into calibrating simplified blade models are presented.

I. Introduction

THERE are a number of reasons why one desires to develop models of wind turbine blades, and in each case one wants to ensure that these models are useful for the intended purpose. For example, correctly predicting failure in blades using a model can reduce the need for numerous costly tests including the fabrication of additional blades for a test-based failure prediction approach. An additional benefit of modeling and simulation is that the time required to complete the design and fabrication cycle can be reduced significantly when validated models are used to evaluate key aspects of the design that would otherwise require testing. Additionally, modern blades are large and costly – a validated predictive tool would be useful for assessing larger blades of the future.

An important step in ensuring that a model is useful for the purpose of the analysis, that is ensuring that a model accurately predicts the behavior of interest, is a process called model validation. A validated model is one in which an analyst or designer can place a great deal of confidence – one can use this model to accurately predict performance. The validation process incorporates both testing and analysis. A set of calibration experiments are designed which provide enough data to improve the model so that the observations from the test and the corresponding predictions from the analysis are suitably correlated. In the next step, additional "validation experiments" are conducted in order to ensure that the model is predictive for the conditions of the validation experiments. If the validation experiments can be predicted, then the model is considered validated, otherwise additional experiments must be performed to provide data for further improvement of the model. It is important to note that a model which has been calibrated to match the test data is not necessarily a valid model. The process of calibrating a model is called model updating, while model validation includes the additional step of performing validation experiments.

The main objective of the paper is to detail a general model validation process applied to wind turbine blades designed and tested at Sandia National Laboratories. The key points to be covered include those related to 1) testing (experiment design), 2) analysis (model development), and 3) comparison of test-analysis data for use in model calibration. Key points are covered in each of these areas; however, the focus of this paper is on model calibration. Optimization of the model parameters incorporating various types of blade test observations, including modal testing and static testing, is a novel development. As an example encompassing the key points, a program aimed at improving current modeling capabilities for a research-sized wind turbine blade is discussed in detail.

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II. Key Components of Model Validation

Model validation is a comprehensive undertaking which requires carefully designing and executing experiments, proposing appropriate physics-based models, and applying correlation techniques to improve these models based on the test data. Each of these three components of model validation is discussed in the following sections.

A. Experiment Design

With testing, one is concerned with what types of experiments need to be performed, under what conditions these experiments are to be conducted, to what level of detail the experiments should be carried out. The tests should be conducted in such a way that they correspond with the analysis to be performed. Some typical tests for validating structural models include static testing and modal testing.

First, we discuss static testing, which characterizes the stiffness of a structure. A research blade was static tested at the National Wind Technology Center (NWTC) in Boulder, CO. The blade was bolted to a test stand and subjected to a flapwise bending load to approximate the extreme loading event for the wind class for which it was designed. The blade was loaded using a three-point whiffle tree and saddle arrangement connected to an overhead crane. From this type of test, the strain and deflection response as a function of applied load can be measured along the span of the blade. These observations can be used for calibrating model parameters.

Modal testing is an experimental method for measuring the dynamic properties of a structure, which are commonly referred to as the modes, the structural dynamics, or the vibration response of a structure. In the most common application of modal testing, these dynamic properties are determined by measuring the response at various points on the structure (typically acceleration measurements) due to a known, quantified input (typically a force). Any engineering structure experiences dynamic loads during operation, and wind turbines are certainly good examples because the wind and gravity loads change with time. Thus it is important that a model of a wind turbine blade accurately predict response due to dynamic loads. The dynamic properties, which are measured in a modal test, include mode shapes, natural frequencies and damping ratios. A vibrating structure has multiple modes (structural resonances). For each particular mode of vibration, there is a natural frequency and damping ratio value which corresponds to each mode shape. Mode shapes describe the spatial nature (shape) of the response while natural frequencies and damping ratios describe the nature of the time response. Simply put, a natural frequency describes the rate (cycles per second) at which a corresponding mode shape resonates and damping describes the rate at which the amplitude of a particular mode decays. The total vibration response of the structure is a sum of the responses of all of the modes of vibration. References 1 and 2 provide good general references on experimental and analytical modal analysis.

Modal testing is widely used for evaluating analytical structural dynamics models because mode shapes and natural frequencies can be readily computed numerically from a model. These numerical predictions can be directly compared with experimental observations of mode shapes and natural frequencies. Typically one is not concerned with models which predict damping, thus in a modal test we are principally concerned with natural frequency and mode shape information. However, damping information from a modal test is important and useful for understanding the inherent ability of a structure to attenuate resonant responses which may lead to structural damage, and in fact measured damping is used to model damping.

An important issue is assessment of the uncertainty in test data because test data and analysis predictions must be compared. The decisions made in the design of the test setup are critical to validation of structural models. For example, the design of the instrumentation layout, the type of support conditions (boundary conditions), and choice of excitation type are important variables in the design of a modal test. It is important to quantify the bias errors resulting from the test setup when validating models because the effects of the test setup can hinder suitable comparison with model predictions, thus these bias errors must be well characterized or eliminated. Proper pre-test design and test technique are critical for the validation of blade models. Analytical formulas for assessing support condition effects in a modal test have been developed[3], and an experimental study of the sources of uncertainty in a modal test was performed[4], both applied to the research-sized wind turbine blade discussed in this paper.

B. Model Development

With analysis, one is concerned with the chosen form and level of detail of the model, its correspondence with the test article and the conditions of the test, and the parameters that comprise the model. The analysis should provide predictions which can be directly compared with test data, and the model should include enough detail and be of the proper form. Furthermore, a model with a minimal number of parameters is preferred for reducing computational cost, and in many cases simplified models are more manageable and provide sufficient insight.

Currently, modeling capability exists for levels of detail ranging from low fidelity to geometrically accurate high fidelity models. The decision depends on what type of analysis one needs to perform, and the availability of resources. If desired, the precise geometry of the blade airfoils, placement of materials, and internal structural geometry can be represented in a high fidelity finite element model as shown in Figure 1. These types of models predict a wide range of phenomena including detailed stress contours and local buckling. A highly automated program developed specifically for modeling blades can be used to speed up the modeling effort[5]. However, lower dimension finite element models, such as the beam model shown in Figure 2, are suitable for other purposes. This type of model is based on averaged properties of the blade sections and is useful for calculating, for example, static deflection along the span and natural frequencies, but does not capture the detailed local behavior of the high fidelity model. As a comparison, the high fidelity model shown in Figure 1 contains 35 material regions, 47,426 elements, and 141,454 nodes, whereas the low fidelity model contains 20 elements and 21 nodes, with each element representing a unique material region representative of the averaged properties of that section. The time required to develop the high fidelity model is several days while the low fidelity model can be generated in a matter of hours.

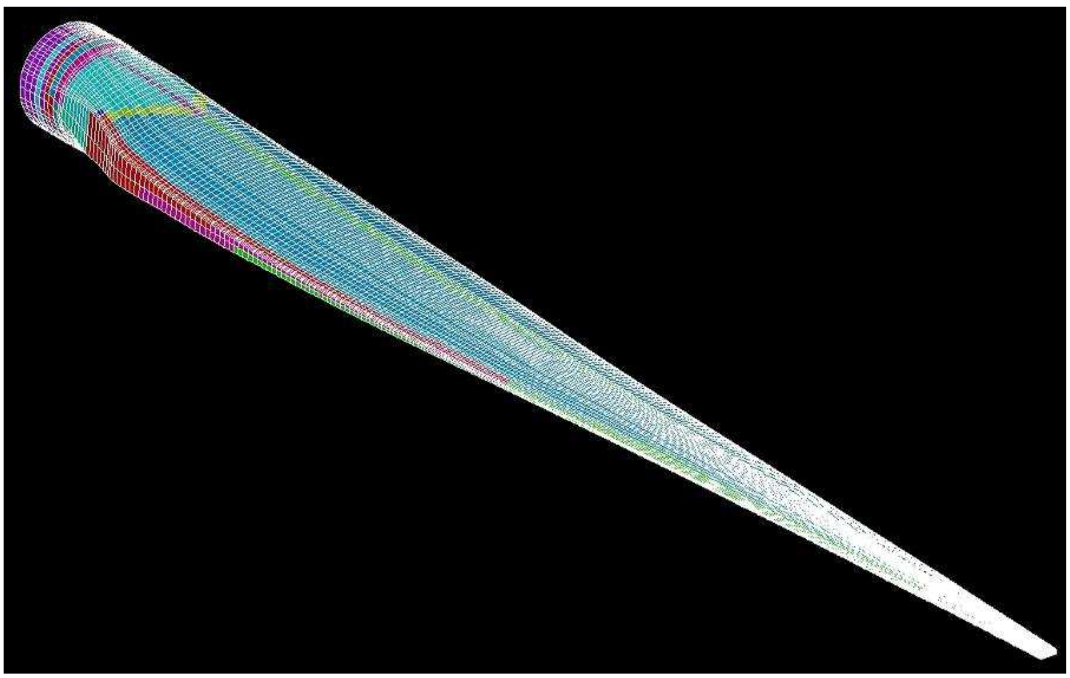

Figure 1. High Fidelity Finite Element Model of a Wind Turbine Blade

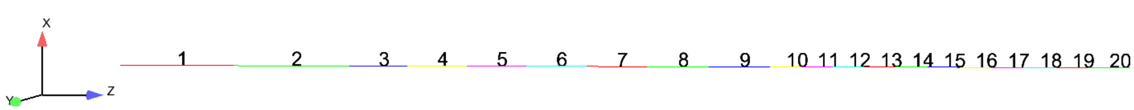

Figure 2. Low Fidelity Finite Element Model of a Wind Turbine Blade

We now consider some of the issues related to the parameter space of a model. Blade structural models are comprised of geometric parameters and material parameters. Geometric parameters include cross-sectional shape, thicknesses, and locations of material boundaries, which are typically measured directly or taken from design definition models (CAD models). Material parameters include mass-related properties such as density and stiffness-related properties such as Young's modulus, which can be found in material property reports, for example. Some of these parameters are well known because they can be directly measured or they can be taken from design definition models (when the manufacturing tolerances are met). On the other hand, some of these parameters may not be well known and the problem becomes one of determining these poorly known model parameters to improve the model. This is the focus of the paper. In the following sections we describe various approaches to determine these parameters.

C. Test-Analysis Correlation

Once tests have been conducted, models can be analyzed using the conditions (e.g. boundary conditions) of the test to make predictions and assess the credibility of the model. Typically a model does not adequately predict all aspects of the test, thus one is then concerned with choosing a model form and/or model parameters (material properties and geometric properties) which best represent reality. Updating model parameters enables one to improve the model such that it agrees with the test data. However, it must be done in a physically meaningful manner. Parameters with well known values are typically fixed; examples include the total mass of the blade because it can be accurately measured. On the other hand, material and geometric properties typically have some uncertainty. These are the parameters which one would consider varying in order to calibrate the model. Many of the related issues were considered in a previous study conducted for a wind turbine blade in Reference 6. Uncertain material parameters were estimated using modal test data for a pultruded blade section with uniform cross-section.

Whether one is interested in low or high fidelity models, a limitation on optimization of the model parameters is that the number of variable parameters be as small as possible. Fewer variable parameters results in more stability in the parameter optimization solution. A good rule of thumb is that the number of variable parameters be less than or equal to the number of comparison data points (e.g. natural frequencies, tip deflection, etc.). Here, we find an additional reason to develop low fidelity models which have a manageable parameter space. The paper will focus on different approaches to calibrating models using modal test data, static test, and a combination of modal and static test data. We note that the traditional means of updating structural dynamics models uses only modal test data.

III. Description of a Series of Validation Tests Performed on Wind Turbine Blades

A number of tests have been performed in this validation effort including static testing which provides load-deflection data and modal testing which provides natural frequency and mode shape data. The blade design under consideration has been named BSDS (Blade System Design Study). The BSDS blade is a research-sized blade and is nominally 8.325 meters (27.3 feet) and 127 kilograms (290 lbs). A key feature of this blade design is the flatback airfoil. The flatback airfoil was designed for the inboard portion to improve the blade structural properties, while minimizing loss of aerodynamic performance. Because we are concerned with structural dynamics models, we need accurate mass properties information for the blade including the blade total mass, the CG (center of gravity) location, and the distribution of mass. The blade total mass and CG location can be fairly easily obtained from two-point force measurements; however, the distribution of mass is more difficult to obtain. Typically, we can compute the distributed mass properties using a design definition model or by direct measurement.

A BSDS blade being static tested is shown in Figure 3. The whiffle-tree apparatus is visible above the blade. From this test, strain and deflection data was obtained that gives insight into the stiffness properties of the blade. The flapwise deflection of the BSDS blade along its length in response to an applied load is shown in Figure 4. With a known load, the flapwise stiffness of the blade can be estimated from these test results. Note, however, there

Figure 3. Static Test on the BSDS Wind Turbine Blade

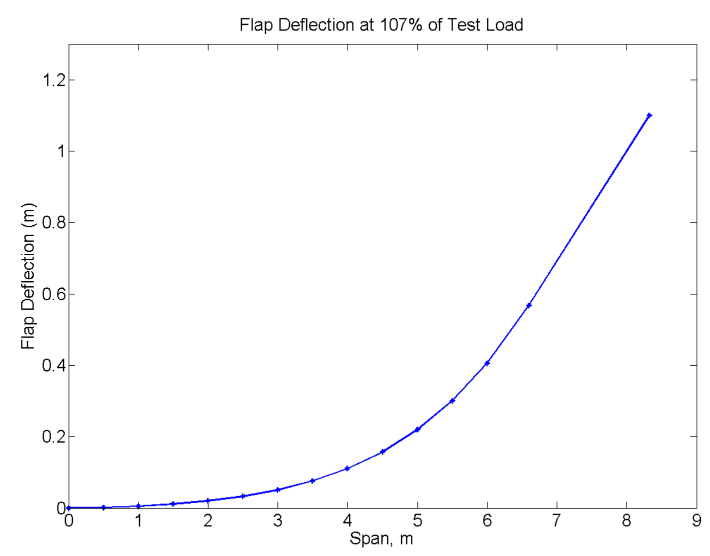

Figure 4. Static Deflection Test Data for the BSDS Blade

is very little information regarding deformation in the section of the blade outboard of outer loading position. Figure 4 shows a straight line from the outer loading position to the blade tip.

Two nominally identical BSDS blades were modal tested. A photo of one of the blades being modal tested is shown in Figure 5. These blades have been tested with approximately free boundary conditions (as shown in Figure 5). The free boundary condition is approximated by softening the two supports using coiled bungee rope as seen in the figure. The blade was instrumented with 48 biaxial accelerometers (96 total accelerometers) using the layout as shown in Figure 6. The markers indicate the location of the biaxial accelerometers; the blue markers indicate the back side of the blade while the red markers indicate the front side. Tests were conducted to evaluate the effects of the two supports, and the mass-loading and damping effect of the instrumentation sensors and cables. The support effects were experimentally evaluated by varying the stiffness of the supports and the location of the supports. The mass-loading and damping effects of the instrumentation were measured by comparing fully instrumented and lightly instrumented data sets – modal tests were conducted with the full instrumentation set (Figure 6) and repeated with most of the instrumentation removed as the experiment was concluding. The support conditions and the mass-loading and damping of the instrumentation are important bias errors that must be quantified. Depending on the magnitude of these bias errors, one chooses to neglect or include them in the model. These results are summarized in Reference 4.

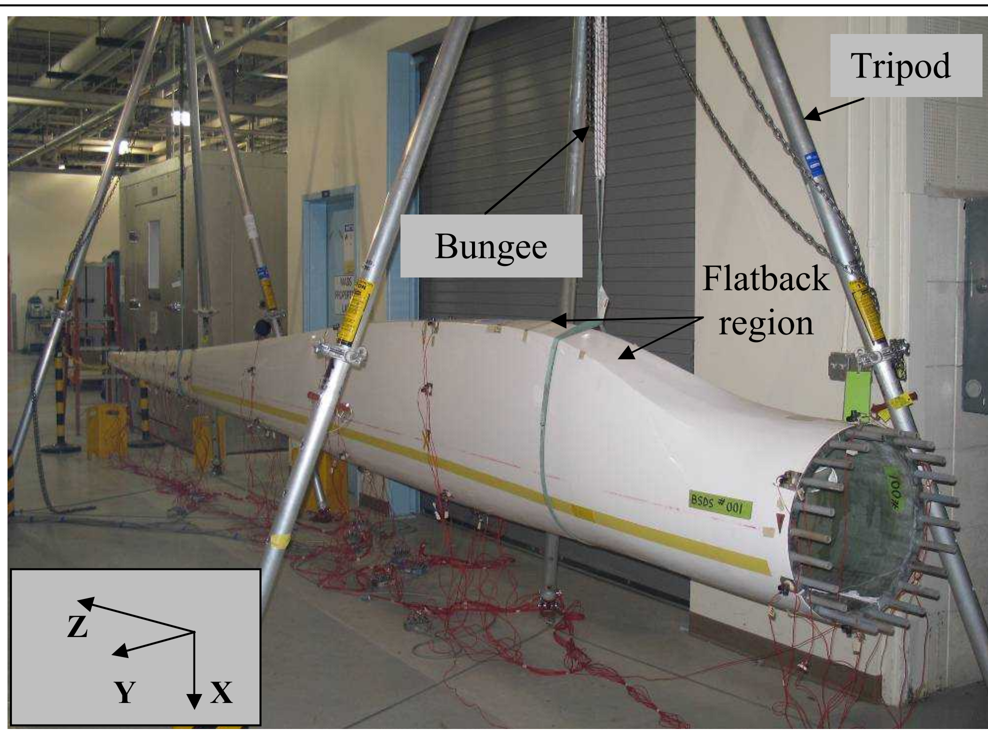

Figure 5. Modal Test of the BSDS Wind Turbine Blade

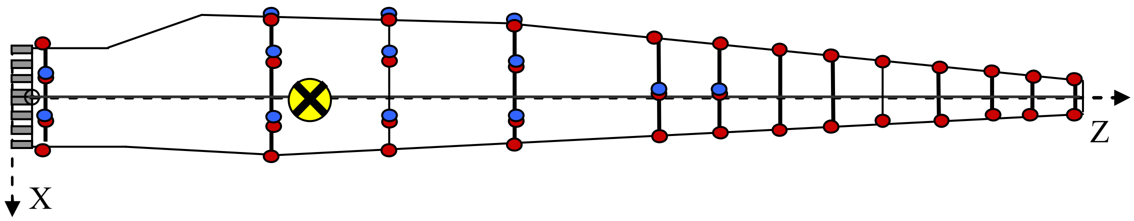

Figure 6. Instrumentation Layout for BSDS Wind Turbine Blade Modal Test

For the BSDS wind turbine blade, the types of modes fall in the following three categories: 1) bending modes, 2) torsional modes, and 3) localized panel (plate) modes. The first six flapwise bending modes, the first three edgewise bending modes, and a panel mode are listed in Table 2 for the two nominally identical blades tested. With the exception of the panel mode, each of the modes can be predicted in a beam-type finite element model. The panel mode can only be predicted in a detailed model such as the one shown in Figure 1 because this is a resonance of the side panels. As can be seen from the table, there is some variability between these blades. In our initial study, we have chosen to calibrate our model to the BSDS 001 blade modal data.

Table 1. Measured Natural Frequencies

Mode Description	*Freq (Hz)*	
	BSDS 001	**BSDS 004**
1st Flapwise	5.43	5.25
2nd Flapwise	13.5	13.5
1st Edgewise	16.5	17.2
Panel Mode	21.4	22.3
3rd Flapwise	25.4	24.5
4th Flapwise	38.6	37.9
2nd Edgewise	40.1	40.7
5th Flapwise	56.5	55.8
3rd Edgewise	73.3	74.1
6th Flapwise	81.4	82.4

IV. Determining the Blade Properties: Model Calibration

As mentioned earlier, the type of model parameters depends completely on the form of the model. For a high fidelity model, the geometric features are explicitly modeled and material regions are modeled individually. When the model is a low fidelity model such as a beam model, one is concerned with the averaged properties over each element as a single element may actually represent a composite of several materials with dissimilar properties. In our initial efforts we focus on beam-type finite element models with the typical set of parameters as listed in Table 2. The task of updating a model begins by evaluating the model parameters. One should consider best estimates of the values of all model parameters and the uncertainty associated with each. The uncertainty can be used to rank the parameters to be varied. In the following paragraphs, we summarize the general process used to arrive at the set of variable parameters in the model optimization problem.

Table 2. Beam Model Properties

Property	Type
Cross-sectional Area	Geometric
Element Length	Geometric
Area Moments of Inertia	Geometric
Polar Moment of Inertia	Geometric
Density	Material
Young's Modulus	Material
Poisson's Ratio	Material

The mass-related properties are typically most well known and can be determined by a variety of means. The total mass and CG (center of gravity) location of the blade can be directly measured and can be checked against those of the model. However, the real challenge is the distribution of mass within the model which, for the beam model, is simply the distribution of mass along the span of the blade. One can acquire this detailed mass properties information by several methods including 1) analysis of sections of the detailed design model or 2) direct measurement of the mass properties of cut-up blade sections. Typically, the former approach is taken because the latter method requires the destruction of a blade. However, the latter method or some test-based variation is preferred when the as-built blade varies from the design definition. With either approach, the total measured mass of each section can be used along with an estimated value for the total section volume (cross-sectional area times section length) to compute the section density. For this study, we have sectioned a blade, which was statically tested to failure, by cutting it at approximately 0.25 meter sections. This permitted an assessment of the internal blade structure and measurements of the section mass to obtain the mass distribution as a function of span. A photo of these sections is shown in Figure 7.

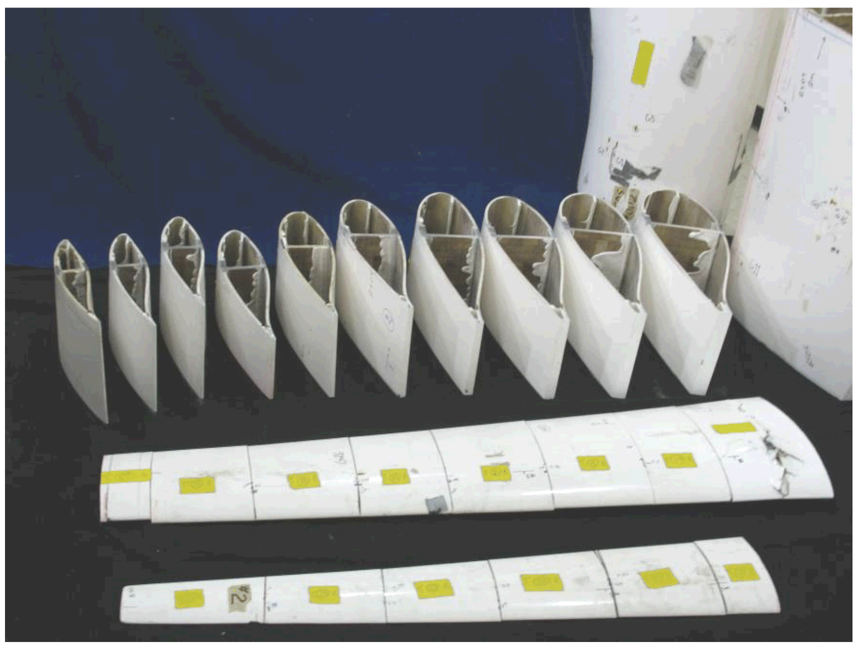

Figure 7. Photo of Cut-up Blade Sections of the BSDS Blade

The stiffness-related properties are typically more poorly known than the mass-related properties because of the difficulty in computing accurate values of the Young's modulus of a composite blade. The difficulty arises due to the complexity of the material lay-up and the uncertainty in the fabrication of the as-built blade. For this work, we were able to measure the cross-sectional geometric properties from the cut-up blade sections. These measurements included chord length, wall thickness, blade thickness, shear web dimensions, and shear web location. The lengths of the finite elements in the beam model were chosen to correspond with the locations of the cut-up sections in order to properly assign the mass distribution. Given the section mass, estimates of cross-sectional area, and the element length we computed an averaged density over each element. Additionally, the measurements made it possible to compute estimates of the moments of inertia. Now considering the parameters listed in Table 1, the problem then becomes one of determining the Young's modulus distribution along the blade span. This can be determined by several methods including: 1) simplification of a detailed high fidelity model, 2) calibration with static test load deflection data, 3) calibration with modal test data, and 4) calibration with a combination of modal test and static test data.

The model can take on a variety of different forms. Beyond consideration of the level of detail required in the model, one must make some additional choices related to model form. For any finite element model, one has a choice of a variety of different types of elements. For example, there are a variety of different types of solid element formulations (8-node, 20-node, etc) and a variety of different types of beam elements (lumped mass or consistent mass). Additionally, we must consider constitutive relationships. A beam model for a wind turbine blade requires orthotropic properties to account for the orthotropic nature of the constituent materials, that is, the Young's modulus in the flapwise and edgewise directions are not equal. In this paper, we have chosen the formulation for the 3-D beam element given in Reference 1; although we make some modifications to this approach in that we choose to specify the Young's modulus individually for each of orthogonal reference directions to properly account for the orthotropic properties.

There are a number of algorithms and codes which exist to solve optimization problems such as this model parameter calibration problem. In our case, we desire a simple algorithm which can be linked with our Matlab-based finite element model. Matlab includes a standard function called *fminsearch*, which is a multidimensional unconstrained nonlinear minimization tool[7]. It is based on the Nelder-Mead method (also, the simpex method and downhill simplex method). In some initial evaluations of *fminsearch* for this application we found that the results were acceptable, although we encountered one of the common difficulties with a direct search method in that the algorithm would not converge for some poor starting parameter values. In these cases, the algorithm was simply restarted with a better set of starting parameters, sometimes determined from the prior nonconvergent case, and typically it converged from this new starting guess. Another method considered was a gradient-based Least Squares type algorithm. This approach is attractive because the partial derivatives of the eigenvalues and eigenvectors associated with the blade model system matrices can be computed analytically[8]. Additionally, a Least Squares algorithm inherently provides an estimate of the uncertainty in the estimated parameter values – the covariance matrix can be used to apply error bounds to the optimized solution. A gradient-based method was used in the prior study in Reference 6, although the eigenvalue partial derivatives were computed by finite differences.

V. Results and Discussion

When calibrating the parameters of a structural dynamics model, one must first consider the total mass and CG location predicted by the model. Calibration of the stiffness parameters of a model should performed after the mass properties have been well characterized. Any bias in the mass properties will bias the stiffness properties when determined by calibration with test observations. In our initial study we focus on a beam-type low fidelity model, although our ultimate goal is to validate a detailed high fidelity model. The mass properties of the beam model were defined such that the total mass in the model equaled the total mass measured for the cut-up sections. The mass associated with the width of the saw cut was also included. As a result the total mass in the model is 281.8 lbs with the CG located 89.5 inches from the root end. The CG measurement from the blade fabricator gives a CG location of 87.9 inches, which is a difference of 1.8%. Although apparently small, in most cases we desire closer agreement to ensure accurately modeled mass properties. However, the agreement in this case is within the uncertainty of measurement of the CG location. Now we consider calibration of the stiffness-related blade properties.

Our objective is to assess three different approaches to calibrating the blade structural model. These approaches differ by the type of test data that is used. The choices include: 1) static test data, 2) modal test data, or 3) a combination of static test data and modal test data. Modal test data provides a number of natural frequencies we can use to calibrate our model. Detailed modal tests were conducted which resulted in the first six flapwise natural frequencies – this provides six test-analysis comparison points. Likewise, six test-analysis comparison points were chosen from the static test data which involved choosing six points along the span of the blade to compare flapwise deflection values. An important consideration when combining different types of data is determining how to weight the importance of the static data versus the modal data. Using a few trials, we determined set of static data weighting parameters and a set of modal data weighting parameters. The basic idea is to make the weighted values of the static and modal prediction error to be close so that each type of data is considered equally important in the optimization process. In order to compare these approaches, we chose a common starting value for the search algorithm used to calibrate the models. As mentioned earlier, we varied the Young's modulus of the beam elements because these are the most poorly known parameters in the model. The model contains 20 elements; thus there are a total of 20 Young's modulus values which can be specified independently. However, in order to stabilize the search algorithm we have chosen to vary only six values. Essentially, we chose to vary the Young's modulus over six groups of elements with each group having a common value. It is important to note that this Young's modulus value is not necessarily the true Young's modulus for that section of the composite structure because the moments of inertia of the cross-sections were computed by approximation. The calibration process will determine a Young's modulus value which will account for the uncertainty in the moments of inertia and provide an accurate value of the section EI property.

The results for the calibrated flapwise EI are given in Figure 8. We present the results for the three cases mentioned above, and also include equivalent beam properties extracted from a post-test high fidelity structural model. The Beam Property Extraction (BPE) code was used to analyze the high fidelity model[9]. We find that the stiffness of the root end of the blade is quite sensitive to the type of calibration data. We consider the estimates coming from the BPE code to be most accurate at the root end because of the simplicity of the geometry and material layup at the root. Using the root estimate from BPE as a reference, we find that calibration with static data results in a better estimate of the root stiffness than modal data alone, although the combined approach results in the best estimate. A key point to keep in mind is that for free modal tests, the root end is not strained very much while it is strained in the static tests. On the other hand, the outboard section is strained for the modal data and in fact there is no curvature of the blade outboard of the outer loading location in the static test data, which is at 6.6 meters. Modal data tends not to be very sensitivity to the root stiffness; however, modal data is quite sensitive in the outboard section. Note that the combined modal and statics calibrated model closely follows that of the modal only calibrated model outboard of 6.6 meters. Also, note that the combined result tends to closely follow the static only calibrated model in board of the 6.6 meter location. Use of both static and modal data tends to overcome the limitation associated with each type of test in that the static data provides root strain information while the modal data provides information related to the stiffness distribution along the blade span with emphasis nearest the tip. The BPE code was developed to extract equivalent beam models from validated high fidelity models so they could be included in full system dynamics codes which require beam-type inputs. However, in this case we are using BPE to generate equivalent parameters from the solid model in order to assess its credibility. We find that for the flapwise EI the BPE result and the combined calibrated result agree well at the root end; however, the BPE result tends to be significantly stiffer along the rest of the span.

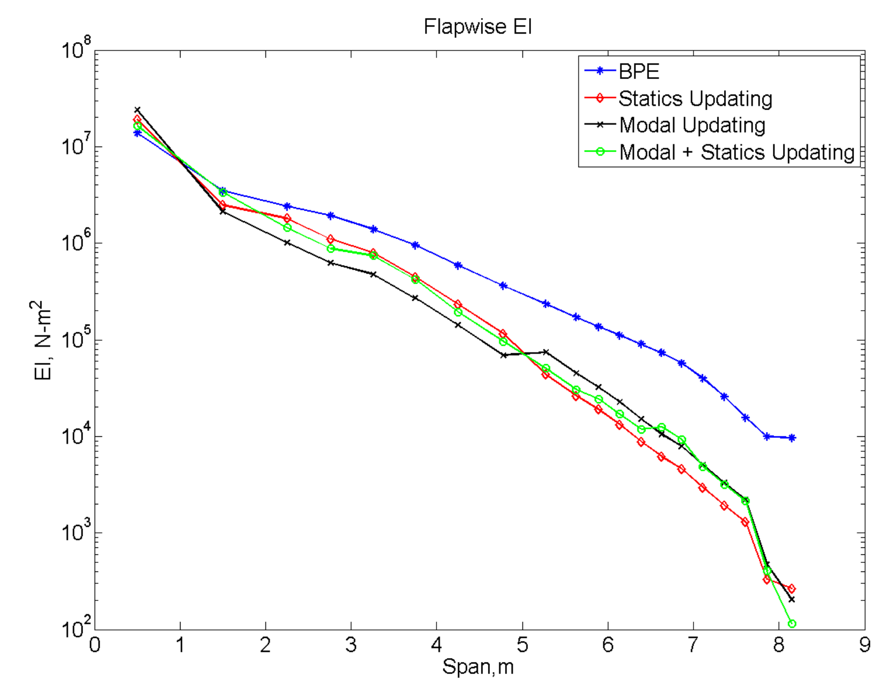

Figure 8. Flapwise EI Comparisons

We also calibrated the edgewise EI. No static tests were conducted edgewise, so only modal data could be used. However, due to near geometric symmetry of the root section (zero to 1 meter span) we can use the root stiffness value from the flapwise EI calibration. For edgewise calibration, we used the first three edgewise natural frequencies as test-analysis comparison points. A comparison of the BPE edgewise EI and the calibrated result are plotted in Figure 9. We can use a comparison such as this to improve the stiffness properties of certain regions of the high fidelity model. In particular the span from about 1.5 to 7.0 meters is soft for the BPE model. A deficiency of the model may be explained by examining the mass properties. Figure 10 shows a comparison of the mass per unit length for the BPE model and the beam model. The beam mass properties are the actual measured values. Thus we find that the BPE model tends to be missing mass in the 1.5 meters to 7.0 meters range. BPE is low in mass and low in stiffness which is consistent with frequency calculation. This illustrates how biased mass properties can result in biased stiffness properties.

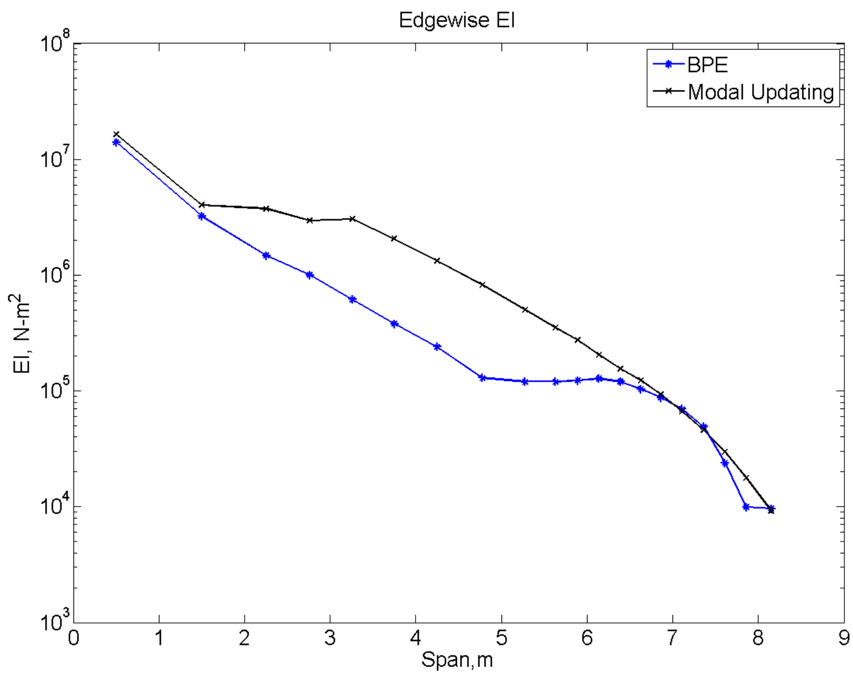

Figure 9. Edgewise EI Comparison

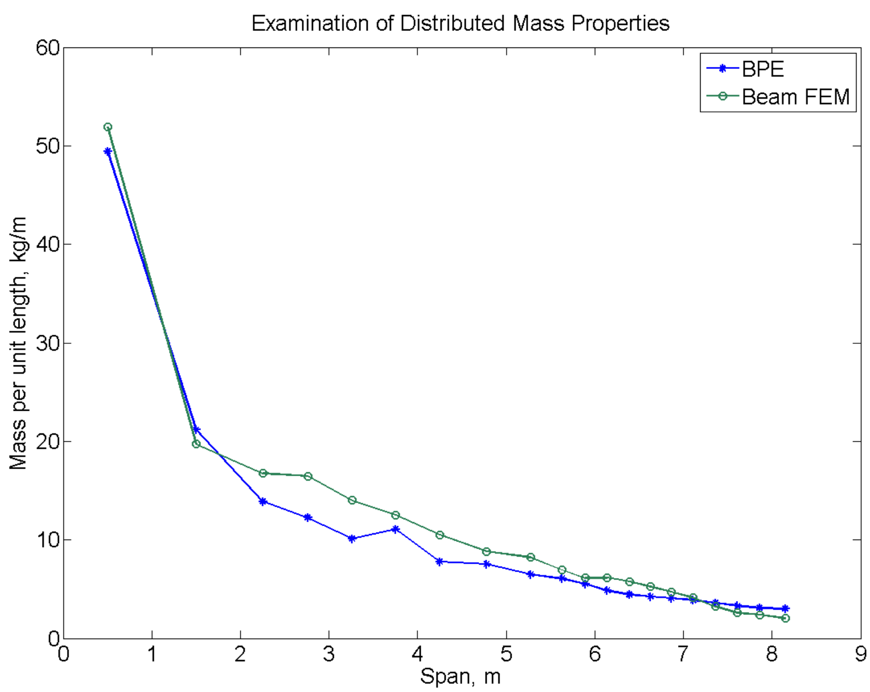

Figure 10. Mass Distribution Comparison

Now, we assess predictions made using the calibrated models to evaluate each of the calibration methods. We will compare predictions of the first flapwise natural frequency and the static deflections due to the loads from the tests shown in Figure 3. To compare static deflections, we will compute the norm of the deflection vector error. A model calibrated with only static test data under predicts the 1st measured natural frequency of the modal test with free boundary conditions by 12%; however, the norm of the static deflection vector error is found to be only 0.01 meters as tabulated in Table 3. When only modal data is used, the frequency is off by only 1.1% and the norm of the static deflection error is 0.31 meters. The closely agreeing predictions for these two cases should not be surprising; they are essentially the residual errors from calibration of the models. However, it is not surprising that a model calibrated with one type of test does not do a better job in predicting the other type of response data. A better approach is to calibrate our model by combining static and modal test data. This provides a frequency error of 1.1% and a static deflection error of 0.03 meters. We have also used the calibrated models to predict the first natural frequency for a fixed root-end boundary condition. The results in Table 3 show how this frequency varies for each model.

Table 3. Prediction of Natural Frequency and Static Deflection

Calibration Type	1st Flapwise Mode (Hz)		Norm of Static Deflection Error (meters)
	Free Boundary Conditions	*Fixed Boundary Conditions*	
Statics Updating	4.76	3.34	0.01
Modal Updating	5.49	3.32	0.31
Modal and Statics Updating	5.37	3.53	0.03

We now make a few remarks about the search algorithm and its application to this problem. Determination of a good starting guess is a challenge in many optimization problems, and this is especially true when the parameter space is high dimensional. Early in the calibration process, one can consider simply using the search algorithm to find an improved guess for the model parameters. This may involve exercising the search algorithm for a few iterations, followed by a restart of the algorithm. Also, we mention a promising approach to the challenge of problem dimensionality. The algorithm can be used to optimize a small number of model parameters. The converged parameter values can be used to restart the algorithm allowing an increased number of variable parameters. We found this approach to be stable for optimizing the entire parameter space of Young's modulus values. Furthermore, we mention that this search method does not inherently provide an estimate of the uncertainty in the parameter estimates as does a Least Squares based method. This is a limitation; however, this may be overcome by considering other methods. For example, the variation in calibrated model parameters can be calculated for a range of natural frequency values representing random experimental uncertainty.

VI. Conclusions and Future Work

In this paper we detailed a methodology and results on the development of validated structural models of wind turbine blades. Validation is a comprehensive undertaking which requires carefully designing and executing experiments, proposing appropriate physics-based models, and applying correlation techniques to improve these models based on the test data. Each of these aspects of model validation is important and key points were summarized for each; however, the focus was on the third -- calibration of the model parameters. The principal conclusion of this work is that incorporation of static data along with the traditional modal test data into the model calibration process results in an improved structural model. This is because the strength of one type of test tends to overcome the weakness of the other – static tests provide important characterization of the root and inboard sections while modal tests provide important characterization outboard. This is not the final word on this model validation exercise because additional "validation experiments" must be performed in order to validate the calibrated model. A modal test with a different root end boundary condition is currently being considered as a validation experiment. Future work also includes applying this model calibration approach to detailed structural models.

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