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Uncertainties in Prediction of Wind Turbine Blade Flutter

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The blades of a modern wind turbine are critical components central to capturing and transmitting most of the loads experienced by the system. Blades are complex structural items composed of many layers of fiber and resin composite material and typically, one or more shear webs. Simplification of the blade structure into equivalent beams is an important step prior to aeroelastic simulation of the turbine structure. There are a variety of approaches that can be used to reduce the three-dimensional continuum blade structure to a simpler beam representation: two-dimensional cross section analysis, extraction of equivalent properties from three-dimensional blade finite element models and variational asymptotical beam sectional analysis. This investigation provides insight into discrepancies observed in outputs from these three approaches for a real blade geometry. Wind turbine blades of the future will be longer and more flexible as weight is optimized. Innovative large blade designs may present challenges with respect to aeroelastic flutter instabilities. Sensitivity of computed flutter speed with respect to variations in computed beam properties is demonstrated at the end of this paper.

Nomenclature

P	=	Power Capture, W
ρ	=	Fluid Density, kg/m^3
C_p	=	Coefficient of Performance
A	=	Rotor Swept Area, m^2
U_∞	=	Wind Speed, m/s
BPE	=	Beam Property Extraction tool
VABS	=	Variational Asymptotical Beam Sectional Analysis
E	=	Young's modulus, Pa
x	=	Flapwise distance from blade section elastic center to the differential area element
y	=	Edgewise distance from blade section elastic center to the differential area element
I	=	Second area moment
G	=	Shear modulus, Pa
J	=	Torsion constant

I. Introduction and Background

Flutter is a self-starting and potentially destructive vibration where aerodynamic forces on an object couple with a structure's natural modes of vibration to produce large-amplitude periodic motion. Flutter can occur in any object within a strong fluid flow, under the conditions that a positive feedback occurs between the structure's natural vibration and the aerodynamic forces (i.e., when the oscillatory motion of an object, like a flexible airfoil, increases an aerodynamic load which in turn amplifies the object's movement). If the energy during the period of aerodynamic excitation is larger than the natural damping of the system, the level of vibration will increase. The

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vibration levels can thus build up and are only limited when the aerodynamic or mechanical damping of the object match the energy input. This often results in large amplitudes and can lead to rapid failure.

Flutter in wind turbine blade designs involve a coupling of blade flapwise bending and blade torsion structural dynamic modes in the presence of aerodynamic forces. Wind turbine blades of the scale used in the industry today are not typically suspect to flutter instability problems within their operating envelopes. Equation (1) shows the relationship between rotor swept area and energy capture. Structural dynamic frequencies of the blades decrease as turbine blades grow longer in pursuit of additional energy capture. Additionally, as turbine blades scale up beyond the current sizes, the structural design becomes increasingly constrained by oscillatory gravitational loads. Thus, future longer, lighter blade designs are likely to be more flexible, which may adversely affect their flutter speeds. Finally, rotors of the future may contain sensing and flow control technologies that enable closed-loop controls that are able to sense and affect loads, both external and internal to the blades. The presence of these unsteady devices could either increase or decrease a blade's tendency to flutter. Bergami has shown examples of how the implementation of active flow control devices can cause reductions to flutter speeds[1]. Understanding of these interactions are critical.

$$P = \tfrac{1}{2}\rho C_p A U_\infty^3 \tag{1}$$

Lobitz[2] has developed a flutter prediction approach based on beam representation of the blade and classical Theodorsen unsteady aerodynamic forces. The approach can be used to predict the turbine operating speed that may induce flutter. The technique requires accurate representation of the wind turbine blade mass, stiffness, and inertia distributions, modeled as a series of beam elements and point masses. This technique will be used for this investigation to compute estimated flutter speeds of wind turbine blades.

Blades can be complex structural items composed of varying shapes, many layers of fiber and resin composite material, sandwich structures and, typically, one or more shear webs (Figure 1). The current approach for wind turbine blade flutter prediction requires simplification of this complex wind turbine blade structure into a beam model. Equivalent beam properties of the blade are determined at a discrete number of locations along the length of the blade in order to create a model consisting of several beam elements.

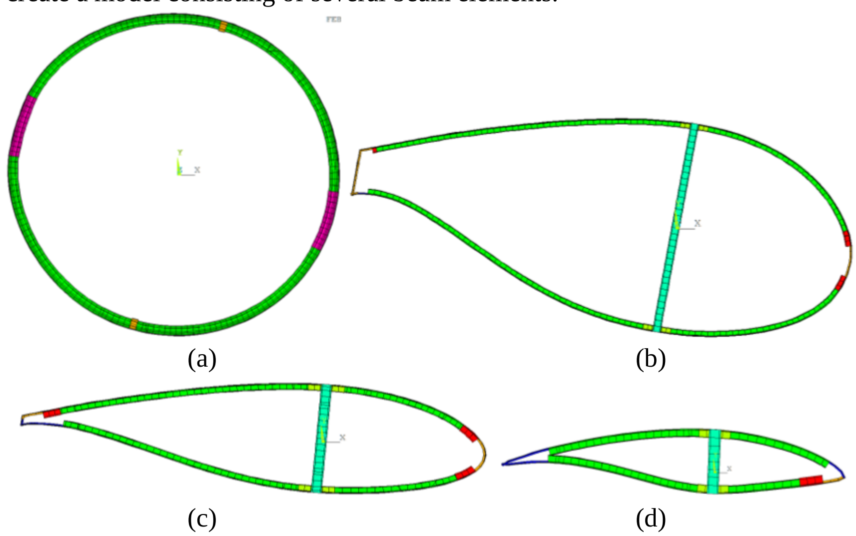


Figure 1 Examples of wind turbine blade cross section shapes for a flat back 9m BSDS blade[3]. Colors correspond to different composite layup regions: (a) root, (b) max chord, (c) mid-span and (d) tip.

Currently there are multiple tools and approaches available to the wind industry that will aid the designer in converting complex blade laminate and structural geometry information into equivalent beam properties for aeroelastic simulations. A common approach is to calculate properties for the Euler-Bernoulli beam based on material properties and skin geometry of each two-dimensional section. The properties at each two-dimensional section are independent of adjacent sections. Simple examples include the following. In addition, warping functions for torsion must be calculated.

$$EI\_flap = \iint E(x,y)x^2 dxdy\,, \tag{2}$$

$$EI\_edge = \iint E(x,y)y^2 dxdy\,, \tag{3}$$

$$GJ = \iint G(x,y)(x^2 + y^2)dxdy \text{ and} \quad (4)$$

$$EA = \iint E(x,y)dxdy \quad (5)$$

A more involved approach is to create a three-dimensional finite element model of the blade and analyze the deflection of selected nodes in response to applied loads, as seen in Figure 2. Effective properties for Timoshenko beam elements are then determined by analyzing the relative displacements for each pair of adjacent sections. This approach can include effects that are difficult to include in a two-dimensional approach, such as axial warping in torsion and cross-sectional deformation in bending.

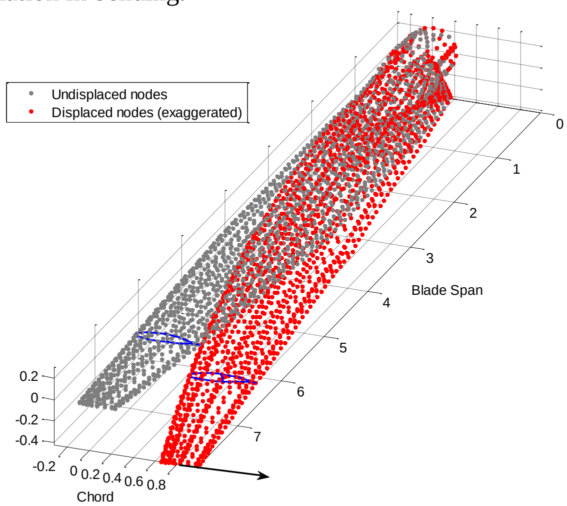


Figure 2. Finite element nodes: single point edgewise load at the blade tip. A set of finite element nodes representing a blade section is highlighted in blue.

Three codes are examined in the current investigation: PreComp[4], BPE[5,6,7] and VABS[8]. Each of these tools utilize one of basic approaches for beam property computation introduced above.

A. Two-dimensional Section Analysis

PreComp[4] is a code developed at the National Renewable Energy Laboratory to provide structural properties for composite blades. PreComp includes a modified classic laminate theory with a shear-flow approach to compute the necessary properties and axis locations required to model the flexible components of a wind turbine. PreComp computes blade torsion stiffness and cross-stiffness properties. Cross-stiffness properties arise if an anisotropic layup of composite laminates is used. These properties couple flap, lag, axial, and torsion motions of the blade and can substantially influence the turbine performance, loads, and aeroelastic stability. Accurate estimates of cross-stiffness properties are of interest to the wind industry members who tailor composites to mitigate turbine loads and enhance performance. PreComp assumes that the blade is straight and that shear webs are normal to the chord. It also assumes that transverse shearing is negligible and that the blade section is free to warp. PreComp computes the necessary set of stiffnesses for use in an Euler-Bernoulli beam model.

PreComp is a desirable tool due its computational efficiency and public availability. It is a tool that should be used especially in early design stages of wind turbine blade composite layup and material placement. Given an external blade shape and a set of material choices, PreComp is used to estimate overall stiffness and mass distributions due to material placement in the blade. These section properties, along with geometry, can also be used to back out estimates of expected material strain for given blade loads.

It is important to note that a modified version of PreComp was used in the investigations for this paper. The current release of PreComp, v1.00.02, was found to handle shear webs incorrectly. Staff at Sandia National Laboratories use a modified version of PreComp, which has proven to be more correct. The source code changes are shown in an Appendix of this paper.

B. Three-dimensional Finite Element Models To Determine Beam Properties

The two-dimensional section analysis tool discussed above is quite efficient in preliminary parameter studies for initial blade designs. In later stages of blade design it is beneficial to create a more detailed three-dimensional finite element model of a blade. Typically such models are created with thousands of layered shell or solid elements. These models are of value in examining the internal stress distribution within the blade and its layers and they are required to perform detailed assessments of phenomena such as panel buckling.

ANSYS® is a commercially available finite element analysis package and is often used to create either shell or solid element models of wind turbine blades. NuMAD[5] is a preprocessor for ANSYS that enables designers to efficiently create three-dimensional, shell element based blade models. NuMAD helps with management of materials, composite layups and geometry of the blade. Subsequent computational analyses are performed with the ANSYS commercial finite element analysis package. NuMAD enables users to define the necessary parameters for subsequent runs in ANSYS and BPE for computation of one-dimensional beam properties used in the FAST[9] full wind turbine aeroelastics code.

BPE is a code and a technique to extract equivalent beam properties from a wind turbine blade finite element model[6]. The method is based on applying loads in each of the six degrees of freedom at the tip of the three-dimensional blade model then processing the resulting nodal displacements to generate the 6×6 Timoshenko stiffness matrices for the specified beam discretization. The method thus includes three-dimensional effects such as shear and warping. It also captures effects arising from nearby boundary conditions and non-uniform blade geometry. Calculation of the section properties are demonstrated in a series of validation examples in Malcolm and Laird[6,10,11]. BPE accommodates blades with curvature in one or both directions and has the ability to identify the center of mass, elastic center, principal directions, shear center and off-axis coupling terms.

There are limitations in the BPE approach. Proper application of the force to the finite element model is important for eliminating effects due to an unwanted boundary conditions. Also, the sectional properties will depend on the size of the blade segment one chooses to designate as an equivalent beam element. Beam segments that are too short are at risk of forming a singular stiffness matrix. Beam segments that are too long may not be able to adequately capture the spanwise gradient in properties.

In the past, issues have been documented regarding the use of certain shell finite element formulations in wind turbine models. Particularly, there have been problems with inaccurate representation of shear forces and torsional stiffness. These effects are documented by Laird et.al.[12] Recently, improved shell element formulations have been implemented and have proven to be more accurate for computation of torsional stiffness of wind turbine blades. Computational exercises from Reference 12 have been recreated using recent shell formulations and are shown in this paper as an Appendix. Finally, examples of computations using the improved shell formulations on blade-like cross sections have been shown by Resor. [16]

C. Variational Asymptotic Beam Sectional Analysis

The VABS approach is gaining increasing popularity in the field of wind energy. The approach has been used extensively in the rotorcraft industry and it includes quite a lot of valuable physics. Use of VABS does not require access to commercial finite element solvers. The usefulness of a VABS approach for simplification of wind turbine blade models is attractive and is investigated in this paper.

VABS[8] is a code implementing the various beam theories based on the concept of simplifying the original nonlinear three-dimensional (3D) analysis of slender structures into a two-dimensional (2D) cross-sectional analysis and a one-dimensional (1D) nonlinear beam analysis using the variational asymptotic method. VABS uses a finite element mesh of the cross section to calculate sectional properties which include structural and inertial properties. These properties are needed for the 1D beam analysis to predict the global behavior of the slender structure. The 3D point-wise displacement/strain/stress distribution within the structure can also be recovered based on the global behavior of the 1D beam analysis. VABS can produce the necessary properties for use in the Euler-Bernoulli model, the Timoshenko model, or the Vlasov model. VABS can only provide accurate 3D fields away from boundary conditions, loads, or abrupt geometry changes.[14] This limitation may be important in wind turbine blade geometries and is a major motivation for the current investigation.

Creation of input files for analysis of wind turbine blade cross sections by VABS is extremely tedious. Fortunately, a preprocessor for VABS, called PreVABS[13], is available. Input files for PreVABS are formatted similarly to PreComp input files. PreVABS utilizes airfoil shape, layup and shear web locations and material information to generate a mesh and assign material attributes for the VABS input file. The use of VABS for analysis of multiple wind turbine sections is simply not practical without a tool such as PreVABS. PreVABS is a relatively young code and several limitations were encountered in the course of the work for this paper. Still, useful results are shown in this paper.

VABS and PreComp were both part of a thorough assessment of cross section analysis techniques by Chen et. al.[14] BPE was also discussed in the article. BPE has great potential as an accurate beam property analysis tool, but its approach is fundamentally different from the other codes examined. Therefore, it was not utilized as part of the investigation by Chen et.al. The current investigation provides some insight into what the results comparison may demonstrate.

D. Approach and Goals

This investigation contains two related pieces. In Part 1 each approach (PreComp, BPE and VABS) is used to compute beam properties of a real three-dimensional wind turbine blade model. Important beam properties from the three approaches are compared. The blade model under investigation is the CX-100 9-meter research blade.[15] Additionally, detailed information from the article by Chen et.al[14] is used to perform a benchmark of current BPE and PreComp analysis results to results obtained by VABS for a simpler, uniform blade section.

Next, Part 2 quantifies the major discrepancies in the important calculated properties and assesses the effect of those property variations on the computed flutter speed of the blade. The technique outlined by Lobitz[2] is used to perform the flutter analyses. Basic sensitivity of flutter prediction with respect to variations in calculated beam parameters is shown.

II. A Uniform Section Verification

A direct comparison of section properties calculated by the modified PreComp, VABS and BPE is done prior to the full blade investigation. The article by Chen et.al[14] describes a very nice cross section code validation problem in great detail. Readers should refer to this article for more information on this part of the code comparison. The shape of the section is shown in Figure 3. The article contains tabulated cross section properties calculated using VABS. The (modified) PreComp and BPE are used to analyze the same section in order to get a sense of baseline uncertainty between the approaches.

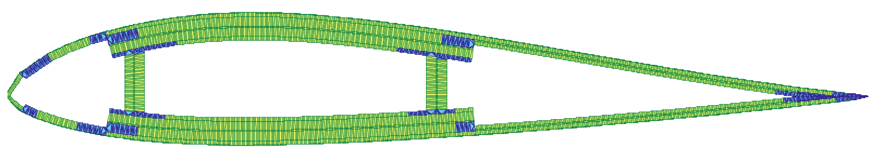


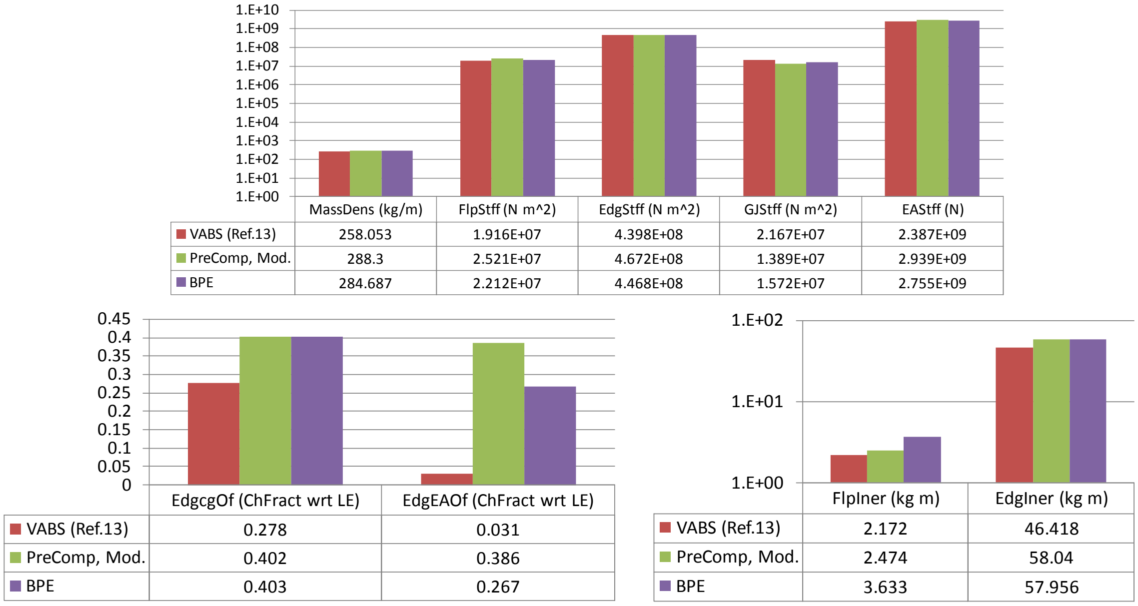
Figure 3 VABS mesh for blade cross Station #1, Reference 14.

BPE results can be sensitive to the element size in the ANSYS model. Sensitivity of BPE analysis results with respect to the finite element model element size was investigated by Resor et.al. [16] Continually decreasing element size did not improve accuracy. In the end, an element size of 0.1 m was chosen for 2m chord sections. Smaller elements may be warranted for other types of analyses, but an average element size of 5% of maximum chord seems to be a good guideline for finite element shell models used for BPE analyses. This analysis uses ANSYS R12.1, Shell 281 elements with edge lengths approximately 5% of chord length. The improved shell formulation is used for the work in this paper.

A special process is used to determine equivalent 2D section properties from the 3D BPE analysis since BPE does capture effects of boundary conditions in the three dimensional model. The shape was modeled as a uniform section in a slender blade with aspect ratio of 20. The equivalent 2D section properties shown here are taken from the middle of the blade span in order to avoid end effects. Comparison of results are shown in Figure 4.

The comparisons indicate mostly good agreement between codes. There are noticeable discrepancies in the calculation of offsets for mass center and shear center. There is some question as to the validity of the value reported in Reference 14 for VABS-calculated shear center offset: a typographical error is suspected. The disagreement between VABS results from Reference 14, PreComp and BPE in mass center prediction location is disturbing. Also, VABS calculation of mass density in Reference 14 is low. The VABS analyses were recreated from scratch for comparison against VABS results from Reference 14. Recreated results agree almost perfectly with the present PreComp and BPE results. Therefore, the authors are not concerned about accuracy of VABS. Root cause for the discrepancy may be in sensitivity of results to the specific discretization of the airfoil geometry used by PreVABS. These details are not included in the paper by Chen et.al.

Calculated values for flapwise section inertia from BPE are likely high because of an issue with how mass is represented in ANSYS offset-node shell elements. When nodes are offset, the mass is relocated to the new offset node locations. The effect leads to mass being placed farther from the chord line than intended and has a noticeable effect on flapwise inertia. The effect on edgewise inertia is minimal. The effect is amplified as skin thickness and chord thickness increase.



	MassDens (kg/m)	FlpStff (N m^2)	EdgStff (N m^2)	GJStff (N m^2)	EAStff (N)
VABS (Ref.13)	258.053	1.916E+07	4.398E+08	2.167E+07	2.387E+09
PreComp, Mod.	288.3	2.521E+07	4.672E+08	1.389E+07	2.939E+09
BPE	284.687	2.212E+07	4.468E+08	1.572E+07	2.755E+09

	EdgcgOf (ChFract wrt LE)	EdgEAOf (ChFract wrt LE)
VABS (Ref.13)	0.278	0.031
PreComp, Mod.	0.402	0.386
BPE	0.403	0.267

	FlpIner (kg m)	EdgIner (kg m)
VABS (Ref.13)	2.172	46.418
PreComp, Mod.	2.474	58.04
BPE	3.633	57.956

Figure 4 Comparison of computed properties for a uniform blade cross section.

With the exception of the properties mentioned above, the balance of properties seem to vary within what would be expected due to uncertainty in modeling of as-manufactured wind turbine blades. There is a reasonable amount of confidence in the modified PreComp and in BPE using ANSYS Shell 281 elements now with the completion of this investigation and with the work documented in Reference 16.

III. CX-100 Finite Element Model

The CX-100 finite element model is created using the NuMAD[5] preprocessor for ANSYS. Subsequent computational analyses are performed with the ANSYS commercial finite element analysis package. The blade model used in this investigation contains 10,071 elements with an average element edge length of 0.04 meters. The blade model mass is 170 kg and the blade length is 9 meters. The geometry is defined at 30 stations along the span of the blade. There is a single fiberglass and balsa core shear web with tapered carbon spar caps. All of the panels are fiberglass, most with balsa core. The maximum chord length of the blade is approximately 1 meter. The blade model is shown in Figure 5.

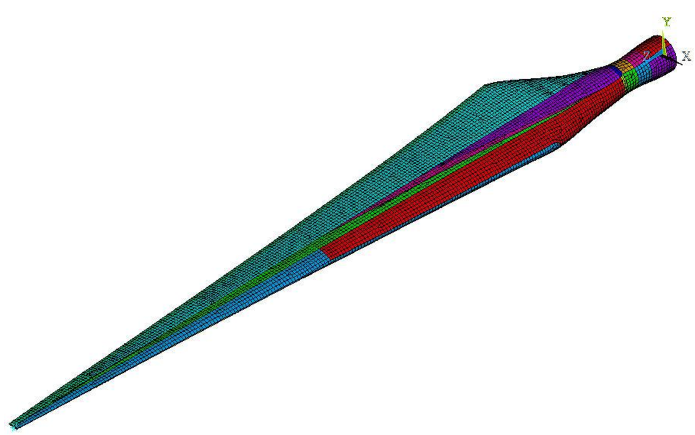


Figure 5. Finite element shell models of the CX-100 blade. Colors correspond to unique composite layup regions.

E. BPE Beam Node Spacing

There are limitations in the BPE approach. The sectional properties are dependent on the size of the blade segment one chooses to designate as an equivalent beam element. Beam segments that are too short are at risk of forming a singular stiffness matrix. Beam segments that are too long may not be able to adequately capture the spanwise gradient in properties. An exercise is performed next to determine the reasonable beam node spacing for a BPE analysis of this turbine blade. BPE beam nodes are easily specified at any blade station that has been included in the model. A blade station is defined as the set of information at a given span location describing everything about the blade shape and material layup at that location. Because the shape has been defined at the station, the user is guaranteed a useful set of finite element nodes and associated displacements and rotations for the subsequent BPE analysis at that location. Specification of BPE analysis nodes between the defined blade stations can be problematic if there is not an adequate density of nodes at that span location.

Three different BPE analyses are performed: one which utilizes all 30 blade stations as beam nodes for the BPE analysis, one using a subset of stations at intervals of approximately 5% span and one using a subset of stations at intervals of 10% span. An illustration of beam node spacing is shown in Figure 6.

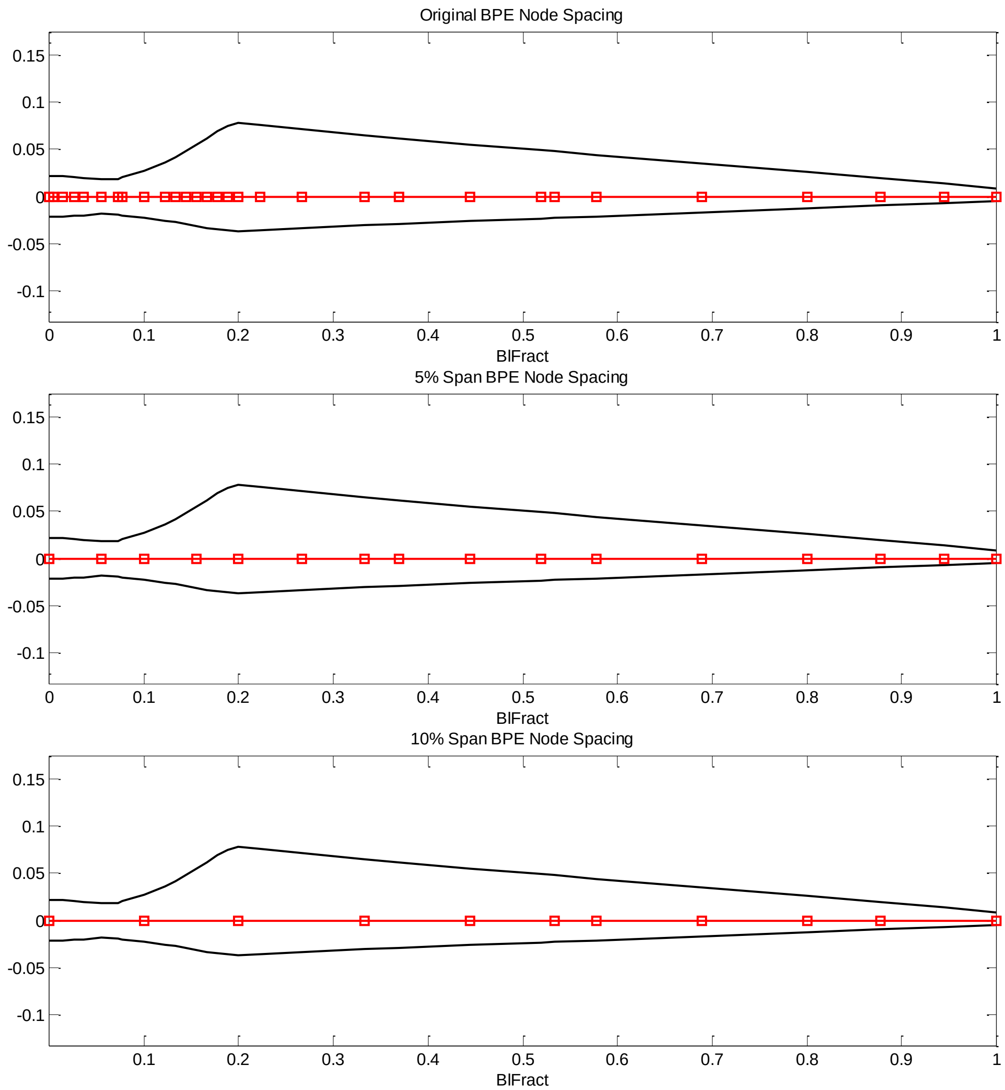


Figure 6 Illustration of BPE node spacing for convergence study. Spacing is approximate.

Selected BPE results for the three cases are shown in Figure 7. The blade properties inboard of 20% span are quite sensitive to the node spacing. At the finest spacing, the large spanwise gradients are captured well, e.g. edgewise inertia. However, equivalent beam elements are too short for accurate calculation of stiffness properties, e.g. axial, flapwise, and torsional stiffnesses. At the course node spacing, too much information about the property gradients is lost. Five percent span spacing seems to be a good balance between small enough spacing to capture features and large enough spacing to avoid numerical issues. The recommendation of this paper for ideal BPE beam analysis node spacing is five percent of blade span.

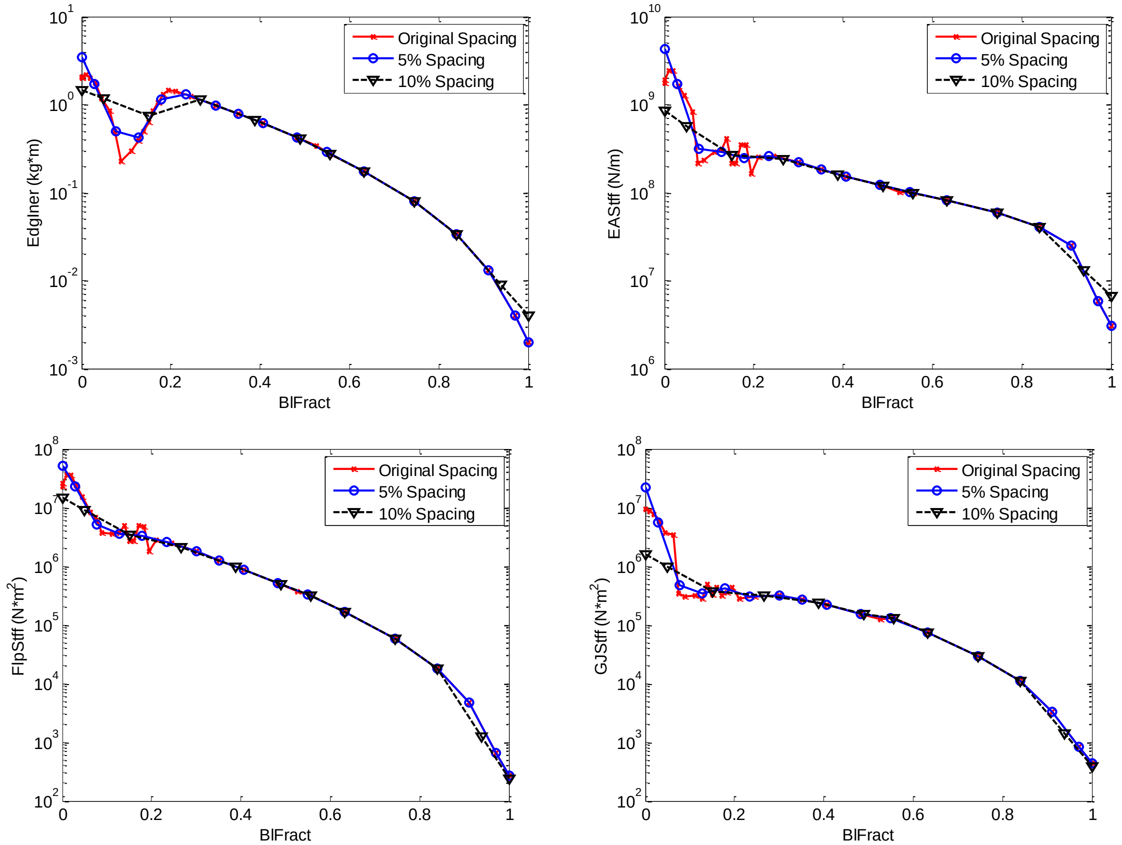


Figure 7 A subset of analysis results showing the effect of BPE node spacing on calculated property distributions.

IV. Comparison of Full Blade Results

In Section II, VABS, PreComp, and BPE are shown to be in agreement with each other for computation of most properties. Section E proposes guidelines for optimal blade discretization of the blade for analysis using BPE. Next, relevant beam property distributions are computed and compared using each of the three tools. In each case, the blade model information in NuMAD is used to generate input files for the subsequent analyses in either ANSYS/BPE, PreComp, or PreVABS. In this way, the results shown below are efficiently and consistently generated from a single model definition. Figure 8 shows the results of the analyses. The results shown here represent the subset of properties that are utilized by the FAST/AeroDyn or ADAMS/AeroDyn aeroelastic simulation codes. Definition of the computed properties can be found in the FAST User's Manual. [9]

Note that during the course of this work the authors came across some minor issues in the use of PreVABS for certain blade sections. The issues will be resolved in future releases of PreVABS. Results in Figure 8 show results at a smaller set of span locations due to the issues that were encountered for the remainder of the sections. The PreVABS analyses that were successful, and are shown in Figure 8, provide adequate insight for this investigation.

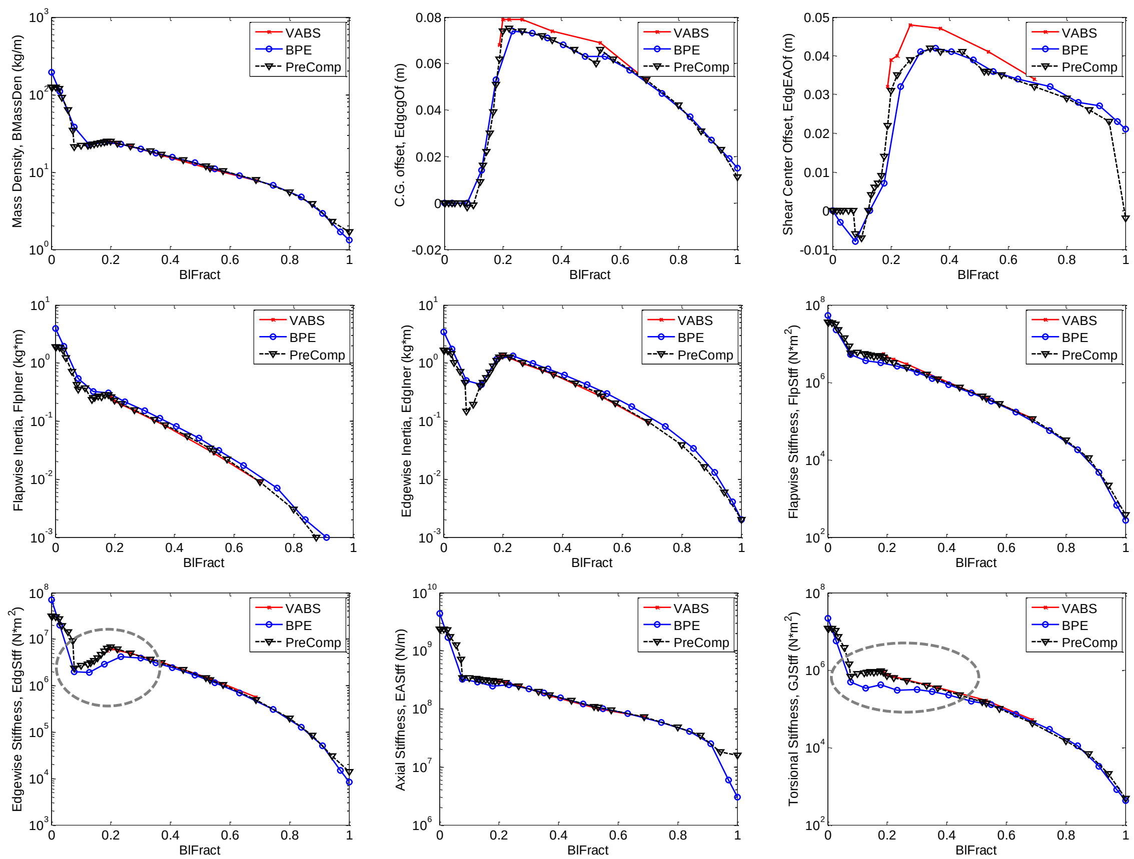


Figure 8 Calculated CX-100 property distributions. Dashed circles in plots of edge and torsional stiffnesses show an interesting region of disagreement between computed properties.

In almost all cases, the three tools predict similar results for the outboard blade. Inboard of 30% span there are notable discrepancies. This inboard region contains the chord maximum as well as the root geometry. This region provides many modeling challenges because of the rapidly changing geometry and material layup definitions.

Regarding mass density, PreComp is probably capturing the distribution most effectively. BPE must compute an average property for each element and therefore is not able to capture rapidly changing properties.

Edgewise and flapwise inertias for PreComp and VABS are in good agreement. BPE which has two issues: 1) inability to capture rapid gradients and 2) slight overestimation of inertia due to the offset node effect from ANSYS. The computed location of elastic axis and mass center from VABS is slightly offset from PreComp and BPE. However, the error with respect to chord length is on the order of only one percent.

Flapwise, edgewise and axial stiffnesses are all in fairly close agreement, though BPE tends to indicate more flexible properties for the inboard blade. Even more noticeable is the additional torsional flexibility that is calculated by BPE. The higher torsional flexibility computed by BPE is believed to be a result of the spanwise geometry gradients in the inboard portion of the blade. It is known that neither the VABS nor PreComp approaches are equipped to deal with 3D fields away from boundaries conditions or sudden changes in the cross-sectional geometry along the span. The discrepancies in edge and torsion stiffness seen here are the result of those effects. The effects of this stiffness discrepancy are investigation in the next section of this paper.

V. Flutter Analysis

Discrepancies in torsional stiffness distributions were demonstrated in the previous section. Torsional properties are critical to the accurate representation of aeroelastic flutter modes and are critical to simulation of passive wind turbine rotor load alleviation concepts (e.g. bend-twist coupling via off-axis material layup or blade sweep). This paper focuses on demonstrating sensitivity of predicted flutter speed resulting from variation in torsional beam stiffness. The effect of torsional stiffness uncertainty on passive load alleviation effectiveness is left for future work.

The methodology used here for classical flutter prediction of horizontal axis wind turbine blades was developed at Sandia National Labs by Lobitz. Details of the approach are found in the Reference 2. Inputs required for the analysis are shown in Table 1.

Table 1. Inputs required for flutter prediction.

Parameter	Description
EI_flap	Flapwise bending stiffness
EI_edge	Edgewise bending stiffness
GJ	Torsional stiffness
Twist	Blade pretwist
Tiner	Torsional inertia
LCS	Lift curve slope
Elastax	Distance along the chord the elastic axis is aft of the pitch axis
Aerocntr	Fraction of the chord that the aerodynamic center is aft of the leading edge.
Masscntr	Distance the mass center is aft of the elastic axis
Chord	Section chord length

In addition to rotor speed, the prediction also depends on the natural frequency of the flutter mode shape of interest. Since this frequency is unknown at the onset of the computations an iterative process is required for obtaining accurate results. The procedure utilizes some basic features included MSC.Nastran: 1) finite element beam model; 2) modification of mass, stiffness, and damping matrices for inclusion of aeroelastic effects; and 3) a complex eigenvalue solver. The end goal in the process is to identify the eigenmode that exhibits a negative damping coefficient for the lowest rotor rotational speed. This speed is designated as the classical flutter speed for the blade. Damping trends for the CX-100 flutter analyses are shown in Figure 9a.

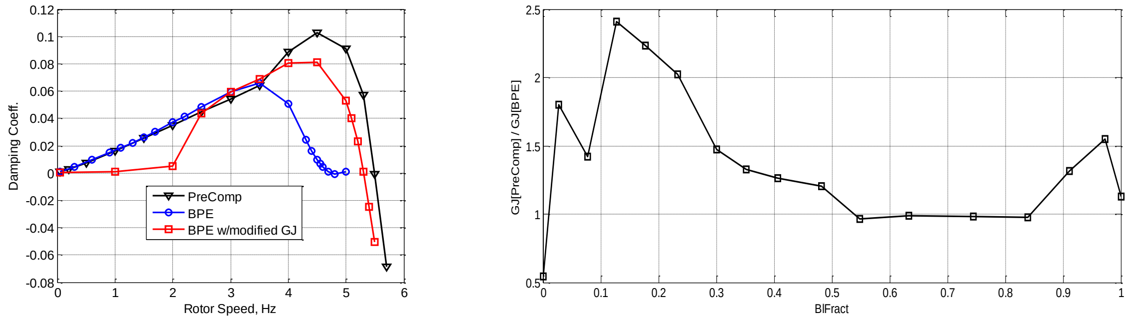
Table 2 summarizes the results for flutter analyses of three different equivalent beam structures. The first is a beam model created using properties directly from the PreComp analysis of the CX-100 blade (black curves in Figure 8). The second is a beam model created using properties directly from the BPE analysis of the CX-100 blade (blue curves in Figure 8). The third is a beam model created using properties directly from the BPE analysis with with GJ properties scaled such that they are representative of the GJ distribution computed using PreComp. The GJ scaling factors are shown in Figure 9b. An analysis of a beam comprised of VABS-computed properties was not analyzed for flutter for two reasons: 1) the full set of blade analysis sections was not available due to the issues that were experienced in running the latest release of PreVABS on this blade geometry and 2) the VABS properties that were computed for the CX-100 blade are nearly equivalent to those computed using PreComp.

The normal operational speed for the Micon turbine with CX-100 blades is approximately 0.92 Hz (55 RPM). The ratio of minimum calculated flutter speed to operating speed is approximately 5 to 1. Flutter speeds for smaller utility scale blades are well above the operating speeds of the rotor. This case is no exception.

Results indicate a noticeably lower flutter speed for a beam with the more flexible properties computed by BPE. The computed flutter speed as a result of using BPE is 14% lower than if PreComp is used to derive the beam. The effect of keeping all beam properties constant, but scaling the torsional stiffness to represent what is predicted by PreComp accounts for a majority of that margin. The remainder of the discrepancy in flutter speed is due to other smaller discrepancies in computed properties used in the flutter analysis, e.g. flap and edge stiffnesses, inertias, mass and shear center locations.

Table 2 Flutter Analysis Results

Analysis input parameters	Unstable blade rotation speed, Hz
PreComp properties	5.50
BPE properties	4.74
BPE with scaled GJ stiffness	5.30



(a) (b)

Figure 9 (a) Damping trends during flutter analyses and (b) Ratios of computed torsional stiffness.

VI. Summary

The process of reducing a detailed wind turbine blade structural model into a simpler, yet accurate, beam representation of the blade is important to the process of wind turbine system aeroelastic simulation. This paper exercises various techniques for computation of an equivalent beam in order to demonstrate the strengths and weaknesses of each. Three tools were used on a variety of section geometries as part of this work: PreComp, VABS, and BPE.

A short verification of the tools was performed using a single blade section. In general, the properties of interest for this investigation demonstrated adequate agreement for the uniform section. Next, a high fidelity model of a CX-100 9 meter turbine blade was converted into an equivalent beam using each of the three techniques. Discrepancies in computed beam properties were noted. In general, PreComp and VABS compute similar property distributions. Beam properties computed using the BPE approach yield a more flexible beam representation than with PreComp or VABS. PreComp and VABS are unable to represent effects due to blade root boundary conditions or significant geometry and material layup variations along the span of the blade, especially for the inner 30% of a CX-100 blade span. Important future work will pursue high quality experiments on structures that could validate the results of these codes.

Finally, the paper focused on assessing the variation in estimated flutter speed of the computed beams with respect to the computed torsional stiffness properties. In the end, a computed flutter speed reduction of 14% occurred by using a beam derived from BPE computed properties compared to the flutter speed computed using a beam derived from PreComp computed properties. Utility scale turbines today likely experience flutter at speeds that are more than twice their operating speeds.[2] An uncertainty in flutter speed prediction of approximately 14% is not catastrophic. However, as turbine rotors increase size in an effort to capture more energy efficiently the safety margin with respect to flutter will decrease. Accurate tools and techniques for blade structural analysis and aeroelastic stability analysis will be needed for safe and effective design of these future systems.

VII. Acknowledgements

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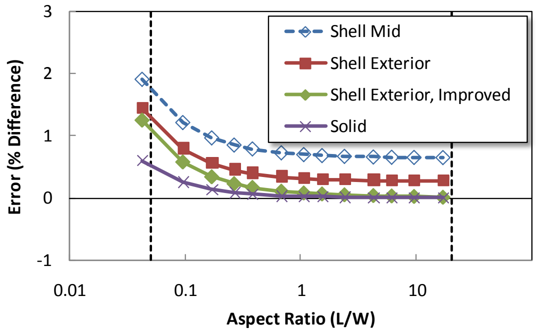
VIII. Appendix A: Demonstration of Shell Element Accuracy

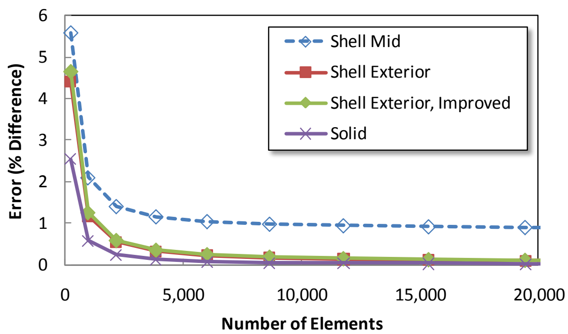
Following are results from an exercise that recreates the work done by Laird et.al in Reference 12. This work showed potential for extremely large errors in computation of shear stresses in cylinders modeled using offset node, or exterior node, shell elements. Each figure contains curves for recreated results from the Laird paper. In addition, each figure shows results obtained using a more recent shell element: the ANSYS Shell281, including the option for an improved formulation. Results obtained using the improved shell formulation demonstrate a vast improvement over the previous offset node formulation.

F. Cylinder Under Bending Load



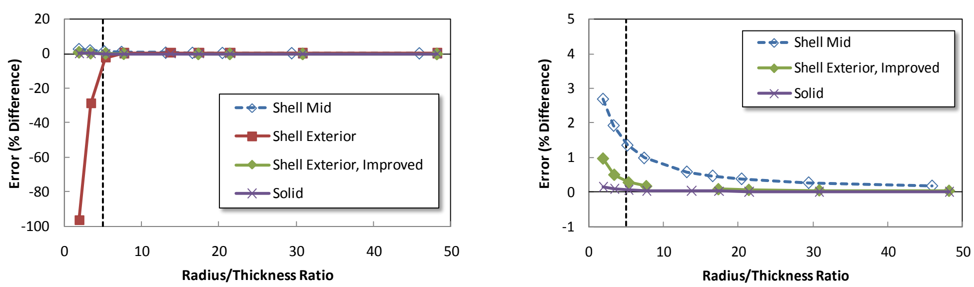
Number of Elements	19200
Radius/Thickness	10
Length/Diameter	10

Figure 10 Error in bending stress as a function of element aspect ratio.



Aspect Ratio	~1.1
Radius/Thickness	7.5
Length/Diameter	13.3

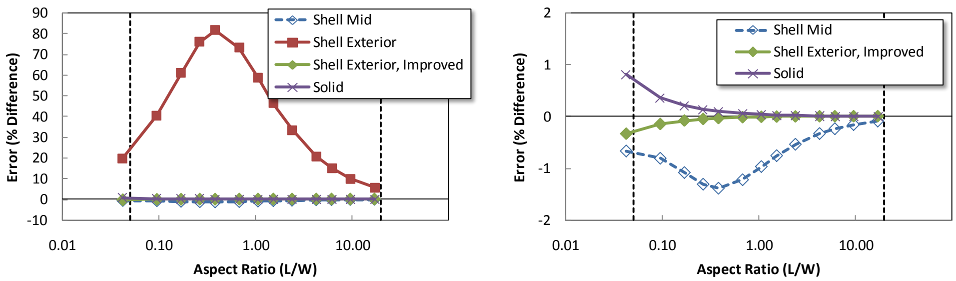
Figure 11 Error in bending stress as a function of number of elements.



Aspect Ratio	~3.4
Number of Elements	2880
Length	20

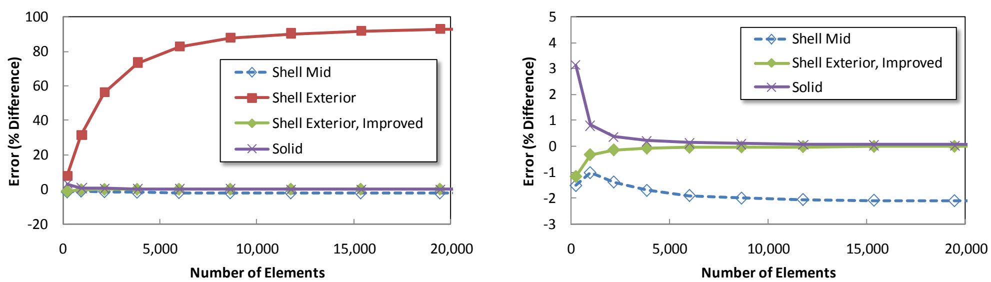
Figure 12 Error in bending stress as a function of radius to thickness ratio.

G. Cylinder Under Shear Loading



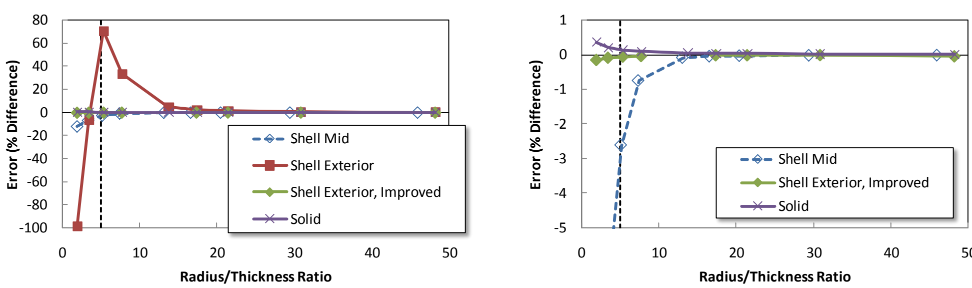
# of Elements	19200
Radius/ Thickness	10
Length/ Diameter	10

Figure 13 Error in shear stress as a function of element aspect ratio.



Aspect Ratio	~1.1
Radius/ Thickness	7.5
Length/ Diameter	13.3

Figure 14 Error in shear stress as a function of number of elements.



Aspect Ratio	~3.4
# of Elements	2880
Length	20

Figure 15 Error in shear stress as a function of radius to thickness ratio.

IX. Appendix B: PreComp Modifications

The following changes were made to the PreComp v1.00.02[4] source code to support this work:

Line 1196 -- Finding the center of a shear web segment lamina stack
old: y0 = y0 - tbar/2. - y_sc
modified: y0 = ysg - tbar/2. - y_sc

Lines 1212-1213 -- This change seems to fix the problems caused by shear webs
old: ipp = iepz - iemz*c2ths
old: iqq = iepz + iemz*c2ths
modified: ipp = iepz + iemz*c2ths
modified: iqq = iepz - iemz*c2ths

X. References

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