Experimental validation of finite element techniques for buckling and postbuckling of composite sandwich shells

by Aaron Thomas Sears

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

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Abstract:

This thesis reports on a series of experimental and finite element modeling studies of sandwich panels typical of wind turbine blade construction. Buckling is a common failure mode in composite structures such as fiberglass wind turbine blades and sandwich construction is often employed in sensitive areas to increase buckling resistance with minimum weight and cost. The panels were flat or curved with, fiberglass facesheets and balsa cores. The primary objective of the study was to investigate the accuracy of linear and nonlinear finite element buckling predictions for panels of this type.

Modeling procedures used for composite structures like blades often utilize linear eigenbuckling and geometrically nonlinear incremental buckling analyses. Often, the nonlinear model used the linear mode shape to perturb the model and to produce a buckling shape on the perfect geometry. The present study uses the random nodal displacement perturbation method for the nonlinear analysis which is entirely independent of the linear mode shape. The random perturbation method can be used for complicated structures and does not impose a mode shape on the model which may or may not be correct. Both methods, linear and nonlinear, were validated with buckling experiments on idealized blade substructures: curved and flat fiberglass/balsa sandwich shells. Five different series of panels were tested incorporating changes to four parameters: support conditions (simple-free-simple-free and four sided simply supported), radius of curvature (flat, shallow and deep), facesheet lay-up, and core thickness.

Good correlation between tests and shell element FE modeling was found for both the linear and nonlinear cases for the critical buckling loads for most models. Good correlation was also found for the early postbuckling response, with late postbuckling strains becoming invalid and deflections being rough approximations after some response shift (mode shift or mesh rippling). Certain combinations of numerical and/or structural parameters were found to present problems to some of the analysis techniques. The combination of curvature and free side edges caused problems for predicting the correct critical buckling mode for both the linear and nonlinear analyses. Deep curvatures and high mesh densities also caused problems predicting the correct mode shape for four sided simply supported panels. Complex boundary conditions tended to compound these problems. Proper modeling of the boundary conditions was found to be critical for accurate results, especially for the curved panels. In this study, this required modeling the load supports of the test fixture. Finally, closed form solutions found in the literature had poor correlation for both critical buckling loads and mode shapes.

The random nodal displacement perturbation method was found to have several general characteristics. First, it tended to give conservative results as compared to the linear models. A statistical study demonstrated relatively consistent results with a standard deviation of 3.7% (down to 2.2% for smooth responses). The random method also tended to exacerbate any problems encountered with all nonlinear models, such as snap-through critical buckling responses, mode shifts to non-symmetric shapes and mesh rippling behavior. Additionally, a model would occasionlly pass the critical buckling mode and

continue loading until finally buckling into a higher mode shape. These last two problems were a function of the average size of the perturbations (slight for the mode shifts, significant for snap-through and higher buckling modes). Finally, large perturbations would sometimes violate curvature requirements for sandwich modeling due to high local curvatures caused by the random displacements.

It is recommended that both linear and nonlinear random perturbation method analyses be run for sandwich structures with curvature or complex boundary conditions. The more conservative result of the two is generally the more accurate. If the nonlinear model buckles in a higher mode shape at a significantly higher critical buckling load, another nonlinear run is necessary to confirm the mode shape.

Numerical parametric studies were also performed to establish FE modeling guidelines for buckling analyses. In addition to the conclusions above several other observations were made. The effect of using sandwich modeling is very significant even for relatively thin cores. The analyses are not particularly sensitive to the core properties, only the approximate range is required for good predictions. The effects of angled loads up to 10% higher on one side are not significant. The mixed element model (solid brick element core and shell facesheets) did not provide accurate predictions (twice the experimental and shell predicted loads).

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APPROVAL

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Aaron Thomas Sears

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

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Chapter 1

INTRODUCTION

While wind power offers great potential in the United States, it currently provides only small amounts of localized energy within the United States [Sesto and Ancona (1995)]. To cultivate wind energy as a widespread renewable, alternative energy source, its cost per kilowatt must be reduced. One factor directly affecting cost is blade weight. Lower weight blades will produce more efficient systems with lighter weight support structures, thereby reducing cost. Current blades are constructed of laminated wood or fiber reinforced plastic materials (referred to as FRPs or composites hereafter). Blades are constructed with a hollow airfoil shell structure [McKittrick et al. (1999)]. Blade structure and design are important elements in the affordability of wind power. The blades are subjected to complex fatigue load spectra, extreme wind loads, and possible impacts during their lifetime of use. Most composite blades tend to be designed conservatively and heavier than necessary, due to the complicated analyses and load-material response predictions required to obtain more accurate results. Among FRPs, fiberglass systems have become popular as blade materials due to their lower cost.

Composite FRPs consist of fibers with high strength and stiffness bonded into a thermoset or thermoplastic polymer matrix. The fibers are usually arranged into layers in an XY plane, creating a shell structure. Within the XY plane, the fibers can be random (continuous or discontinuous strands) or directional (unidirectional or multidirectional). Most FRP structures use unidirectional fiber layers, oriented to resist various loads, arranged to create an orthotropic or even anisotropic shell structure [Jones (1975)]. Since FRPs have high in-plane strength and stiffness, these shells are often thin. Large, thin, unsupported shell structures tend to buckle under compression loads well below their compressive strength due to geometric instability.

To combat the buckling problem, the skin thickness is increased. The extra thickness raises the moment of inertia (I_i), and hence, also the bending stiffness (D_{ij}). Two major methods are used to add bending stiffness without adding significant weight: skin stiffeners and sandwich construction. Skin stiffeners add another shell structure in the *XZ* plane, creating a 'T' or 'I' shaped structure. Sandwich construction utilizes a lightweight material, called the core material, surrounded by the stiffer, thinner shell material, termed face sheets. A composite facesheet sandwich construction diagram is shown in Figure 1-1. Typical core materials include balsa, honeycomb and foam. Most fiberglass wind turbine blades use both methods to increase the bending stiffness of the blade.

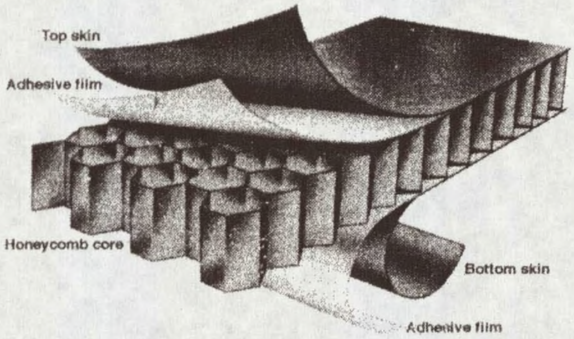

Figure 1-1. sandwich construction

The MSU Composites Group fiberglass AOC15/50 wind turbine blade design is shown in Figure 1-2. The span (skin stiffener) ties the windward and leeward shells together to increase the global bending stiffness of the blade. The sandwich construction on the trailing edge (which undergoes compression under wind loads), mitigates local shell buckling of the relatively flat airfoil surfaces under extreme wind loads.

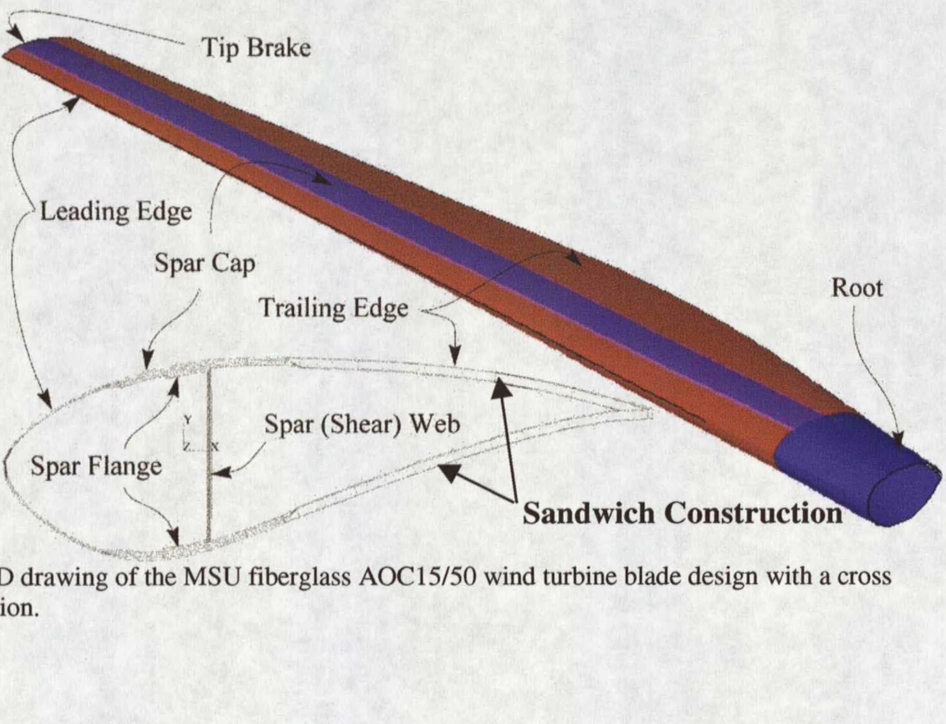

Figure 1-2. CAD drawing of the MSU fiberglass AOC15/50 wind turbine blade design with a cross section.