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Pardo, D.; Branner, K.

Published in:
Wind Engineering

Publication date:
2005

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Pardo, D., & Branner, K. (2005). Finite element analysis of the cross-section of wind turbine blades; a comparison between shell and 2D-solid models. *Wind Engineering*, 29, 25-32.

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Finite Element Analysis of the Cross-section of Wind Turbine Blades; a comparison between shell and 2D-solid models

Daniel R. Pardo and Kim Branner

Wind Energy Department, Risø National Laboratory, DK-4000 Roskilde, Denmark. Email kibr@dtu.dk

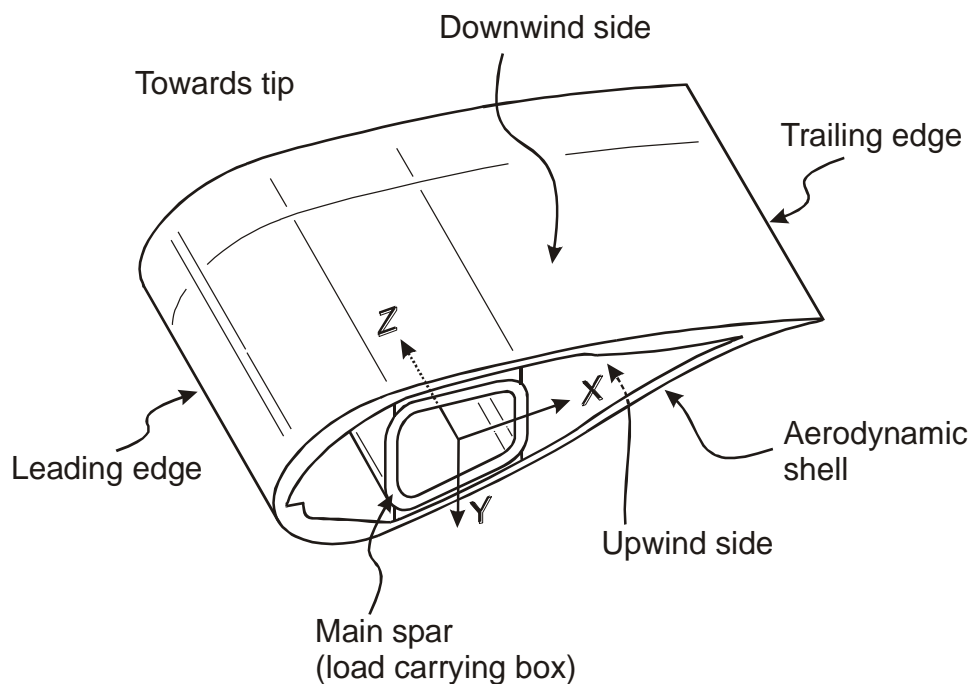
ABSTRACT

A very detailed 2D-solid finite element model is developed representing the load carrying box girder of a wind turbine blade. Using typical geometrical values for the girder dimensions and public available material data, the overall cross-sectional behaviour is analysed for a simple compressive line load. The results are compared with result from similar shell models, which typically are used for practical design. Usually, good agreement between the shell models and the detailed 2D-solid model is found for the deflections, strains and stresses in regions with loads from pure bending. However, large differences can exist in regions where the loading is dominated by shear. It is found that geometrical non-linearity starts to become important when deflections are of the same order as the laminate thickness.

Keywords: FEA model, Wind turbine blade, Box girder, Strain and stress, Non-linear analysis.

1 INTRODUCTION

Many modern wind turbine blades are constructed with a load-carrying box girder that supports the outer shell. The box girder usually extends from the root of the blade to a position close to the tip. The outer shell is mainly designed from aerodynamic considerations and behaves as a secondary structure that transfers the pressure loads on the blade to the box girder. See Figure 1.



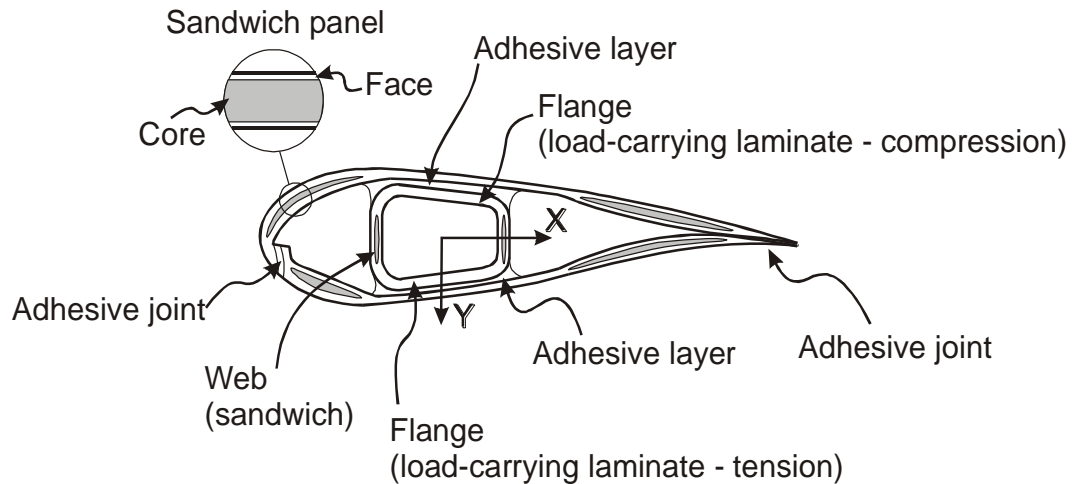


Figure 1. A typical blade structure. From Sørensen et al. (2004).

The purpose of the box girder is to give the blade sufficient strength and stiffness, both globally and locally. Globally, the blade should be sufficiently stiff not to collide with the tower during operational loading. Locally, the box girder, together with the stiffness of the outer shell, ensures that the shape of the aerodynamic profile is maintained.

The pressure load on the blade results in edgewise and flapwise bending, as well as torsional loading of the blade. The box girder primarily carries the flapwise and torsional loads, while the edgewise bending is carried primarily by strengthening the leading and trailing edges of the aerodynamic profile. In flapwise bending, one side of the box girder is in compression and one side in tension. The compressive loading may cause the flange to fail in buckling, as seen in Figure 2. As the size of wind turbine blades is increased, structural stability against buckling may be expected to govern the design.

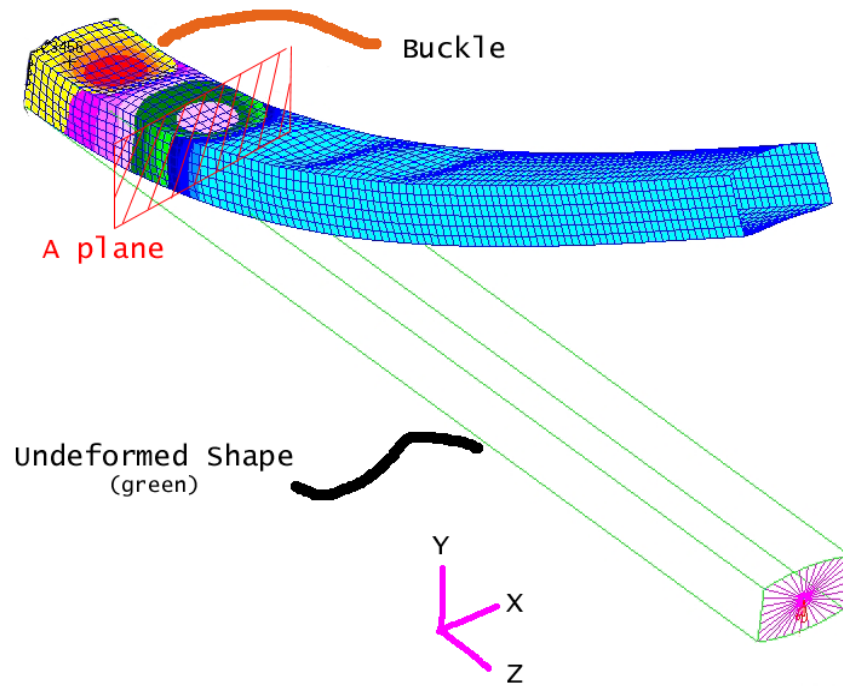


Figure 2. Buckling of a box girder.

As it is seen in Figure 2, large local deflections occur in the transverse direction (section A) as the flange starts to buckle. It is clear that the webs also are taking part in the deformation. Usually a limited number of shell elements are used in the transverse direction to model the box structure, so it can be questioned how well strains and stresses are predicted in the transverse plane. It is also well known that the boundary conditions have a great influence on the buckling strength of a panel. The accuracy of the modelling of the support of the flange panel is questionable, considering the limited number of shell elements in the transverse direction. Therefore, the purpose of this paper is to give some light to these questions by comparing results from a very detailed 2D solid FE-model, with results from coarser 3D shell FE-models.

2 FINITE ELEMENT MODELS

In order to make the finite element models, a realistic lay-up sequence was reproduced, as followed during a manufacturing process, and then this was translated into a geometric model. In the MSC.Patran modeling environment, a series of Patran Command Language (PCL) functions were used to create the desired geometry from a list of predetermined variables. The variables were chosen in order to easily generate many different box girder cross-sections.

The advantages of using PCL are:

- Automated generation of geometry.
- Time saving.
- Capability for constructing many different cross-sections.
- Easy to perform parametric studies.

Some guidelines for building up the models are given below:

The Shell Model

- The composite structure is represented by a single surface.
- The total thickness of the composite structure is related to the direction of a vector normal to the surface.
- The behaviour of the surface is as predicted by Classical Laminate Theory (CLT) for a composite structure.

The 2D Solid Model

- The composite structure is represented by a set of surfaces, where one of the dimensions of each surface represents the thickness of one material layer from the composite.
- The direction of a vector normal to the surfaces is related to the spanwise direction. For this case, this is a non-relevant direction, as plane strain is assumed.

Figure 3 shows the geometry of the shell and 2D solid models that are generated based on the guidelines presented above. See Pardo (2004) for a more detailed description.

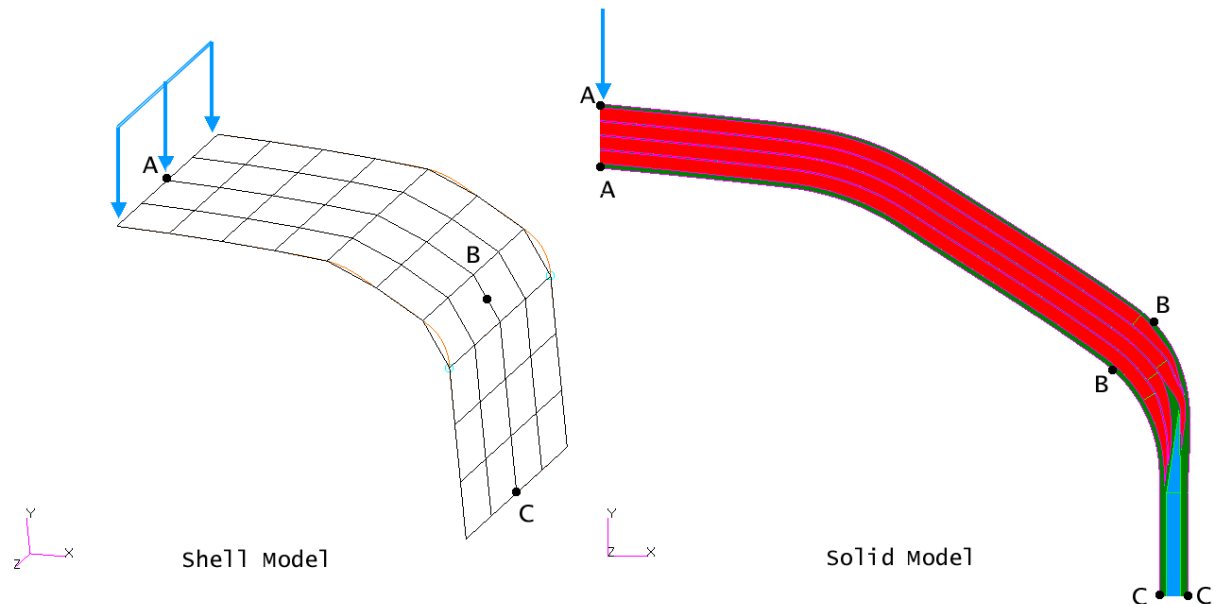


Figure 3. One quarter of the blade box girder. Left: Shell model, Right: 2D-solid model.

For the shell model, two mesh densities have been used: a fine one with 400 elements and a coarser one with 40 elements. When using finite element analysis for the practical design of wind turbine blades, most of the blade is usually modelled as one shell model. In order to achieve acceptable solution times, especially for non-linear analyses, the mesh needs to be quite coarse. Therefore, the coarse mesh model represents a more realistic mesh density for shell models of an entire blade. It is even believed to be in the finer end of commercial used mesh densities. For the 2D-solid model, 2 or 3 elements are used through the thickness of UD or biaxial lamina stacks and 4 elements are used through the thickness for the core material in the webs.

3 MATERIAL PROPERTIES

The material properties used in this study (see Table 1) are based on publicly available data for E-glass/Epoxy prepreg. The index 1 represents the properties in the spanwise direction, while index 2

represents the properties in the transverse direction. As we are only interested in the transverse behaviour (plane strain is assumed), isotropic materials with the index 2 properties are used for reasons of simplification.

| Material | E1 [Mpa] | E2 [Mpa] | G12 [Mpa] | G13 [Mpa] | v12 |
|---------------------|----------|----------|-----------|-----------|------|
| Unidirectional (UD) | 38600 | 8300 | 4100 | 3000 | 0.26 |
| Biaxial | 12600 | 12600 | 10800 | 3000 | 0.52 |
| Core | 70 | 70 | 19 | 19 | 0.35 |

Table 1. Material properties.

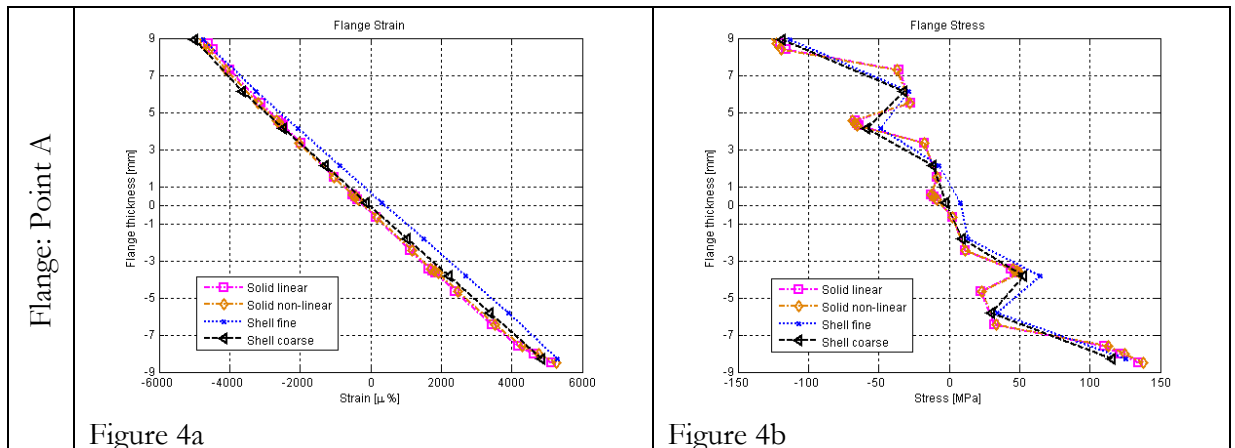
4 LOADS AND BOUNDARY CONDITIONS

The pressure loads on the blade are transferred to the box girder in a quite complicated manner. In the present analysis the box girder section is loaded in a very simplified manner, namely as a line load in the centre of the flange as shown in Figure 3. In order to simplify the complexity of the analysis, symmetry is assumed for the box girder cross-section about both main axes. This is not always true in reality, as the ply lay-up and location can vary both between the top and bottom flanges and also in sidewise direction.

When the above simplifications are introduced, only a quarter of the entire cross-section geometry should be analysed under the boundary conditions (BC) presented in Table 2. The boundary conditions refer to the coordinate system of Figure 3. Here Tx refers to translation in the x-direction and Ry to rotation around the y-axis, and so on.

| Area | Tx | Ty | Tz | Rx | Ry | Rz |
|-----------------|----|----|----|----|----|----|
| Flange midplane | X | √ | X | X | X | X |
| Web midplane | √ | X | X | X | X | X |

Table 2. Model boundary conditions. √ : Unrestrained. X: Restrained.



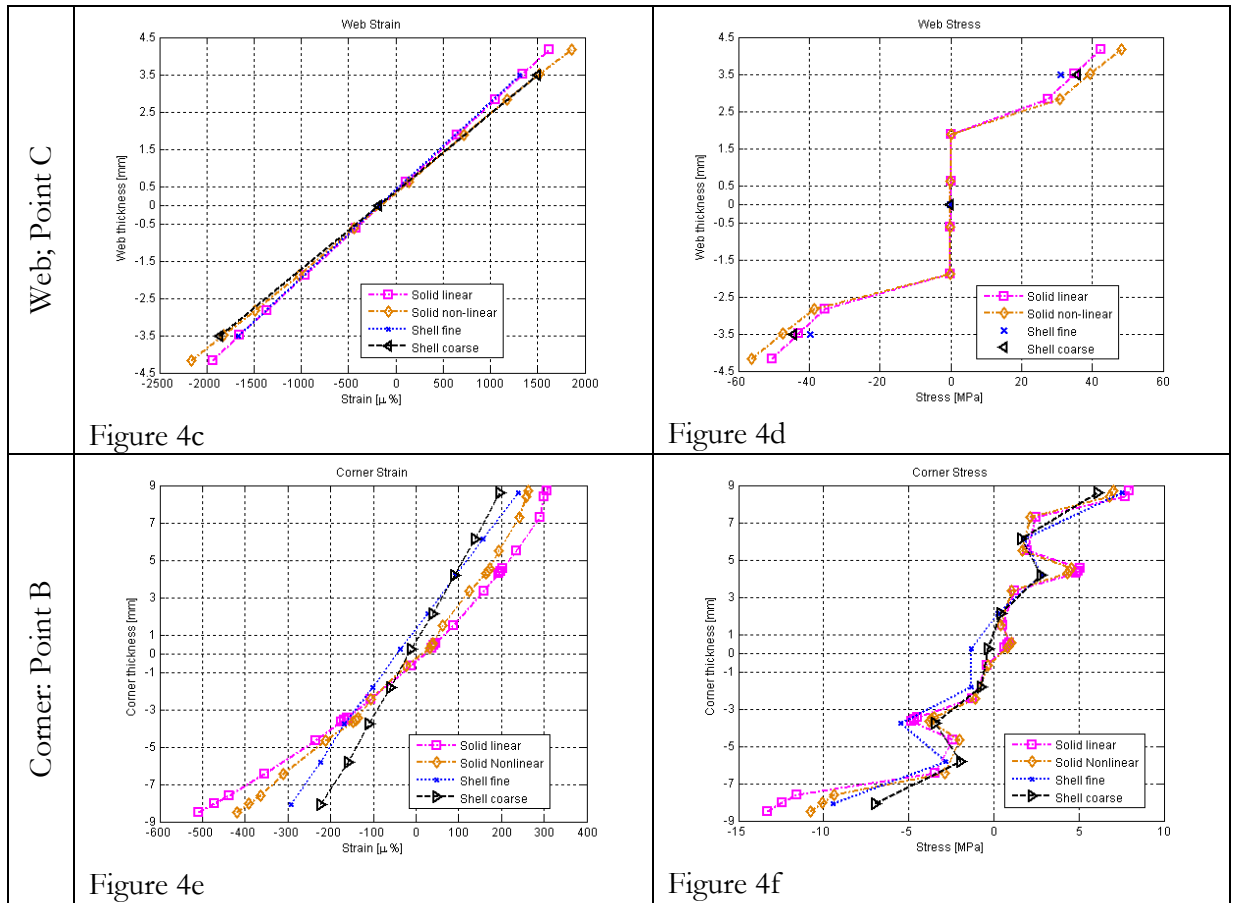


Figure 4. Strains and Stresses in the box girder for a load of 16.25N/mm.

5 RESULTS

Figure 4 presents the calculated strain and stress distributions through the laminate thickness, for the three different locations A, B and C in Figure 3. The “Shell fine” and “Shell coarse” results come from the fine and coarse mesh shell models described in section 2. For both models linear analyses are used. For the shell models, the values presented are values at the mid-plane of each stack of similar layers. The “Solid linear” results come from the 2D-solid model using linear analysis, whereas “Solid non-linear” results refer to a solution where geometrical non-linearities are taken into account. A large displacement and small strain formulation is used.

At the symmetry planes (point A and C), the structure is only subjected to bending and the different models are found to give very similar prediction of the strains (see Figure 4a and 4c). This complies with the Kirchhoff-Love hypothesis, in which it is assumed that planes perpendicular to the plate’s mid-surface remain plane (see e.g. Jones 1999). The classical laminate theory used in the shell model solution is based on this assumption. At point B (see Figure 3) the structure is subjected to both bending and shear. Here the strain is not linear through the laminate and the shell models are not found to predict the strain distribution well (see Figure 4e).

As it is seen from the results in Figure 4, some non-linearity is found at point B and C especially. In Figure 5, the deflection at the midpoint of the flange (point A) and web (point C) are shown as a function of load.

It is found that the non-linearity starts to become important when deflections are of the same order as the respective laminate thickness.

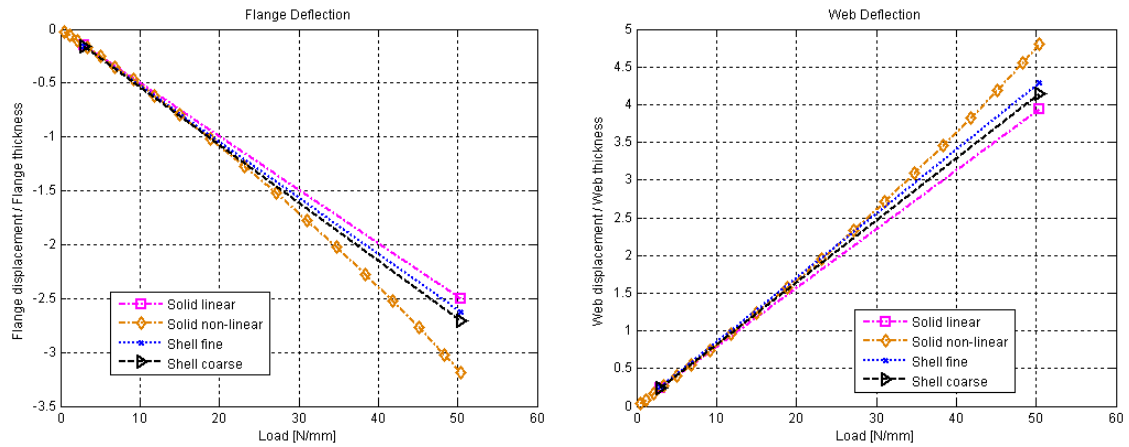


Figure 5. Flange and web midpoint deflections as function of load magnitude.

6 CONCLUSIONS

In the analysis of wind turbine blade structures, shell models and the detailed 2D model is found to give similar results for the deflection, the strain and the stress in regions where there is ‘pure bending’. However, large differences in the calculated strain and stress can occur between the shell models and the more realistic detailed 2D-solid model, especially in regions where the loading is dominated by shear. This should be taken into account when using strain and stress results from shell models in the practical design of structures. It is found that geometrical non-linearity starts to become important when deflections are of the same order as the laminate thickness.

7 ACKNOWLEDGEMENTS

The work was partly supported by the Danish Energy Authority through the 2003 Energy Research Programme (EFP 2003). The supported EFP-project is titled “Improved design of large wind turbine blades of fibre composites – phase 2” and has journal no. 1363/03-0006. The support is gratefully acknowledged.

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