ANALYSIS OF GRID-SCORED SANDWICH STRUCTURES OF DIFFERENT CURVATURES AND GRID SIZES FOR WIND TURBINE BLADES

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Abstract

The stress and strain field developed locally in-situ the core of grid-scored sandwich structures in wind turbine blades is investigated. Due to the many singularities occurring from the “tri-material corners”, a full 3D analysis of the sandwich structure in terms of the Finite Element Method is not directly feasible considering the computational time compared to the required mesh density. Thus, an alternative analysis based on a stiffness homogenisation of the core properties is adopted, which is compared with detailed analysis results and experimental data.

1 Introduction

Wind turbine blades are typically manufactured using a combination of different composite materials including sandwich structures. The aerodynamical requirements for wind turbine blades often dictate that the sandwich structures should have a single or double curved geometry, which implies that the materials in the production process of the sandwich structure needs to be draped to follow the geometry. This is usually not a problem for the face sheets, since these are made of thin layers of glass or carbon fibre fabrics, but the core materials, however, are usually delivered as thick plates of foam (or balsa wood), which due to the thickness cannot be fitted directly to the geometry. To accommodate for this, the materials are cut in small blocks and attached to a thin carrier fabric, which then can be draped. This type of core is known as "grid-scored". If the manufacturing process is based on resin transfer moulding, which is the typical production method for wind turbine blades, resin passes through these scores, thus creating a resin grid within the foam material. Since the resin is much stiffer than the foam, the presence of the grid will affect the local stiffness and load transfer of the core material. This in turn will change the stress distribution locally, and induce local stress concentrations in the interfaces between the different constituents. These stress concentrations may jeopardize the structural integrity of the composite sandwich structure and lead to failure. Due to the singularities occurring from the interconnections between the three different constituents, also referred to as “tri-material corners” [1], a conventional numerical 3D stress and strain analysis in terms of the Finite Element Method is not directly feasible. The main reason for this is the required computational time, when considering the required mesh density compared to the size of the structure of interest. Thus, an alternative analysis based on a homogenisation of the core properties, [2], is normally adopted. The homogenisation approach further becomes advantageous and necessary, when analysis in terms of shell elements is performed. This is explicitly the case for wind turbine blades.

1.1 Objectives

Based on the above, the objective is to investigate the stress and strain fields developed locally in-situ the grid-scored sandwich core with special focus on foam-to-resin and foam-to-face sheet interfaces, where failure initiation potentially can occur. The adopted methodology to analyse the grid-scored sandwich assembly is based on a parametric numerical study of a generic sandwich configuration, which includes parameters such as curvature, grid size, thicknesses for core and face sheets, and stiffness properties of the constituents. To obtain results applicable to the grid-scored sandwich structures in wind turbine blades, the loading conditions, geometry and constituents are adopted from a full scale combined experimental and numerical study of a composite wind turbine blade reported in [3].

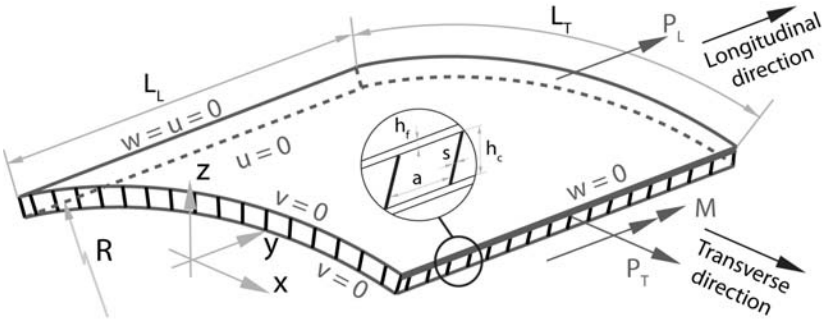


Figure 1. The loading conditions of the grid-scored sandwich structure

The determined loading conditions, shown in Fig. 1, consist of a dominating in-plane tension or compression force in the longitudinal direction of the blade, due to the global bending deformation mode, combined with a transverse compression or tension load generated from constrained contraction of the panel. Further, the global bending deformation causes different levels of ovalization due to the Brazier effect [4], depending on the blade design, which causes an out-of-plane bending moment in the transverse direction.

2 Framework of analysis

To analyse the grid-scored sandwich configuration, a special geometry has been developed. As shown in Fig. 2, this specimen model operates as a numerical global model, which is used to translate the applied panel loads into displacement boundary conditions for the local model, constituting the region of interest.

As explained earlier failure in the vicinity of the interfaces of the constituents is most likely to occur. Further, due to the design of the specimen, the bi-axial loading conditions gradually develop and have maximum values at the centre of the specimen. For this reason, the stress and strain fields are analysed in this region. The localised effects in sandwich beams with internal core junctions have been investigated extensively [5] and display some similarities with the localised effects induced in grid-scored sandwich panels. When a sandwich beam is subjected to in-plane tension an increase of the face bending stresses and the core shear and through thickness normal stresses occur.

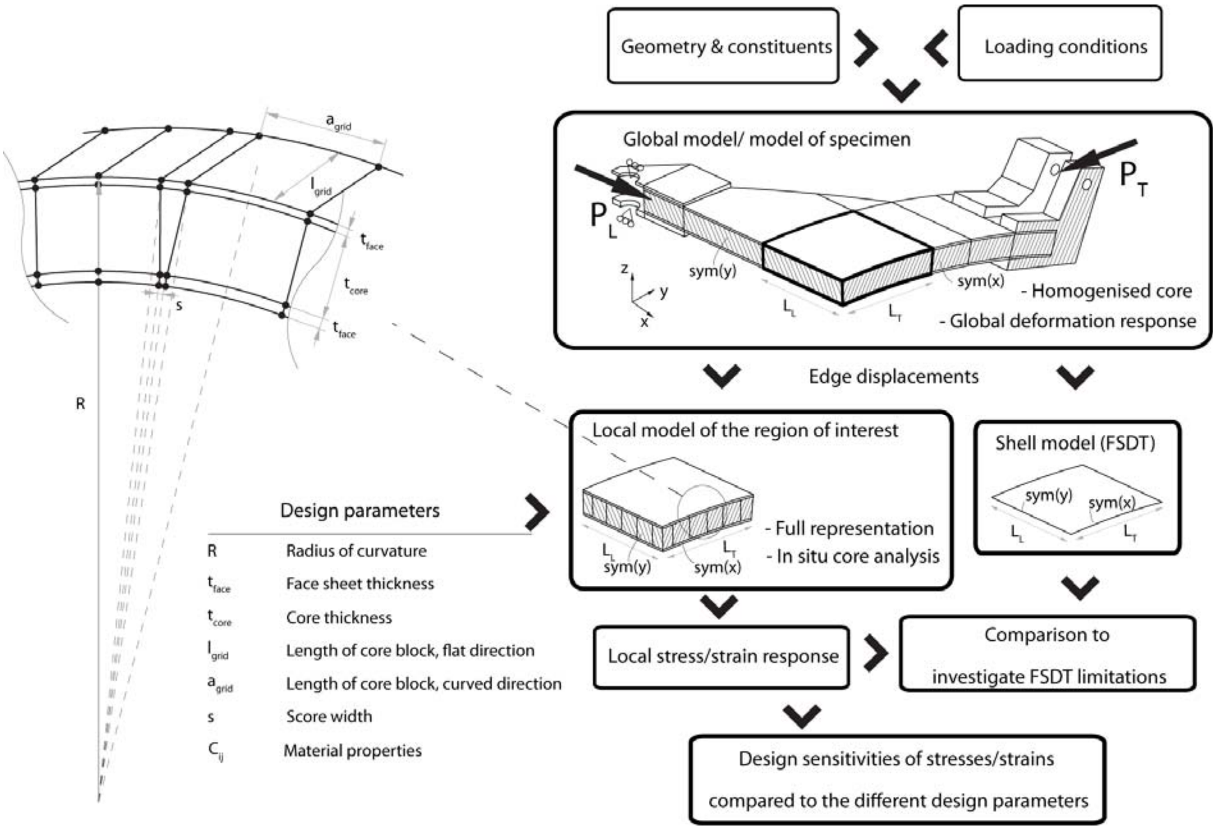


Figure 2. The framework of the analysis of the grid-scored sandwich structure

Equivalent observations have been made for grid-scored sandwich beams although these have been less pronounced, because of the localised stiffness change from resin to foam. Due to this, the stresses and strains at the interfaces between the constituents and in the face sheets are monitored. Further, to have a more general measure of the local load response the volumetric stresses and strains of the core and resin are monitored. The chosen points and volumes of interest are shown in Fig. 3.

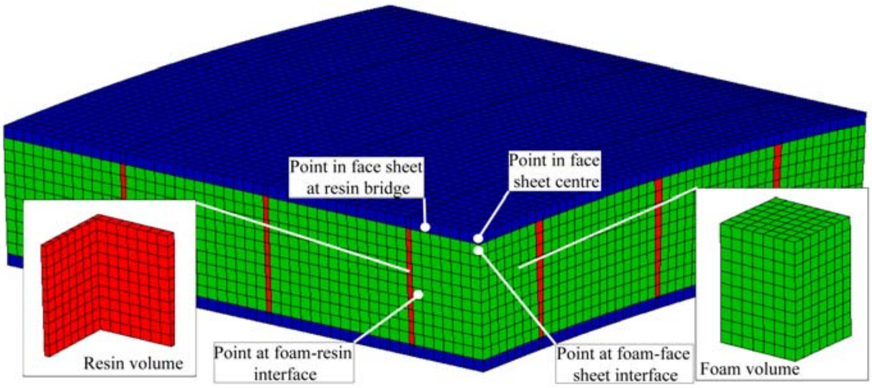


Figure 3. The chosen locations for investigating stresses and strain sensitivities

Six stress and six strain quantities are chosen for monitoring and compared in the following. As explained in [5], the prediction of failure initiation will be more accurate if material non-linear analyses are chosen, but due to the amount of analyses required and since this study mainly serves to clarify the required analysis efforts, to indicate possible failure phenomena, and to identify the governing design parameters, when analysis of grid-scored sandwich structures is considered, the following will be based only on linear analyses. The elastic properties used for the computations are shown in table 1.

Material	Elastic properties
GFRP	E_{11} = 24,800 MPa, E_{22} = 11,500 MPa, E_{33} = 11,500 MPa, G_{12} = 7,260 MPa, G_{23} = 4,861 MPa, G_{31} = 4,861 MPa, ν_{12}= 0.416, ν_{23}= 0.3, ν_{31}= 0.3
Resin	E = 3000 MPa, G = 1154 MPa, ν= 0.35
Foam (H60)	E_{11} = 32 MPa, E_{22} = 32 MPa, E_{33} = 70 MPa, G_{12} = 19 MPa, G_{23} = 19 MPa, G_{31} = 19 MPa, ν_{12}= 0.4, ν_{23}= 0.4, ν_{31}= 0.4

Table 1. The elastic properties of the three materials.

2.1 Sensitivity study

As indicated in Fig. 2 the setup allows for a parametric sensitivity study of the different design parameters, which defines the grid-scored sandwich structure. Due to the implicit relationship between the design variable and the chosen monitored stresses and strains, the derivatives are computed from a finite difference (FD) analysis. If a quantity, which defines the response of the structure, e.g. displacement, mass, stress, compliance etc. is calculated by a function of the design variables, $f(\vec{a})$, the forward FD approximation of the sensitivity $\partial f(\vec{a})/\partial a_i$ is derived from a first-order Taylor series expansion;

$$\frac{\partial f(\vec{a})}{\partial a_i} \approx \frac{f(a_1,\cdots,a_i+\Delta a_i,\cdots,a_n)-f(\vec{a})}{\Delta a_i} \tag{1}$$

Whenever a FD scheme is used to approximate derivatives, there are two sources of errors; truncation and condition errors. The truncation errors are a result of the neglected higher order terms in the Taylor series expansion. These errors can be reduced by using a smaller perturbation Δa_i. The condition errors are the difference between the numerical evaluation of the function and its exact value, which may be caused by e.g. computational round-off errors. The condition errors are typically very small, unless the perturbation Δa_i is small. Thus, if Δa_i is chosen too small the result may be an excessive condition error, therefore a suitable Δa_i must be chosen. In the current case a perturbation Δa_i equal to a_i /1000 is chosen.

3 Results

Basesed on the above outlined analysis approach, chosen geometry, material constituents, and loading conditions, a parametric stress/strain analysis of the grid-scored sandwich structure is enabled. As a reference the displacement field of the global and local model is shown in Fig. 4 together with the von Mises strain field of the local model, to give the reader an impression of the loading distribution.

From the strain field it is apparent that the resin bridges introduce a load redistribution in the sandwich core. Further, bending of the face sheet on top of the resin bridge is seen. As explained, the grid-scored sandwich structure can exist in many different configurations as indicated in Fig. 2. Thus, the shown strain distributions do not indicate, which design parameters have a significant influence on failure alone.

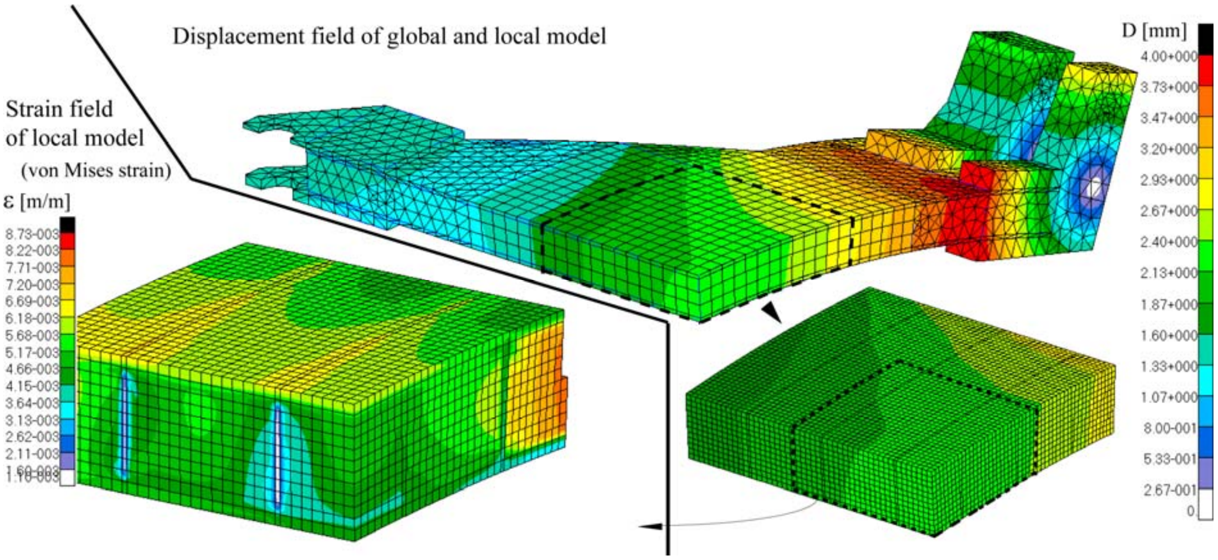


Figure 4. The displacement field of the specimen and local model, and the equivalent von Mises strain field of the local model

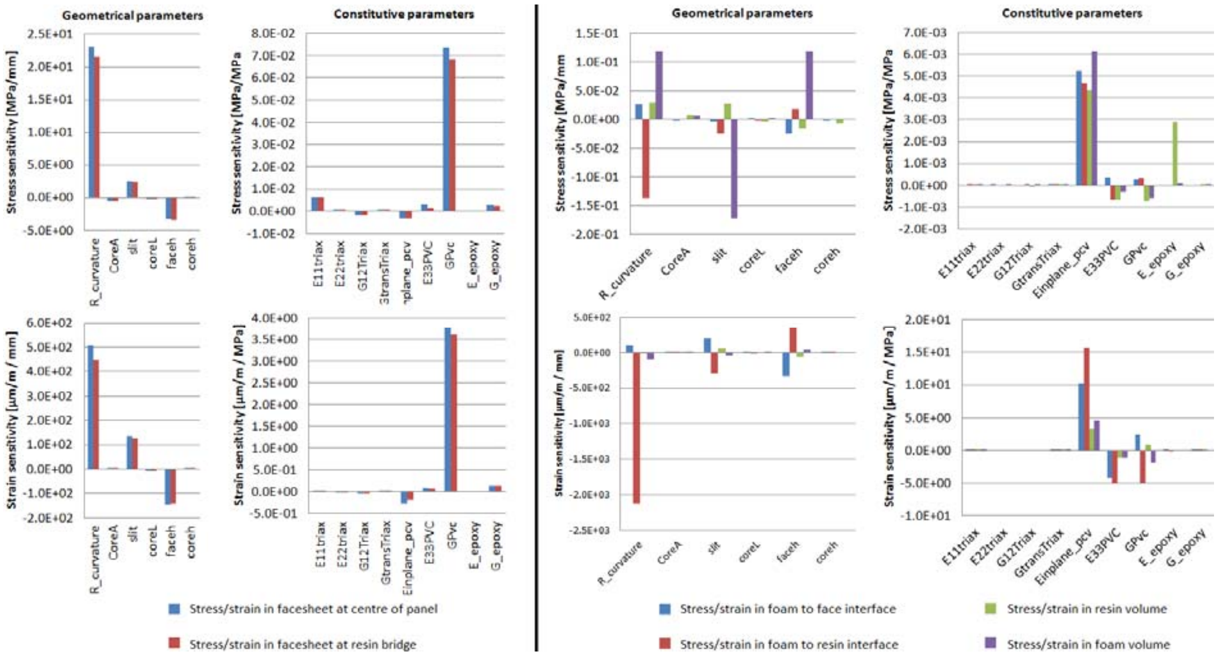


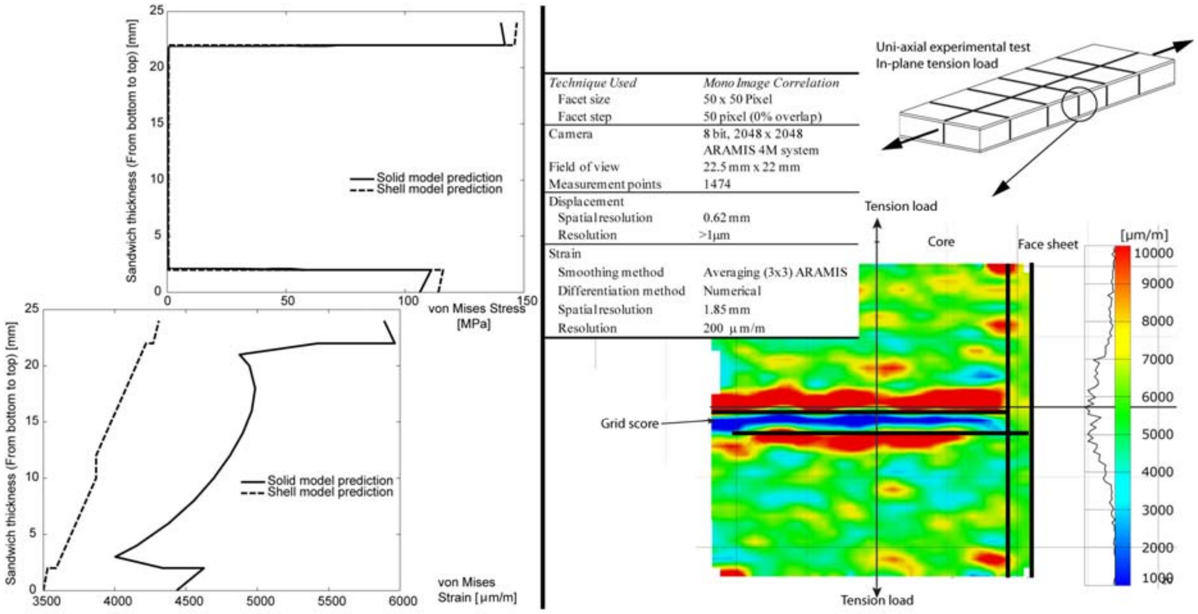
Figure 5. The stress and strain sensitivities compared to the different design parameters

In Fig. 5 the results of the sensitivity study is shown. Due to the fact that the geometrical and constitutive design variables are associated with different physical units of the sensitivities, the results have been separated into different plots. Furthermore, the sensitivities for the face sheets are shown separately due to their higher sensitivities compared to the foam and resin materials. Also the face sheet sensitivities are monitored only in terms of longitudinal stresses and strains, whereas the resin and foam materials are monitored in terms of the von Mises stresses and the equivalent von Mises strains. From the face stress and strain sensitivities it is seen that the radius of curvature of the panel, the slit width of the resin bridges, and the shear modulus of the foam have the highest influence on the longitudinal stresses and strains.

Although the three parameters potentially could cause increased localised bending of the face sheet on top of the resin bridge, the sensitivities indicate otherwise. As shown in Fig. 5, the sensitivities are almost of same magnitude, hence no increased difference between the stress and strain values at the two locations will occur. For the interfaces between the constituents it is seen that the foam to resin interface is very sensitive to the radius of curvature. Thus, the higher the curvature of the panel, the greater the stress difference between resin and foam. As shown in Fig. 6 the in-plane Young's modulus of the foam material has an impact on both interfaces. The reason for this is found from the stress sensitivity of the foam and resin volume. If the in-plane stiffness of the foam material is increased, the sandwich core will tend to be more homogenised, which will have the same influence on the loading distribution. In addition to the above, the slit width and the face sheet thickness are both found to have a significant impact on the localised stress and strain distribution, although these are not as apparent as the above mentioned effects.

3.1 Comparison with results from FSDT and experimental investigations

As explained in the introduction, wind turbine blades are normally modelled by shell elements, which in most commercial FE codes are based on First Order Shear Theory (FSDT). Thus it is interesting to compare FSDT results with the results obtained above, although a basic FE shell model will not be able to include the geometrical features of the grid-scored core.



Technique Used	*Mono Image Correlation*
Facet size	50 x 50 Pixel
Facet step	50 pixel (0% overlap)
Camera	8 bit, 2048 x 2048 ARAMIS 4M system
Field of view	22.5 mm x 22 mm
Measurement points	1474
Displacement	
Spatial resolution	0.62 mm
Resolution	>1μm
Strain	
Smoothing method	Averaging (3x3) ARAMIS
Differentiation method	Numerical
Spatial resolution	1.85 mm
Resolution	200 μm/m

Figure 6. Stress and strain distribution in the centre of the panel and experimental investigations of uni-axial experimental test in terms of Digital Image Correlation

In Fig. 6 the von Mises stress and equivalent von Mises strain predictions of the solid and shell models are shown. From this it is seen that the face sheet and face to core interface stresses are modelled quite accurately. For the internal strain distribution, significant discrepancies are identified, however. The main reason for this is the limitations of the FSDT, which first of all exhibit stiffer response due to the restrictions imposed with respect to transverse shear and through-thickness normal strains as well as the ability to exhibit only a linear through-thickness strain distribution. Furthermore, the localised load redistribution in the vicinity of the resin bridge, which cannot be modelled in the shell model, is also responsible for some of the deviations.

The localised redistribution of loads in-situ the sandwich core has been experimentally verified in terms of a uni-directional tension test. Fig. 6 shows the full field measurement made from Digital Image Correlation [6], where the von Mises strain distribution is shown on the edge of a sandwich beam. The main difference, as compared to the numerical results, shows from the very high foam strain values very close to the resin bridge. The reason for this difference is found to be the surface measurement, where a state of plane stress is present. The experimental results do however still confirm that the resin bridges cause interface strains between the resin and foam, which potentially can cause failure.

4 Discussion and conclusion

The detailed analysis of the grid-scored sandwich structure shows that a redistribution of the internal loads in the vicinity of the resin bridges occurs. Due to the many design parameters governing a specific configuration, a sensitivity study was conducted to identify the parameters that are most critical with respect to failure initiation. The sensitivity results indicate that the most significant stress raisers in the face sheets are the radius of curvature of the panel in the transverse direction and the shear modulus of the foam material. For the interface stresses, the sensitivity at the foam to resin interface stress concentration was found to be highest for the radius of curvature. Thus, the larger the curvature of the panel, the greater the stress difference between the resin and the foam. Further, the in-plane Young's modulus of the foam material was also found to influence the local stress states at both interfaces. Finally the slit width and the face sheet thickness were both found to have a significant influence on the localised stress and strain distributions. This numerical study serves to identify the potential failure modes occurring in grid-scored sandwich structures subjected to combined longitudinal tension/compression, transverse tension/compression and bending loading conditions. But a detailed investigation of the most critical design parameters, including the radius of curvature and the constitutive foam properties, in combination with the critical failure load levels, still needs to be investigated experimentally. However, the present study indicates that if failure initiation occurs due to the local load redistribution in-situ the core, the predictive capabilities of shell models are insufficient. This again means that sandwich panels subjected to potentially critical loads need to be modelled using more detailed 3-D FE models. However, if the design parameters are selected such that a more homogeneous load distribution is obtained, sufficient predictive capabilities might be obtained from the shell models.

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