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Analysing the strength of wrinkle defects in glass-epoxy laminates

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Summary. In this paper a new method for predicting the failure load for glass-epoxy laminated sandwich structures containing wrinkle defects is proposed. In previous work the pointwise evaluated, stress based NU criterion has been used to predict the occurrence of delamination in such defects. The NU criterion only provided information regarding delamination initiation in non-critical parts of the structure, and thus underpredicted the load carrying capability. In this work cohesive zone modelling is used in the finite element method together with a modified max stress criterion for failure prediction. This method provides a greater insight into the failure process.

Key words: composite structures, glass-epoxy, wrinkle defect, cohesive zone modelling, composite materials, fracture mechanics.

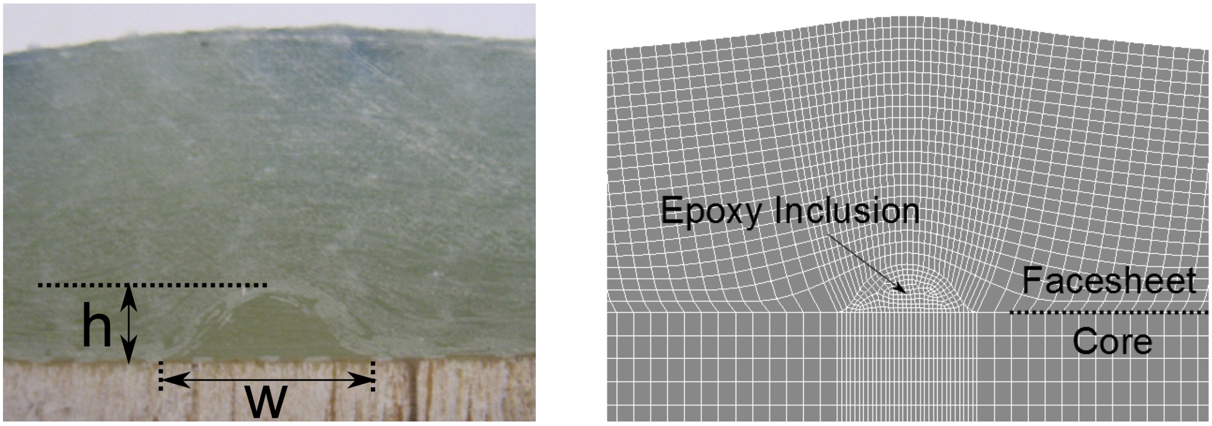
Introduction

This work is conducted at Aalborg University in collaboration with Siemens Wind Power A/S as a part of a master thesis [1]. Siemens Wind Power A/S is one of the leading manufacturers in the wind turbine industry. The blades for their turbines are manufactured as glass-epoxy laminated sandwich structures using balsa wood as core material. In the infusion process of large glass-epoxy composite structures, such as a wind turbine blades, several types of manufacturing defects can arise. One of these defects is an out-of-plane misalignment of the glass fibers, also termed a "wrinkle" defect. The occurrence of wrinkle defects presents a great expense in the production of the blades since they are, in most cases, repaired due to lack of reliable methods of estimating the reduction in load carrying capability [2].

The main failure mode of a glass-epoxy laminated structure containing a wrinkle defect is layerwise delamination in the defect. This has been found in previous work in which, besides a phenomenological study of the failure mode, the pointwise evaluated, stress based NU-criterion has been used for predicting the onset of this delamination [2]. In the present work Cohesive Zone Modeling (CZM) has been used in the framework of the Finite Element (FE) method. The use of CZM facilitates the simulation of the fracture process and can thus provide more information regarding the failure process than the NU-criterion.

Methodology

The study has been performed using an advanced parametrised FE model, created in the ANSYS Parametric Design Language (APDL). Material data, geometry and normalization of results has been chosen so that comparison to the experimental results obtained in [2] is possible. In Figure 1a one of the wrinkle defects, that has been examined in [2], is shown. These specimens will henceforth be referred to as the test specimens.



(a) (b)

Figure 1: (a) Photograph of test specimen with wrinkle defect used in [2]. (b) Illustration of the meshed model.

ANSYS 14.0, which has been used for the present work, features a basic 3D 8-node isoparametric CZM element called INTER205 [4]. This element does not have the required possibilities for this study, so a new implementation was created and used as a User Programmable Feature (UPF) [5]. The UPF was implemented as a 3D 8-node isoparametric interface element using a bilinear constitutive model, the Benzeggagh-Kenane mode interaction criterion [7] and a 1st order Newton-Cotes integration scheme. For details on the mentioned models and the element kinematics see [6]. The work carried out concerning the development, implementation and verification of the UPF is presented in [3].

The FE model was created with one quarter the width of the test specimens for the sake of reducing the solution time, and this was found not to have any significant influence on the results. The bulk material was meshed with the SOLID185, a 3D 8-node solid element, using the enhanced strain formulation [4]. In Figure 1b an example of the meshed model is shown. Note that the mesh presented in the figure is coarser than the one used for actual computation. Two types of interfaces were meshed with the UPF: The interface between the balsa core and the facesheet (C/F-interface), and between individual plies in the facesheet (P-interface).

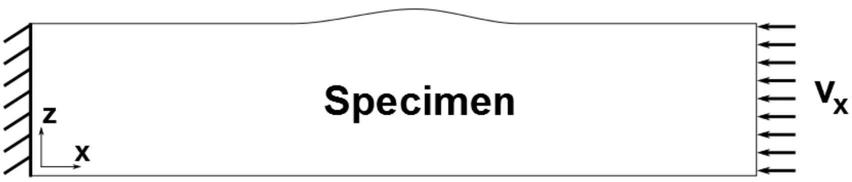
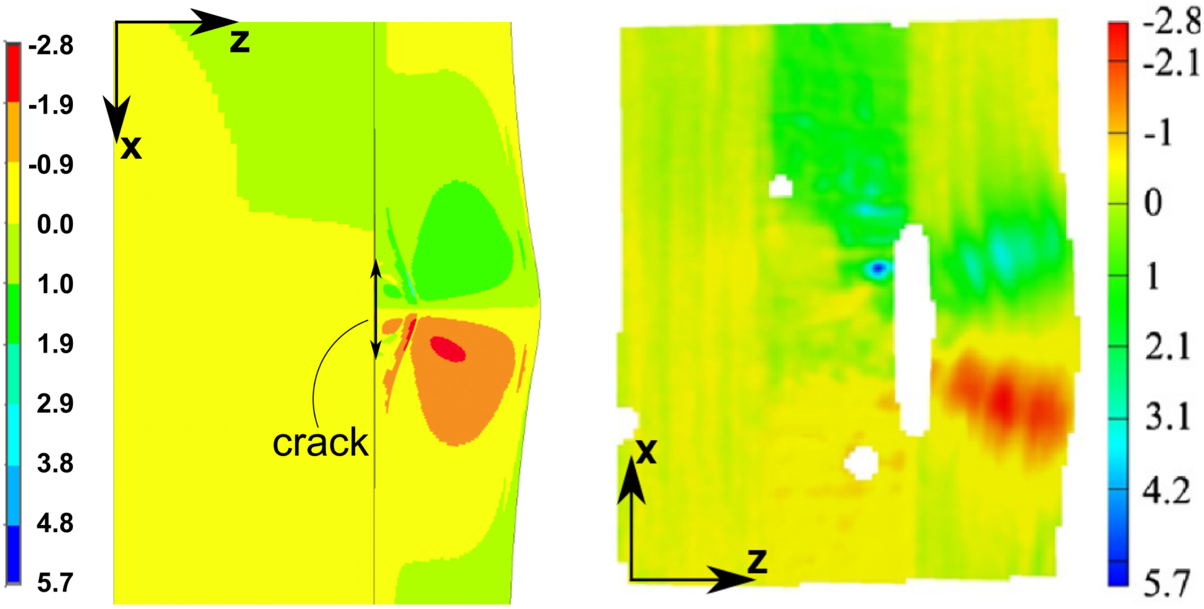


Figure 2: Boundary conditions for the model.

The model was clamped in one end and a displacement BC was imposed on the other as shown in Figure 2. The physical specimens were tested under load control. A displacement BC was chosen in order to avoid unstable behaviour when solving the nonlinear problem. By doing this the standard Newton-Raphson solver, which provided faster solving than e.g. the arc-length method, could be used.

Results

In the work of [2] it was found that at $70 - 90\%$ of the specimen failure load, a crack developed in the C/F-interface. This behaviour was reproduced in the FE simulation by manually fitting the fracture mechanical properties of the CZM constitutive model in this interface. The found properties indicated a very low interface strength which might be attributed to residual stresses in the resin inclusion. In Figures 3a and 3b the transverse shear strain field, γ_{xz}, as obtained from the FE model and DIC measurements respectively can be seen. Note that the strains are normalized w.r.t. the far field normal strain, ϵ_x, according to [2]. In these figures, CZM elements have only been used in the C/F-interface. It is seen that the strain fields match well, apart from a few localized peaks in the DIC measurements which can be attributed to measurement error/inaccuracy. It was found that the presence of a crack in the C/F-interface increased the normalised local strain concentrations in the slanted bands seen in Figure 3 compared to those seen in an uncracked model. Thus the capability of the model to show the crack development in the C/F-interface increases the predictive capabilities of the simulation.



(a) (b)

Figure 3: The normalised γ_{xz} field as obtained from (a) the FE model and (b) using DIC [2].

Complete failure of the specimens occurs when the P-interfaces delaminate. This behaviour was not possible to reproduce since the required onset tractions of the CZM constitutive model would require a model with an impractically fine mesh (>2M nodes as compared to the ~90k nodes of the present model). When using CZM in predicting crack propagation, the onset traction is less important than the energy release rate, and can thus in many applications be lowered without compromising the overall behaviour of the model [3]. However the failure process in the examined specimens is very sudden and delamination occurs in all the P-interfaces simultaneously [2]. This behaviour indicates that crack initiation and complete delamination occurs at the same load, and the result is that even the smallest crack in the P-interfaces will be unstable at this load. Therefore the correct onset of crack initiation is important in order to obtain good predictions from the model. The need for a high onset traction was also evident in that, with a reduced onset traction, a physically unreasonable compliance in the P-interfaces of the model was observed at loads much lower than the failure load.

It was found that the delamination in the P-interfaces is governed by the transverse shear stress. This was both indicated by the stress distribution in the model and by the fact, that CZM elements in the P-interfaces showed mode II crack development only. Since it was not possible to simulate the delamination in these interfaces with the proper onset traction, the Max Stress Criterion was used to predict the onset of crack initiation. For this purpose the transverse shear strength of the plies was replaced with the maximum transverse shear stress that was observed in the model at the failure load for one of the specimens. In this way, the model is specifically adjusted to exactly predict the failure load for the selected specimen.

Using the described method for failure load prediction, a parametric study has been carried out, where the height and width of the wrinkle defect (h and w respectively in Figure 1a) are varied independently. In Figure 4 the results from this study are compared to the experimental results from [2].

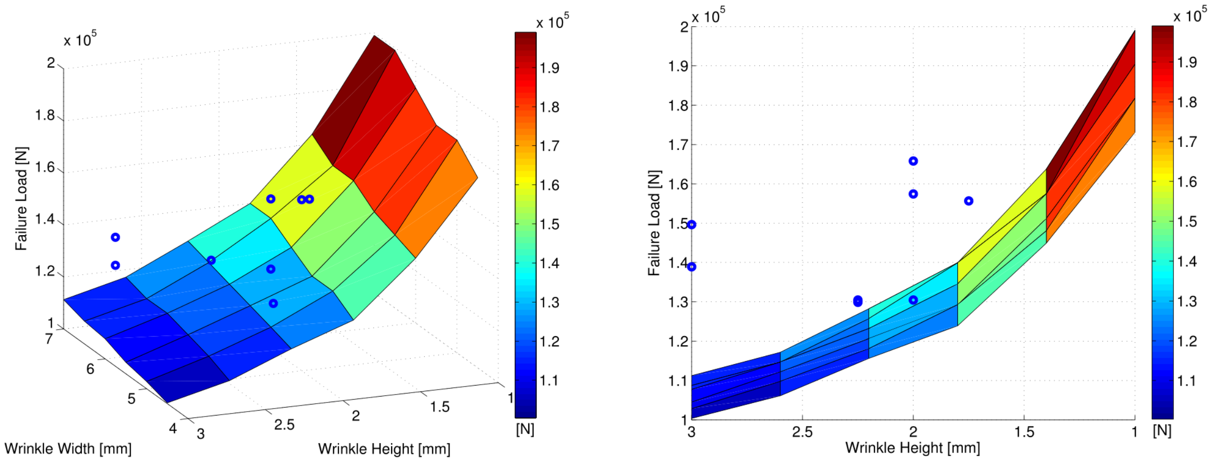


Figure 4: The predicted compressive failure load (surface) and experimental results (points).

From Figure 4 a tendency agreement is apparent although more experimental data would be required to properly verify this. For the chosen shear delamination strength the model provides conservative estimates. It should also be noted that increasing the wrinkle width or decreasing the wrinkle height increases the failure load of the specimen. This conforms well with the observation, that the transverse shear stress governs the failure process.

References

[1] E. T. Christensen, J. Glud and J. Sjølund. *Formulation of Cohesive Finite Element for Analysing Strength of Wrinkles in Glass-Epoxy Laminates.* Master Thesis, Department of Mechanical and Manufacturing Engineering, Aalborg University, Denmark, 2013.

[2] M. Leong. *The Influence of Defects on the Failure of Wind Turbine Blades.* Ph.D. Thesis, Department of Mechanical and Manufacturing Engineering, Aalborg University, Denmark, 2012. ISBN: 87-91464-44-7.

[3] J. Glud, E. T. Christensen, E. Lindgaard, and B. L. V. Bak. *Implementation of a State-of-the-art Cohesive Zone Element for ANSYS Mechanical.* Proceedings of the 26th Nordic Seminar on Computational Mechanics, Eds. A. Logg, K.A. Mardal, Oslo, Norway, October 23-25, 2013.

[4] ANSYS, Inc. *ANSYS Mechanical APDL Element Reference.* Release 14.0, 2011.

[5] ANSYS, Inc. *ANSYS Mechanical APDL Programmer's Manual.* Release 14.0, 2011.

[6] A. Turon, P. P. Camanho, J. Costa, and C. G. Dávila. *A Damage Model for the Simulation of Delamination in Advanced Composites under Variable-Mode Loading.* Mechanics of Materials, 38(11):1072-1089, 2006.

[7] M. L. Benzeggagh and M. Kenane. *Measurement of Mixed-Mode Delamination Fracture Toughness of Unidirectional Glass/Epoxy Composites with Mixed-Mode Bending Apparatus.* Composites Science and Technology, 49:439-449, 1996.