Analysis of model and data uncertainties for the failure of adhesive bonds in composite materials

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This study has been performed within the research project MuScaBlaDes “Multi-scale failure analysis with polymorphic uncertainties for optimal design of rotor blades” as part of the DFG Priority Programme (SPP 1886) “Polymorphic Uncertainty Modelling for the Numerical Design of Structures” started in 2016. Stress concentrations in adhesive bonds of a composite structure influence the structural integrity and can initiate the overall failure. Their numerical prediction always depends on present model and data uncertainties. For that, the development of an efficient numerical model and the role of the quality of data is presented. The assessment of the numerical models is shown by comparing predicted strains to measured ones.

1 Introduction

Rotor blades of wind turbines are thin-walled spatial structures typically consisting of two composite shells and one or two shear webs assembled with adhesive bonds. One of the typical failure mechanisms of rotor blades in operation are fatigue cracks caused by stress concentrations on included air voids or insufficient bonding. The definition of the Henkel beam [1] as representative sub-component as well as applied model reduction and multiscale modeling techniques lead to diverse model uncertainties. Additionally, the role of data uncertainties concerning included air voids has been investigated.

2 Numerical model of the Henkel beam

The Henkel beam with a length of \( l = 1500 \text{ mm} \) and a width of \( w = 80 \text{ mm} \) has a typical I-beam section composed by tapered flanges and a shear web assembled by adhesive bonds. The shear web is reinforced on both sides by a wood and a laminate plate near the loading and fixations, see Fig. 1. An asymmetric three point bending test is conducted by a vertical point load \( F \) on the right and two fixations on the left. The adhesive bonds are mainly loaded by the axial stress \( \sigma_x \) [1], which is also shown in Fig. 1 between the reinforcements (570 mm \( \leq x \leq 1320 \text{ mm} \)). Further details about the Henkel beam are given in [1].

![Fig. 1: left: Henkel beam, finite element model and axial stress \( \sigma_x \) in the upper adhesive bond between the reinforcements by applying a load of \( F = 10 \text{kN} \); right: reinforced cross-section and finite element model](image)

In [2], it has been observed that air voids and insufficient bonding significantly reduce the bearing capacity of the Henkel beam. As an extension to [3], the air voids are modeled as ellipsoids in this study. Each air void is defined in the following by nine parameters \( p_i = (m_{ix}, r_{ix}, \phi_{ix}) = (m_{iy}, r_{iy}, \phi_{iy}, r_{iz}, \phi_{iz}) \) for location, size and orientation.

The air void parameters \( p_i \) are a-priori unknown and here modeled as random variables. Since the Henkel beam model is computationally expensive, it is suitable to use model reduction and multiscale modeling techniques. First of all, the upper adhesive bond is extracted from the Henkel beam model by applying the Guyan reduction on the remaining structure [6]. In the case that the air voids might be embedded within non-intersecting simpler geometries, here chosen as cuboids aligned with the ellipsoids, the uncertainties can be localized. A domain decomposition technique based on Schwarz alternating method [7] is

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consequently applied. In particular a supermodel without air voids exchanges information with \( n \) decoupled submodels. Each of the latter only has dependence on the size parameters \( r_i \), the submodel size factor \( \delta_i \) and the Dirichlet boundary conditions on the boundary of the cuboid \( \Gamma_1^n \). \( \Gamma_1^n \) is approximated by a polynomial \( II = \Pi(q_{i,j}) \) of total degree 3 with coefficients \( q_{i,j} := (q_{l,k})_{kl}, k + l \leq 3 \) on each of the six faces \( \mathcal{F}_j, j = 1, \ldots, 6 \). This ansatz introduces a non-linear mapping

\[
p_{i,\text{in}}^j := \left( r_i, \delta_i, \left( q_{l,k}^j \right)_{l,k} \right) \rightarrow \left( \sigma_{1,\text{max}}, \left( q_{l,k}^j \right)_{l,k} \right) =: p_{i,\text{out}}^j, \quad i = 1, \ldots, n, \tag{1}
\]

including the parametric Dirichlet-to-Dirichlet response and the maximum first principal stress \( \sigma_{1,\text{max}} \). To speed up computation these mappings are replaced by a single deep artificial neural network based surrogate response using ideas from [5].

### 3 Experimental validation

In [3], a Henkel beam with \( n = 4 \) relatively large imperfections in the upper adhesive bond has been investigated experimentally. The axial strain \( \epsilon_x \) resulting from a static vertical load of \( F = 17.5 \, \text{kN} \) has been measured by fiber-optical sensors, see black line in Fig. 2 (left). In order to illustrate the role of data uncertainties concerning the numerical prediction of strains and stresses in the adhesive bond due to air voids, the following cases have been investigated by \( 10^4 \) simulations with uniform distributed stochastic variables:

- **case 1**: \( n = 0 \): no air voids
- **case 2**: \( n = 4 \): \( r_{i,x,y,z} \geq 2.5 \, \text{mm} \) \( \forall i = \{1, \ldots, 4\} \) between the reinforcements (570 mm \( \leq x \leq 1320 \, \text{mm} \))
- **case 3**: \( n = 4 \): \( r_{i,x,y,z} \geq 2.5 \, \text{mm} \) \( \forall i = \{1, \ldots, 4\} \) in the region of interest (690 mm \( \leq x \leq 890 \, \text{mm} \))
- **case 4**: \( n = 4 \): midpoints and radii are modeled by uniform distributions \( \sim \mathcal{U}(a, b) \) with \( b - a \in [1, 2] \, \text{mm} \) based on computertomographic scanning [4]. The orientations are set to \( \phi_{4,x} = \phi_{4,y} = \phi_{4,z} = 0^\circ \) for simplification.

![Fig. 2](image-url)

*Fig. 2:* left: Axial strain \( \epsilon_x \) (min-max-range, 5%-95%-range and mean values) in the upper adhesive bond between the reinforcements; right: Scaled histogram and mean value of maximum first principal stress \( \sigma_{1,\text{max}} \) in the upper adhesive bond between the reinforcements

Case 1 cannot depict higher axial strains \( \epsilon_x \) and leads to the smallest value for \( \sigma_{1,\text{max}} \). Present air voids lead to higher values for \( \sigma_{1,\text{max}} \), see Fig. 2 (right), with an increasing standard deviation caused by more knowledge about the uncertain parameters \( p_i \). Reducing the data uncertainty obviously reduces the scattering of \( \sigma_{1,\text{max}} \) and consequently improves the numerical prediction. Comparing the axial strains \( \epsilon_x \) with the experimental data in Fig. 2 (left), it is remarkable that the SSE (sum of squared estimate of errors) for the mean values of case 2 and 3 is similar to the SSE for case 1. The measured strains can only be retraced in case 4 using more detailed information about the air voids. It is noted that the data and the model itself should be of same quality. Nevertheless, deviations are still present resulting from measurement errors, model errors and model simplifications.

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