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Optimal design and testing of laminated light-weight composite structures with local reinforcements considering strength constraints Part II: Testing

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ABSTRACT

The present paper explains details of the measurement methods applied in the testing of strength-optimized locally reinforced laminates whose design has been explained in Part I. The measurement methods are an optical surface method, based on Digital Image Correlation (DIC), and measurements of Acoustic Emission (AE) which can originate from anywhere within the test specimen. Both methods are intended to identify early damage events or accumulation and the corresponding loads are compared to predicted first-ply-failure loads. The DIC method identifies non-linearities in the displacement path which infer that damage events have occurred. The AE method utilizes the signal energy rate per time to identify damage events. The results of the particular specimens show no correlation between the two measurement methods. The averaged values for the different type specimens show a significant dependency.

1. Introduction

The material properties of unidirectional fiber reinforced plastics are highly anisotropic. The strength values in fiber direction are one to two orders of magnitude higher than values perpendicular to the fibers which are mainly governed by the matrix properties. Unidirectional layers are typically used to build multi-directional laminates and the fracture behavior as well as the associated analysis become complex. The generally accepted failure criteria of Tsai–Hill [1,2] or Tsai–Wu [3,4] predict first-ply-failure (FPF) without taking the fracture modes into account.

Their reliability is rather low due to its weak physical fundamentals. However, it has been employed for the design method presented in Part I due to its closed-form, quadratic expression which provides the possibility of calculating the required sensitivities.

More sophisticated criteria do not only indicate a damage event but they distinguish also between fiber and matrix cracking, e.g. Hashin [5], Puck and Schürmann [6] or Cuntze and Freund [7]. They are based on physical models, but their application is more expensive since the failure indices for the several fracture modes have to be evaluated and distinguished. Extensive comparative studies of failure criteria, both theoretical and experimental, are given in the textbook of Hinton et al. [8].

In case of multi-directional laminates, first damage is usually caused by matrix cracking. The material properties of regions in which sub-critical matrix damages occur are degraded with growing damage. The structural behavior between first matrix damages and ultimate failure is consequently highly non-linear. A few approaches try to model such a behavior by iteratively degrading the matrix properties of areas in which matrix cracking is predicted, e.g. Gotsis et al. [9], Liu and Tsai [4], Puck and Schürmann [6], Cuntze and Freund [7] or Bogetti et al. [10]. Such procedures, also called progressive failure analyses, are strongly dependent on the choice of the degradation factor. The load-carrying capacity until the laminate fails ultimately is usually significantly higher than the first-ply-failure load.

Sub-critical matrix damage happens on a microscopic scale wherefore its experimental detection is not trivial at all.

Lomov et al. [11,12] try to identify first matrix damage by means of visual methods, namely Digital Image Correlation. A detailed explanation of this measurement method is given in [13,14]. A review of research work using DIC for displacement and strain measurements is given by Pan et al. [15]. Here, cracks are not detected explicitly, but they cause a non-linearity in the strain curve which is used to conclude that they occur. A more

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common method for the detection of FPF in fiber reinforced laminates is Acoustic Emission (AE) measurement which is sensitive to microscopic damage mechanisms in materials. Kam and Lai [16] investigated FPF for several lay-ups of CFRP epoxy plates using center point and uniform loads and determined FPF from energy–load diagrams (either energy rate or cumulative energy versus load). Pahr and Rammerstorfer [17] investigated damage from tensile tests on woven CFRP specimens and used cumulative AE events or AE signal amplitude plotted versus time to determine FPF. Sihn et al. et al. [18] also used tensile loading on quasi-isotropic CFRP laminates made from specially prepared thin-plies, either unmodified or with open holes. The number of AE counts was recorded as a function of tensile load but the observed increase in AE activity (number of AE signals per unit time) was not used for a quantitative determination of FPF. Chang and Chiang [19] again used AE signal energy rate for a determination of FPF in simply supported, center loaded laminated GFRP plates. FPF was determined by the first detected major energy rise. Daggumati et al. [20] again used AE signal energy plotted versus quasi-static tensile load in a weave reinforced CFRP composite for the determination of FPF. Alternatively, matrix cracking can be detected by measuring the electric resistance change which has been done by Schulte and Baron [21], Kaddour et al. [22], Seo and Lee [23] and Todoroki et al. [24].

The application of local laminate reinforcements for strength increase is only efficient if the stress distribution is inhomogeneous or if stress concentrations occur. A common test configuration with inhomogeneous stress field that is also investigated here is the open-hole tension specimen which is used to determine the so called notched strength. An overview of the early work on the notched strength of composites is given by Awerbuch and Madhukar [25]. Whitney and Nuismer [26] present two criteria to determine the stress concentrations of notched plates made of laminated composites, also known as point-stress and average-stress criteria, which have been further developed by Pipes et al. [27]. An alternative analytical approach with experimental validation is presented by Eriksson and Aronsson [28] called the Damage Zone Criterion. The criteria above assume a two-dimensional stress state. However, the stress state near a hole in a laminate is three-dimensional. Hu et al. [29] analyze the interlaminar stresses taking advantage of a 3D finite element model and de Morais [30] models the stress distribution near the hole of quasi-istropic laminates with 3D finite elements. Experimental investigations on the effect of scaling on the tensile strength of notched composites by varying hole diameter, ply- and laminate thickness have been carried out by Green et al. [31] and Wisnom et al. [32].

This publication presents the experimental determination of the first-ply-failure load of laminated carbon fiber reinforced specimens with a centered hole using two different measurement methods, namely Digital Image Correlation and Acoustic Emission measurements. Four different types of specimens, two having local reinforcements obtained with the design process presented in Part I, are tested. The results obtained with the two measurement methods are compared and discussed

1.1. Specimens

The notched plate has been optimized regarding strength by generating local reinforcements. The applied method and the corresponding results are presented in Part I. Goal of the optimization is to double the first ply failure (FPF) load according to the Tsai–Hill criterion. Specimens have been manufactured using the sequential curing process also presented in Part I. They are made of an unidirectional CFRP-laminate (see Table A.4) with a basic layup of $(0/45/-45)_S$. For this configuration, only in-plane loads and no bending occur. The classical laminate theory homogenizes the material properties through the thickness and the membrane stiffness becomes invariant in terms of stacking position. Therefore, the stacking of the reinforcement layers can be chosen arbitrarily without disregarding the simulation. Based on that, four different types of specimens have been manufactured. Type A is the reference configuration made of the basic laminate $(0/+45/-45)_S$ with no reinforcements. It is used to quantify the strength increase due to the reinforcements. Also type B, which consist of the double basic laminate $(0/+45/-45)_{2S}$, is used as a reference. It is expected to have twice the tensile strength of type A. However, not only strength but also its mass is doubled. Type B will help to identify strength reduction due to local stress concentrations caused by the reinforcements. Types C and D are specimens having local reinforcements. Fig. 1 schematically shows the different stacking schemes of specimen types C and D where the dark layers represent the reinforcements. For both, the reinforcement layer shapes are identical corresponding to the simulation results obtained in Part I. However, for type C the reinforcements are attached externally using the sequential curing process. For type D, the reinforcements have been placed between the 45°- and the 0°-layer. Analogously to the reinforcements, the 0°-layer has been attached after the first curing cycle. Initially, the reinforcements for type C were expected to peel away due to interlaminar stresses. The risk of interlaminar failure could be eased using the specimens of type D. However, for none of the C-specimens, failure at the interfaces between basic and reinforcement laminate could be noticed. The number of manufactured specimens is 5 each for types A and B and 10 each for types C and D.

2. Experiments

2.1. Experimental setup

According to the simulation, the reinforcements have been generated to double the FPF-load. Excepting unidirectional laminates, FPF is usually caused by matrix cracking. For the validation here, an experimental method for identification of matrix cracking is needed. However, there exists no standardized method for it. Here, two complementary measurement techniques have been applied. Digital Image Correlation (DIC) has been used as visual and surface method and Acoustic Emission (AE) measurements as acoustic and volumetric method. The application of two techniques based on different physical principles is expected to give a more complete picture of evolving damage. The specimens have been loaded at constant cross-head speed in a uniaxial tensile machine until ultimate failure. The test set-up with the camera for DIC and the sensors for the AE-measurements is illustrated in Fig. 2.

2.2. Digital Image Correlation

Digital Image Correlation (DIC) is an optical method to measure deformation or strain on the surface of an object. It is widely used in science and engineering due to its simplicity in application. The DIC is used to compare digital images taken at different times and loads, respectively, and to determine the changes of deformation between them. The out-of-plane deformation of the considered specimens is insignificant, wherefore a 2D-DIC, which only requires a single camera, is feasible. However, there exist also

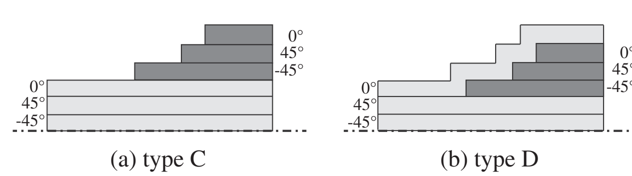

Fig. 1. Symmetric half of the locally reinforced specimen types.