Composite Structures 133 (2015) 707–718

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

A model for brittle failure in adhesive lap joints of arbitrary joint configuration

N. Stein *, P. Weißgraeber, W. Becker

Fachgebiet Strukturmechanik, Technische Universität Darmstadt, Franziska-Braun-Straße 7, D-64287 Darmstadt, Germany

ARTICLE INFO

Article history:
Available online 23 July 2015

Keywords:
Adhesive joints
Joint design
Failure load prediction
Finite Fracture Mechanics
Weak interfaces

ABSTRACT

In this work an efficient general Finite Fracture Mechanics model for crack initiation in adhesively bonded joints is presented which is applicable to various joint configurations with shear flexible laminate and metallic adherends. The mechanical behaviour of the adhesive joints is modeled by a general sandwich-type model for the analysis of bonded joints with composite adherends which gives solutions for the peel and shear stresses in the adhesive. The failure behaviour is described by a physically sound combined stress and energy criterion which requires only two basic failure parameters: the strength and the fracture toughness of the adhesive. The implicit equations are solved with a highly efficient iterative solution scheme. In a comprehensive study, experimental and numerical results of an elaborated Cohesive Zone Model (CZM) are used for comparison. It is shown that the predicted failure loads are in good to very good agreement with the experimentally determined results and the effects of the geometric parameters on the failure load are rendered correctly.

1. Introduction

For the widespread use of adhesive joints a solid understanding of the failure process as well as a precise prediction of the failure load are vital in order to increase confidence in the design of bonded structures. It is necessary to develop models that allow a quick and efficient evaluation of the failure load which is of particular importance for pre-dimensioning and optimization processes.

Most of the current failure models for adhesive joints are very limited in terms of applicability: many of them only address the prediction of failure loads of single and double lap joints under tensile loading while other approaches only cover the failure analysis of peel joints. In real structures various adhesive joint configurations are present under complex loading as demonstrated in Fig. 1 for a wind turbine blade. Moreover, many of the proposed failure models in literature still lack to explain some important effects of the involved geometric parameters on the failure behaviour, as e.g. the adhesive bondline effect [2].

Despite the geometric simplicity of common joint designs the mechanical behaviour and failure mechanisms of adhesive joints are very complex. Stress concentrations with singularities occur at the bi-material junctions between adherend and adhesive. These singularities typically exhibit a lower singularity order than the classical crack tip singularity which characterizes them as weak stress singularities. The singularity order at the bi-material points generally depends on the stiffness ratio and the enclosed notch angle between the corresponding materials [3]. Here, classical strength of material approaches fail because of the singular nature of the stress field. Linear Elastic Fracture Mechanics (LEFM) concepts fail as well since the energy release rate vanishes at the occurring singularities. Damage mechanics concepts such as numerical implementations of CZMs can be used for the strength prediction of adhesive joints and allow for the analysis of various joint designs. However, the corresponding simulations are non-linear, require high computational effort and problems can arise in the determination of the involved parameters [4–6].

In former works the coupled stress and energy criterion by Leguillon [7] settled in the framework of Finite Fracture Mechanics has proven advantageous for the prediction of crack initiation in various structural situations exhibiting stress concentrations and singularities as e.g. crack onset at U-notches or V-notches in isotropic materials [7–9], in plates with open holes [10–12], in bolted joints [13] or thermal crack patterns [14]. Crack initiation in bonded joints has also been addressed by numerical approaches using linear [15,16] or non-linear Finite Element Analyses [17,18] as well as analytical models [19–21]. However, these approaches are joint specific and the numerical implementations are expensive.

* Corresponding author.
E-mail address: stein@fsm.tu-darmstadt.de (N. Stein).

http://dx.doi.org/10.1016/j.compstruct.2015.07.100

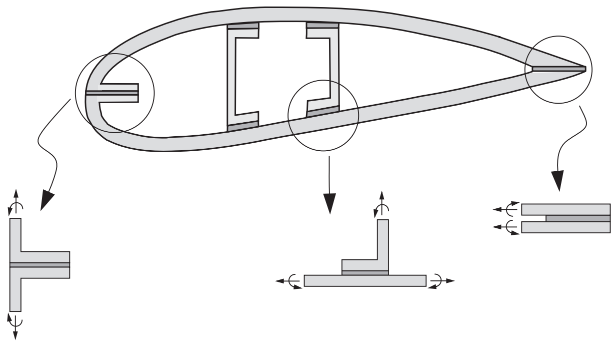

Fig. 1. Simplifications of adhesive joints in a wind turbine blade, cf. [1].

In the present work, a general Finite Fracture Mechanics model is presented which allows for a quick evaluation of the failure load of various adhesive joint configurations, e.g. single lap joints, double lap joints, L-joint, T-joint or inclined T-joint, see Fig. 2. A general sandwich-type model proposed by the authors in [22] is used for the underlying stress analysis and an efficient iterative solution scheme is implemented for the solution of the governing equations.

After a brief introduction to the theoretical setting of the coupled stress and energy criterion in Section 2 and the modeling of the adhesive joints in Section 3, the solution procedure of the corresponding optimization problem is outlined in Section 4. In Section 5 the numerical implementation of the CZM approach and the investigated joint designs are presented. Results of the present failure model are given in Section 6 and compared to the failure load predictions of the CZM approach and to experimental results found in literature. A final discussion is given in Section 7.

2. Failure model

In contrast to Linear Elastic Fracture Mechanics (LEFM), Finite Fracture Mechanics (FFM) [23] allows for the analysis of crack initiation at weak stress singularities. In FFM the assumption of infinitesimal crack lengths is dropped and a spontaneous formation of cracks of finite size is considered. The differential energy release rate is replaced by the incremental energy release rate

$$\bar{\mathcal{G}} = -\frac{\Delta\Pi}{\Delta A}, \tag{1}$$

where $\Delta\Pi$ and ΔA are the finite change of the total energy potential and the finite crack area, respectively. In the two-dimensional case, crack growth is considered over the whole depth b of the structure, so that the finite crack area ΔA is determined by the crack length Δa multiplied by b.

In this framework Leguillon [7] proposed to consider a strength criterion in addition to an energy criterion for the determination of the unknown failure load P_f and the corresponding finite crack size Δa. The instantaneous formation of cracks is predicted if these two criteria are fulfilled simultaneously. As brittle material behaviour is considered the maximum principal stress criterion is used. The stress criterion is evaluated in a point-wise manner as proposed by Leguillon [7] which is often referred to as Point Method [24]. The energetic condition embedded in the coupled criterion is given by a linear interaction law of the incremental energy release rates in pure modes $\bar{\mathcal{G}}_I, \bar{\mathcal{G}}_{II}$ with respect to the corresponding fracture toughnesses $\mathcal{G}_{Ic}, \mathcal{G}_{IIc}$ [25–27]. Further, it is assumed that the fracture toughness in mode II equals two times the fracture toughness in mode I ($\mathcal{G}_{IIc} = 2\mathcal{G}_{Ic}$) which is a common simplifying assumption [28–30]. In the case of monotonically decaying stresses in the close vicinity of the singularity and monotonically increasing incremental energy release rates the coupled criterion can finally be written as

$$\sigma_I(\Delta a) = \sigma_c \;\wedge\; \frac{\bar{\mathcal{G}}_I(\Delta a)}{\mathcal{G}_{Ic}} + \frac{\bar{\mathcal{G}}_{II}(\Delta a)}{2\mathcal{G}_{Ic}} = 1 \tag{2}$$

where $\sigma_I(\Delta a)$ and σ_c denote the maximum principal stress at the distance Δa from the singularity and the tensile strength, respectively. The failure load P_f can be defined as the smallest load which satisfies both conditions under the consideration of all kinematically admissible cracks. In the general case of non-linear dependence of the incremental energy release rates and the stresses on the applied load the following underlying restrained optimization problem has to be solved to determine the failure load

$$\begin{aligned} P_f &= \min_{P,\Delta a} \quad P \\ \text{subject to} \quad & \sigma_I(P,\Delta a) = \sigma_c, \\ & \frac{\bar{\mathcal{G}}_I(P,\Delta a)}{\mathcal{G}_{Ic}} + \frac{\bar{\mathcal{G}}_{II}(P,\Delta a)}{2\mathcal{G}_{Ic}} = 1. \end{aligned} \tag{3}$$

In recent works [11,12] some authors decouple the equations in their FFM framework by combining the energy criterion and the square root of the stress criterion to obtain an implicit non-linear equation for the finite crack length. Unfortunately, this is not possible in the present case since the incremental energy release rate is obtained by numerical integration and geometric non-linearity is considered for some joint configurations. However, the optimization problem can be efficiently solved by an iterative solution scheme which is presented in detail in Section 4.1. Only the strength and the fracture toughness in mode I of the adhesive are required as fundamental failure parameters for the whole model.

3. Modeling of adhesive joints

3.1. Linear elastic analysis for adhesive joints

So far, the stress analysis of adhesive joints has been intensively investigated by many researchers. The earliest closed-form

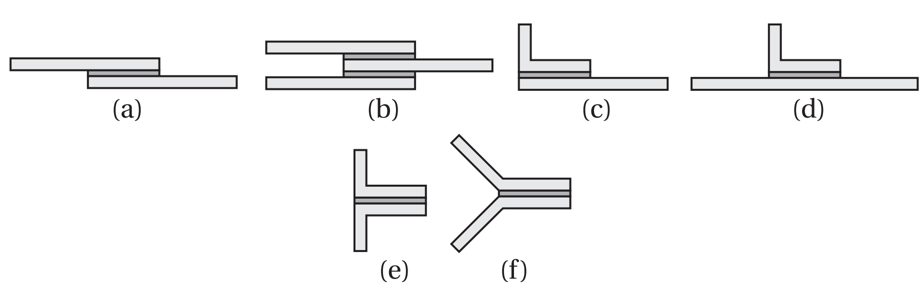

Fig. 2. Examples of commonly used adhesive joint configurations that can be analysed with the present model. ((a) single lap joint, (b) double lap joint, (c and d) L-joint, (e) T-joint, (f) inclined T-joint).