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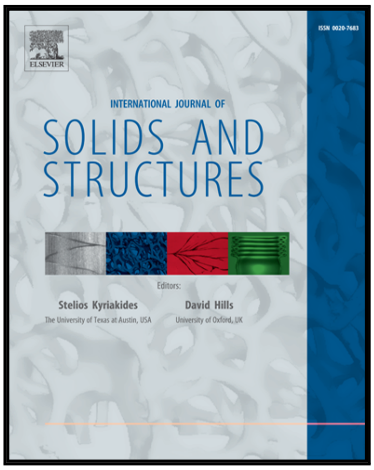

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P.L. Rosendahl, P. Weißgraeber, N. Stein, W. Becker

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Asymmetric crack onset at open-holes under tensile and in-plane bending loading

P. L. Rosendahl[a,*], P. Weißgraeber[b], N. Stein[a], W. Becker[a]

[a]Technische Universität Darmstadt, Fachgebiet Strukturmechanik, Franziska-Braun-Str. 7, 64287 Darmstadt, Germany
[b]Robert Bosch GmbH, Corporate Research and Advance Engineering, Renningen, Germany

Abstract

Plates notched with open-holes that are subject to combined tensile and in-plane bending loading are studied in this analysis of crack onset. A finite fracture mechanics approach is employed to study the onset of asymmetric crack patterns in the notched structure. The stress field and the energy release rates required to solve the coupled stress and energy criterion are obtained from linear elastic finite element analyses. Closed-form expressions for the dependence of the solution on governing parameters as e.g. the structural size, the Young's modulus or the ratio of bending to normal loading are given significantly reducing the computational effort required for the failure model. A comparison to experimental results and to numerical analyses using a cohesive zone model highlights the model's ability to render brittle failure of the notched structure and to provide reliable failure load estimates. The results reveal that a certain threshold of the hole diameter exists, below which the hole does not affect the failure load. The threshold and the corresponding bearable loads are discussed using explicit solutions.

Keywords: Crack nucleation, Finite fracture mechanics, Asymmetric crack pattern, Open-hole bending, Brittleness number

1. Introduction

Stress raisers such as flaws, open-holes or notches are ever present in engineering structures and can significantly facilitate structural failure. The emanation of cracks from stress concentration typically leads to the premature failure of the structure. The assessment of crack or damage onset at stress concentrations requires detailed understanding. Classical approaches such as stress-based criteria as well as fracture mechanics can only be applied using an additional length parameter. Neuber (1936) and Peterson (1938) and later Whitney and Nuismer (1974) developed concepts which evaluate stress-based criteria at a particular distance from the stress concentration. Waddoups et al. (1971) applied classical fracture mechanics under the assumption of a finite sized pre-existing crack. More recently, Taylor (2007) unified these similar non-local approaches under the common name theory of critical distances (TCD). A mutual shortcoming of all these theories is that the length parameter involved lacks a definite physical meaning as the works of Awerbuch and Madhukar (1985), Pipes et al. (1979) and Tan (1987) find a dependency of the critical distance on feature properties such as geometry. The necessity of including a length scale which is not a material constant in the analysis is avoided using a coupled stress and energy criterion, originally introduced by Leguillon (2002). In the framework of finite fracture mechanics (FFM), it is assumed that cracks of finite size initiate instantaneously, if a stress-based and an energy based criterion are satisfied simultaneously. Therefore the length parameter has a clear physical meaning, the finite crack increment. The coupled criterion enables assessment of crack onset at stress concentrations requiring only two fundamental material parameters, the strength and the toughness. Further, it allows for the analysis of arbitrary crack initiation patterns of cracks of finite size.

Many researchers have successfully applied the coupled criterion to a wide range of structural situations such as delamination in laminates due to free-edge effects (Hebel et al., 2010; Martin et al., 2010), adhesive joints (Weißgraeber and Becker, 2013; Hell et al., 2014; Stein et al., 2015; Carrère et al., 2015), bolted joints (Catalanotti and Camanho, 2013), thermal crack patterns (Leguillon, 2013; Leguillon et al., 2014) and crack onset at V-notches (Leguillon, 2002; Carpinteri et al., 2008; Sapora et al., 2013) as well as U-notches (Hebel and Becker, 2008; Andersons et al., 2010; Carpinteri et al., 2012; Cicero et al., 2012). Additionally, the coupled criterion has proven successful for the analysis of crack onset in open-hole composite plates under uniaxial tension and compression (Camanho et al., 2012; Martin et al., 2012; Erçin et al., 2013; Romani et al., 2015) and in plates with elliptical holes (Weißgraeber et al., 2015). A comprehensive overview of applications of the coupled criterion can be found in Weißgraeber et al. (2016).

The flexural strength of open-hole structures is a topic of continuous research in wood science. Several authors engaged the task of assessing the failure of open-hole beams, typically subject to lateral force loading (Williams et al., 2000; Falk et al., 2003; Aicher et al., 2007; Smith et al., 2007; Hijikata et al., 2010).

The objective of the present work is to provide an efficient numerical modeling approach of the coupled criterion for the assessment of failure in open-hole plates under combined tensile and in-plane bending loading. Associated to the combined loading asymmetric crack patterns are expected to occur. Although for open-hole plates embedded in real structures combined ten-

*Corresponding author. Tel.: +49 6151 16-26147, Fax: +49 6151 16-26142
Email address: rosendahl@fsm.tu-darmstadt.de (P. L. Rosendahl)