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Mechanics of Materials 38 (2006) 1001–1011

MECHANICS OF MATERIALS

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Convex interfacial joints with least stress singularities in dissimilar materials

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Received 9 February 2004; received in revised form 24 August 2005

Abstract

An integrated experimental and numerical investigation is employed to evaluate a new axisymmetric convex joint for the least free-edge stress singularity. Quasi-static tension and dynamic tension experiments of both straight and convex bi-material joints are conducted. Experimental results show that the convex joint yields an increase in final failure strength (up to 22%) and a reduction in material volume (at least 18%), compared to the traditional straight-edged joint. Finite element results indicate that the new axisymmetric convex interfacial joint is effective in removing the stress singularity at the bi-material edge and consequently, a relatively uniform interfacial stress distribution is achieved. The uniform stress distribution leads to more reasonable interfacial strength measurements and higher tensile strengths of dissimilar material joints.

Keywords: Bonding; Dissimilar materials; Stress singularities; Interfacial strength; Finite element analysis

1. Introduction

Dissimilar material joints/bonds have been extensively used in modern engineering fields, such as adhesive joints of two kinds of dissimilar materials, fiber/matrix interfaces of advanced composite materials, among others. It is found that the failure of these material systems often initiates at the interface corners or free edges. The reason is that very high stresses are developed near the free edges under external loading. Therefore, reducing local stress levels near the free edges may result in higher joint strengths of dissimilar materials. On the other hand, interfacial strength is a very important parameter for material designs and evaluations. For example, modern computational mechanics tools, such as cohesive zone modeling, need interfacial strengths and toughnesses for specific mechanics simulations (Wappling et al., 1998; Li et al., 2002; Roychowdhury et al., 2002; Roe and Siegmund, 2003; Tvergaard, 2004). However, researchers have shown that stress singularities (stresses tending to infinity based on elasticity solutions) exist at the corners of bi-material interfacial joints due to high material property mismatch (Williams, 1952; Bogy, 1971). The presence of free-edge stress singularities at bi-material corners makes macro-scale interfacial strength measurement a big challenge (Reedy and

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0167-6636/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mechmat.2005.10.002

Guess, 1993; Akisanya and Fleck, 1997; Tandon et al., 1999).

Hence, in order to evaluate intrinsic interfacial strengths or to improve load capacity of dissimilar materials, reduction or elimination of the free-edge stress singularities is essential. Very recently, Xu et al. (2004) have proposed a convex design for dissimilar material joints with reduced free-edge stress singularities. In their study, planar convex and straight-edged metal/polymer joints were tested under quasi-static loading conditions using in situ photoelasticity. Their experimental results incorporating with finite-element analysis show that a pair of specific convex joints can efficiently remove the free-edge stress singularities for most engineering material combinations. As a result, a quite uniform stress distribution along the interface is obtained.

However, it should be noticed that in their planar convex specimens, the free-edge stress singularity still exists at the straight free edge along the width direction, although the stress singularity at the free edge along the thickness direction is removed. In order to solve this problem, a planar convex specimen could be "rotated" to form an axisymmetric convex configuration, just like a bamboo joint. This axisymmetric convex joint is obvious to provide more reasonable interfacial strength measurements but it still needs further validation. Besides, the dynamic response of the convex joint has not yet been studied in the previous work (Xu et al., 2004). Therefore, in this investigation, the planar convex interfacial design is extended to axisymmetric configurations, and both quasi-static and dynamic response of the new axisymmetric convex joint will be evaluated. For comparison, conventional straight-edged joints of dissimilar materials commonly used in current test standards are taken as the baseline. Furthermore, to show the disappearance of the free-edge stress singularities in convex joints, the stress states across bi-material interfaces will be examined using finite-element analysis. In the following section, before all experimental and numerical studies are expanded, detailed theoretical background will be reviewed for design guidance.

2. Theoretical background

2.1. Free-edge stress singularities in dissimilar material interfaces/joints

As illustrated in Fig. 1(a), a butt-joint specimen was used to demonstrate the free-edge stress singularity in steel 4340 and Plexiglas (polymethyl methacrylate or PMMA) joints (Xu et al., 2002). Significant stress concentrations (physical phenomena) resulting from stress singularities (theoretical elasticity results) were found at the bi-material corners using the coherent gradient sensing (CGS) technique, which was developed by Tippur et al. (1991) for full-field mechanical-optical measurements. The CGS fringe patterns correspond to the gradients of $\sigma_{xx} + \sigma_{yy}$. It is indeed this stress concentration that leads to free-edge debonding, especially when the joint is subjected to dynamic loading.

For some specific bi-material corners or edges, Williams (1952), Bogy (1971), Hein and Erdogan (1971), Munz and Yang (1993), Pageau et al. (1996), and Akisanya and Meng (2003), to name a

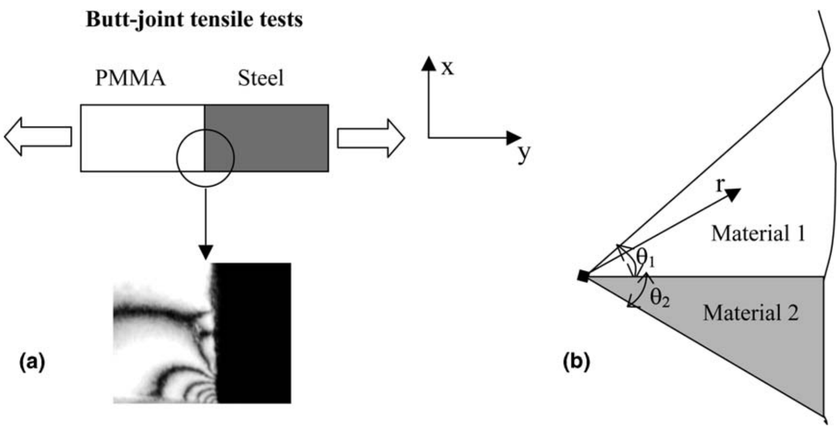

Fig. 1. (a) Coherent gradient sensing (CGS) photographs showing strong stress concentrations (associated with fringe concentrations) at the free edges of bonded metal/polymer joints subjected to tensile loading (Xu et al., 2002); (b) Angular definition of a bi-material wedge.