COMPUTER SIMULATION AND EXPERIMENTAL INVESTIGATION OF A NOVEL DISSIMILAR MATERIAL JOINT FOR STRUCTURAL APPLICATIONS

Luoyu Roy Xu*, **Ping Wang and Sreeparna Sengupta**

Department of Civil and Environmental Engineering, Station B 351831
Vanderbilt University, Nashville TN 37235, USA

ABSTRACT

The proposed design in this investigation, inspired by the shape and mechanics of trees and bones, aims to produce valid interfacial strength data through an integrated theoretical, numerical and experimental investigation. The static tensile strength of the new planar convex joints increased by 50% while the joint volume was reduced by at least 15% compared to those of traditional butt joints. Quasi-static and dynamic tension tests of axisymmetric specimens also showed that 20% failure load increase was achieved for the convex joints. Numerical results obtained from finite element analysis indicated that for interfacial joint angles of 65 and 45 degrees, there is no stress singularity for most engineering material combinations. And interfacial normal stress is quite uniform in the new design. Beside significant load capacity increase, the new convex design also yields accurate interfacial strength measurements. The interfacial tensile strengths obtained from our new specimens are almost twice as that from traditional standard specimens.

KEYWORDS: biologically inspired design, finite element analysis, free-edge stress singularity, interfacial strength, dissimilar structural joints.

INTRODUCTION

Dissimilar material interfaces/joints can be found in numerous modern engineering and science fields, for example, adhesive bonded interfaces of two dissimilar materials; fiber/matrix interfaces of composite materials; thin film/substrate interfaces in micro-electromechanical systems (MEMS), to name a few. One major research effort in interface studies has been the interfacial strength evaluation of dissimilar materials. Numerous studies have shown that failure often occurs along the interface/joint between two kinds of materials with high property mismatch (e.g., free-edge delamination in composite laminates and debonding between thin films/substrates), and that improving the interfacial properties (especially reducing the interfacial stress level) can modify the overall material/structural behavior (Hutchinson and Suo, 1992; Needleman and Rosakis, 1999; Xu et al., 2003).

* Corresponding author: Fax: 615-322-3365, Email: l.roy.xu@vanderbilt.edu

However, macro-scale interfacial strength measurement is still a major challenge due to the stress singularity problem, i.e., the theoretical stress will be infinite at the free-edges. On the other hand, modern numerical tools such as the cohesive element method have an urgent need for interfacial strengths and toughnesses as important data input. Hence, it is necessary to develop reliable quantitative measurements in order to characterize interfacial properties. The key issue in measuring intrinsic interfacial strengths is the creation of a uniform interfacial stress state. So the first important step for intrinsic interfacial strength measurement is the elimination of stress singularities. Actually, elimination of stress singularities is also very valuable for structural/material joints subjected to fatigue and dynamic loading, since failure often occurs at the bi-material free-edge due to stress singularities (Pelegri et al., 1997; Xu and Rosakis, 2002).

The objectives of this investigation are to propose novel specimen designs to remove the stress singularity, and therefore to provide reasonable interfacial strength measurements and suppress edge debonding of dissimilar material joints. We shall review the origin of stress singularities, and propose a general solution inspired by mechanics during formation of trees (Bruck et al., 2002).

THEORETICAL BACKGROUND

FREE-EDGE STRESS SINGULARITIES AT DISSIMILAR MATERIAL INTERFACES/JOINTS

As illustrated in Figure 1(a), a butt-joint specimen was used to demonstrate the free-edge stress singularity in steel 4340 and Plexiglas (PMMA) joints (Xu et al., 2002). Significant stress concentrations were found at the bi-material corners using the Coherent Gradient Sensing (CGS) technique. The CGS fringe patterns correspond to the gradients of $\sigma_{xx} + \sigma_{yy}$. It is indeed this concentration/singularity that leads to free-edge debonding, especially when the joint is subjected to dynamic and fatigue loading.

For some specific bi-material corners or edges, Williams (1952), Bogy (1971), Munz and Yang (1993), Akisanya and Meng (2003), to name a few, showed that stress singularities exist. The asymptotic stress field of a bi-material corner can be expressed as

$$\sigma_{ij}(r,\theta) = \sum_{k=0}^{N} r^{-\lambda_k} K_k f_{ijk}(\theta) \qquad (i,j=1,2,3) \tag{1}$$

where $f_{ijk}(\theta)$ is an angular function and K_k is also known as the "stress intensity factor". The stress singularity order λ may be real or complex. The theoretical stress values become infinite as r (defined in Figure 1(b)) approaches zero, if λ has a positive real part. This leads to a problem referred to as the "stress singularity problem". But, if λ has a non-positive real part, then, the stress singularity disappears.

Bogy (1971) found that the stress singularity was purely determined by the material property mismatch and two joint angles of the bi-material corner θ_1, θ_2 (defined in Figure

1(b)). Generally, the material property mismatch can be expressed in terms of the Dundurs' parameters α and β (Dundurs, 1969). Therefore, our basic idea is to vary these four independent parameters $(\theta_1, \theta_2, \alpha, \beta)$ in order to obtain a negative real part of the stress singularity order λ. Thus, the stress distribution close to the free edge will be smooth.

CONVEX INTERFACIAL JOINTS FOR UNIFORM INTERFACIAL STRESS DISTRIBUTION

The first step to establish a uniform stress state at the interface is to reduce or eliminate the stress singularity at the bi-material edge. After several numerical case studies, we chose an interfacial design with two joint angles: $\theta_1 = 65^o$ and $\theta_2 = 45^o$ and assume material 1 is a typical hard material and material 2 is a soft material then, there will be no stress singularity for a wide range of current engineering materials. This result is illustrated in Figure 2 within the entire possible range of two Dundurs' parameters. We can see that for this specific pair of joint angles, the stress singularity is limited to a very small zone near $\alpha \cong 1$. These extreme material joint combinations are quite rare in engineering applications since they represent extremely high mismatch in Young's moduli.

EXPERIMENTAL INVESTIGATION

Quasi-static tests were conducted using a Materials Test System (MTS 810). In order to employ in-situ photo-elasticity measurements, planar specimens were used. Two types of specimens were designed and prepared for comparison, as seen in Figure 3(a) and (b). The straight edge specimen is the baseline for comparisons. The test materials were PMMA, polycarbonate and aluminum. Two groups of material combinations were tested: (1) PMMA and aluminum and (2) polycarbonate and aluminum. The nominal thickness of planar specimens was 6.35mm (0.25inch).

On the other hand, it should be noticed that in planar convex specimens, the free-edge stress singularity still exists at the straight free-edges along the width direction, although the stress singularity at the free-edges along the thickness direction is removed. In order to solve this problem, a planar specimen could be "rotated" to form an axisymmetric configuration (see Figure 3(c) and (d)). The axisymmetric specimens for quasi-static tests were cylindrical with 21.1 mm in diameter (0.83 inch) and 279.4 mm in height (11 inches). Dynamic experiments were conducted using a split Hopkinson tension bar. The jointed interfacial area for dynamic specimens was 45.6 mm^2.

FINITE ELEMENT MODELING

Elastic finite element analysis of the baseline and the proposed convex metal-polymer joint specimen was carried out. Due to the similarity between the aluminum/polycarbonate and aluminum/PMMA joints, we only modeled the aluminum/polycarbonate joint subjected to static loading. The material constants of aluminum were chosen as Young's modulus E=71.1 GPa, Poisson's ratio ν=0.33 and density ρ=2780 kg/m^3, and for polycarbonate, E=2.4 GPa, ν=0.34, ρ=1200 kg/m^3. An axisymmetric model was constructed using axisymmetric elements to model the axisymmetric samples. The material properties of PMMA were E=5.6 GPa, ν=0.35, ρ=1190 kg/m^3.

RESULTS AND DISCUSSION

The increase in static tensile load capacity of the convex interfacial joints of aluminum-polycarbonate and aluminum-PMMA combinations has been recorded in Table 1. The dynamic test results of aluminum-PMMA joints are shown in Table 2. All shaped specimens showed a marked increase in nominal tensile strengths (ultimate load/interface area) over that of straight-edged specimens. The static tensile strength of the convex planar joints increased by 50% while the joint volume was reduced by at least 15% compared to those of traditional butt joints. Quasi-static and dynamic tension tests of axisymmetric specimens also showed 20% failure load increase was achieved for the convex joints.

More interesting results are revealed using finite element analysis. The influence of the geometrical parameters in planar specimens, on the stress distribution at the interface, has been illustrated in Figure 4(a). For zero extension distance, i.e., straight-edge specimens, a prominent stress singularity is seen at the bi-material corner. However, for increasing extension distances, the interfacial normal stress has finite values at the interface corner and their respective distributions are seen to smoothen out over the interface to uniform values. From this analysis, we find that the free-edge stress singularity is successfully removed and the convex extension distance t mainly affects local stress distributions close to free-edges. Since stress singularity directly contributes to free-edge delamination or debonding, this results in a corresponding increase of the load transfer capability of the new joint as long as we use the specific convex joint. As mentioned before, the free-edge stress singularity still exists along the thickness direction in planar specimens, so we extended the planar configuration to axisymmetric shape. The stress distribution at the bi-material interface of axisymmetric joints is shown in Figure 4(b). It clearly showed the stress redistribution was similar to that in planar specimens. All these results indicate the efficiency of convex joints in removing free-edge stress singularities.

CONCLUSIONS

Convex-edged joints of dissimilar materials are quite effective in eliminating free-edge stress singularities. An integrated experimental and numerical investigation shows that the convex joint not only produces more accurate interfacial strength measurements, but also improves the ultimate tensile load capacity of hybrid joints subjected to both static and dynamic loading.

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Table 1. Quasi-static test results

Joint materials	Joint angles (metal-polymer)	Nominal interfacial tensile strength (MPa)	
		Planar specimens	Axisymmetric specimens
Aluminum-PMMA	90^0-90^0 (baseline)	5.9 ± 1.2	11.35 ± 2.53
Aluminum-PMMA	65^0-45^0	10.1 ± 1.4	12.84 ± 2.53
Aluminum-Polycarbonate	90^0-90^0 (baseline)	2.6 ± 0.7	8.90 ± 2.39
Aluminum-Polycarbonate	65^0-45^0	4.7 ± 2.0	10.89 ± 1.32

Note: The thickness of planar specimens is 6mm

Table 2. Dynamic tensile test data of aluminum/PMMA joints

Joint angles (metal-polymer)	Dynamic tensile strength (MPa)	Change of strength	Standard deviation (MPa)
90^0-90^0 (baseline)	25.64	0%	4.77
65^0-45^0	30.15	+17.59%	5.71

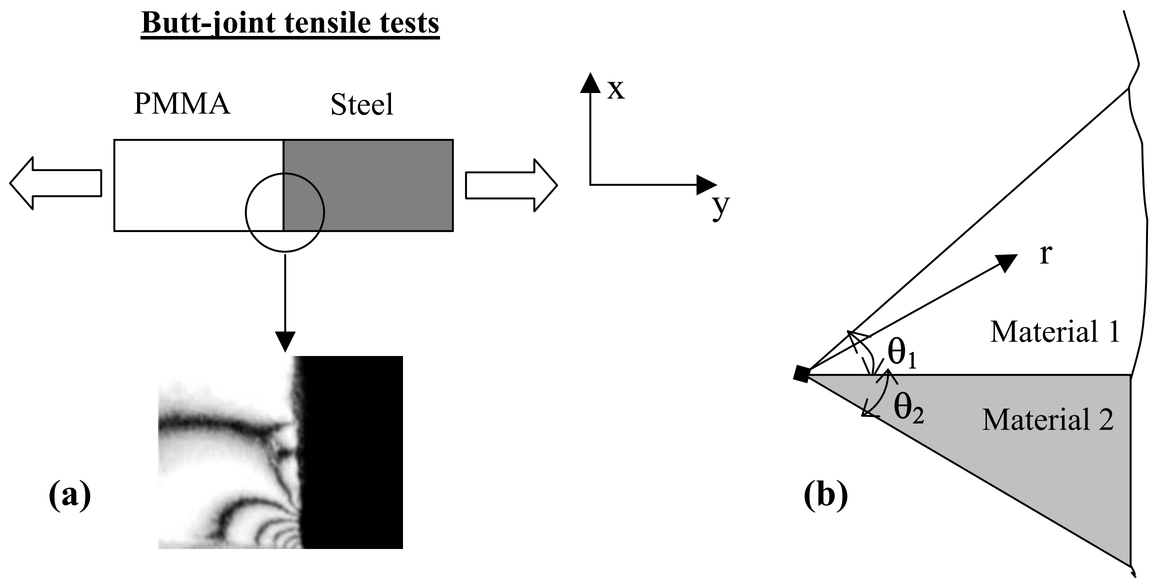

Figure 1, (a) Coherent gradient sensing (CGS) photographs showing strong stress concentrations (associated with fringe concentrations) at the free edges of bonded metal/polymer joints subjected to tensile loading (Xu et al., 2002); (b) Angular definition of a bi-material wedge.

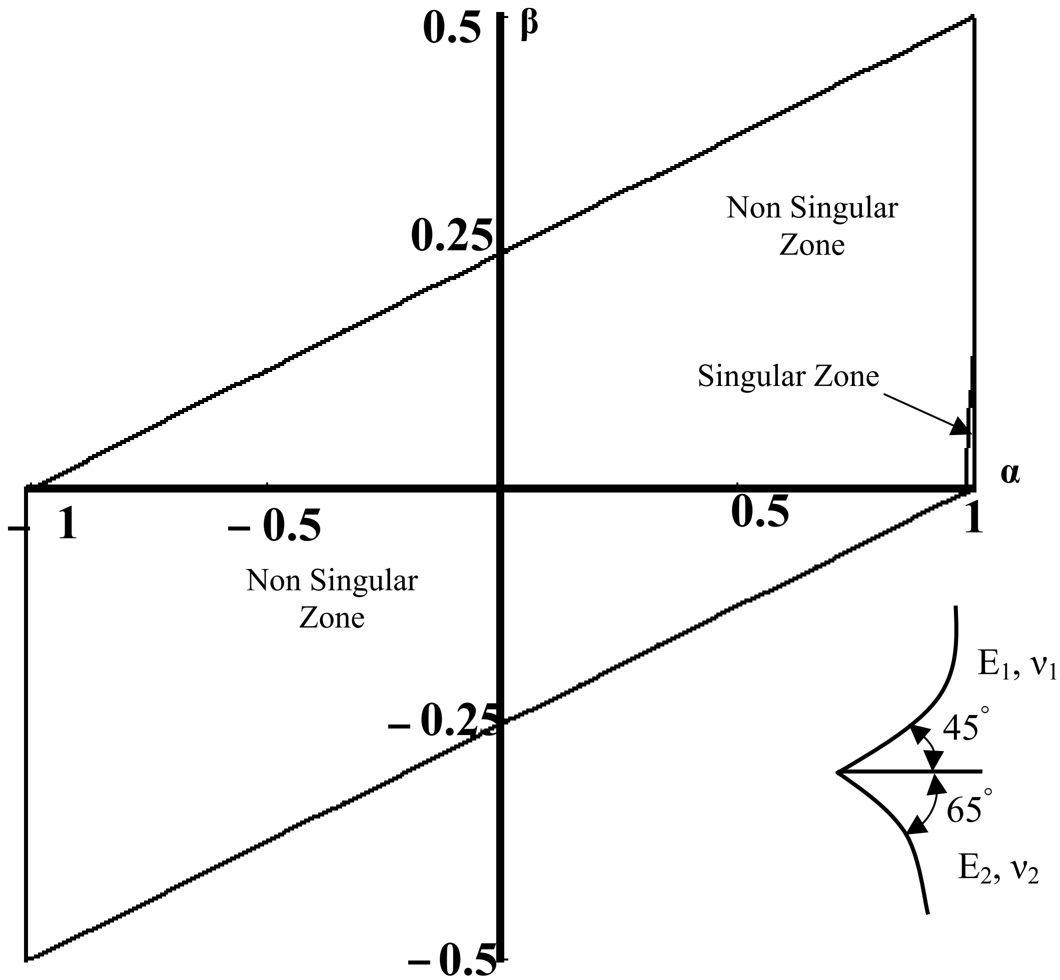

Figure 2, Stress singularity order λ as a function of two Dundurs parameters for a proposed pair of joint angles (45 and 65 degrees for soft and hard materials, respectively). A very small singular zone implies the given pair of angles is applicable for a wide range of engineering material combinations.

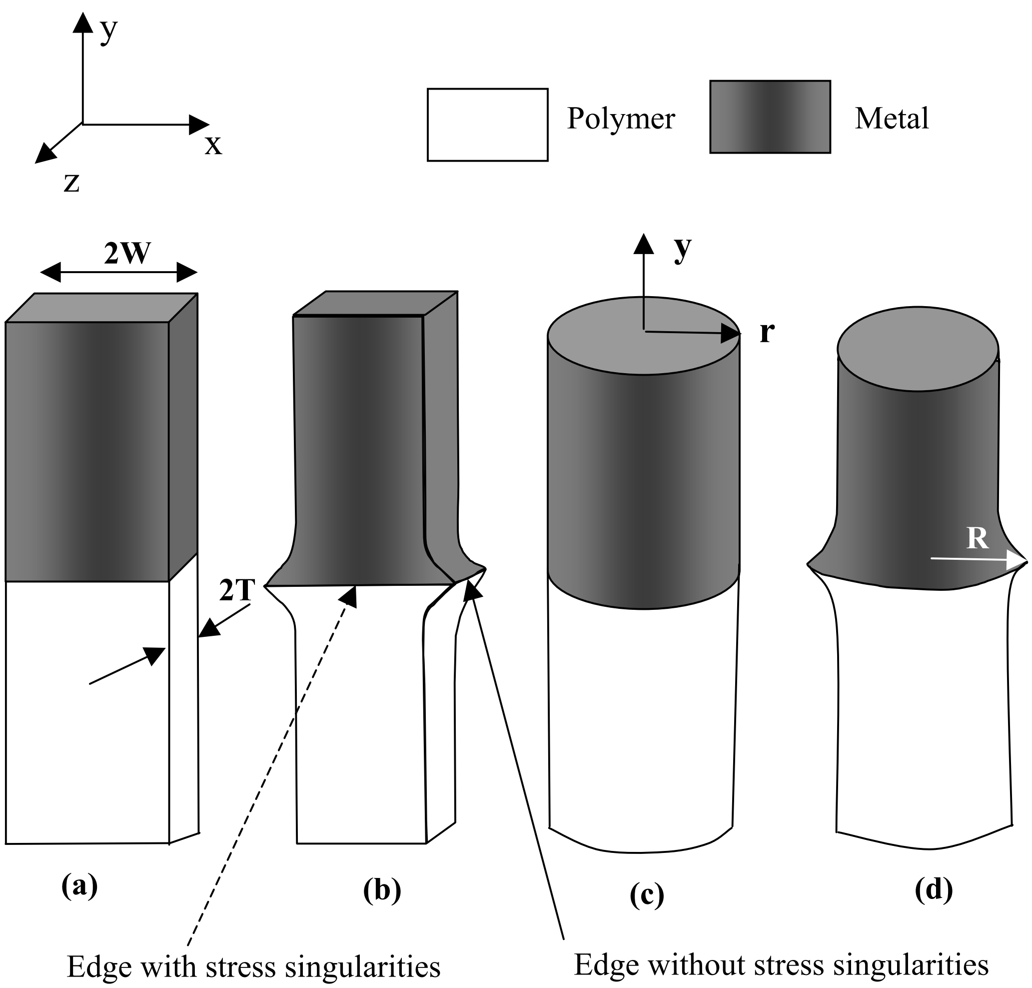

Figure 3, Schematic diagrams of metal-polymer joint specimens with (a) straight edges (baseline); (b) convex edges with least stress singularities; (c) axisymmetric straight joints (baseline); (d) axisymmetric convex joints with least stress singularities.

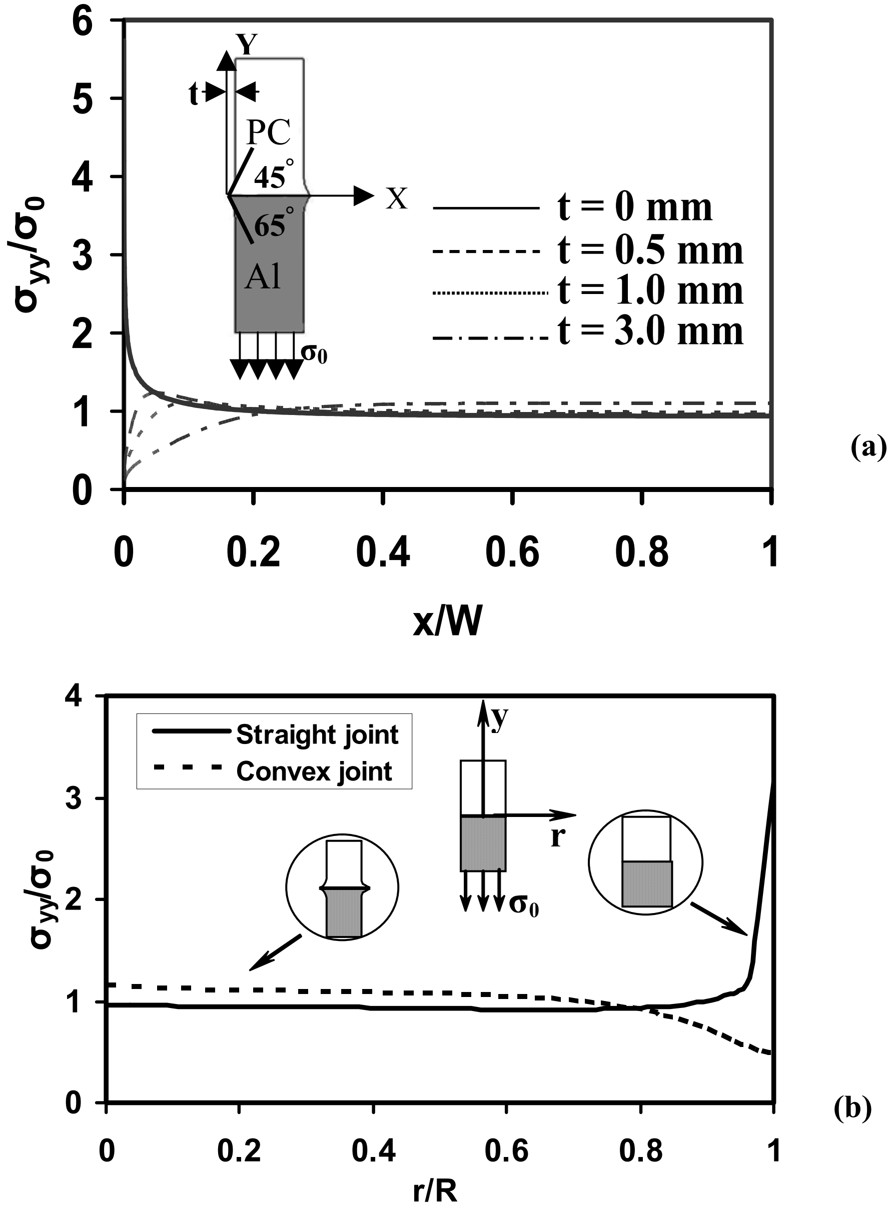

Figure 4, Variations of the interfacial normal stress at (a) planar joints; (b) axisymmetric joints with different extension distances (fixed joint angles θ_1 (for polycarbonate) = 45°, θ_2 (for aluminum) = 65°). If t=0 (straight edge), stresses are singular at the free edges.