Dissimilar Materials Joint and Effect of Angle Junction on Stress Distribution at Interface

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Abstract—in dissimilar material joints, failure often occurs along the interface between two materials due to stress singularity. Stress distribution and its concentration depend on materials and geometry of the junction. Inhomogenity of stress distribution at the interface of junction of two materials with different elastic modules and stress concentration in this zone are the main factors resulting in rupture of the junction. Effect of joining angle in the interface of aluminum-polycarbonate will be discussed in this paper. Computer simulation and finite element analysis by ABAQUS showed that convex interfacial joint leads to stress reduction at junction corners in compare with straight joint. This finding is confirmed by photoelastic experimental results.

Keywords—Elastic Modules, Stress Concentration, Joining Angle, Photoelastic.

I. INTRODUCTION

DISSIMILAR material joints can be found in numerous modern engineering applications. Meanwhile, it has been shown that failure often occurs along the interface between two types of material with high property mismatch, due to stress singularity. Thus, a lot of work on the stress singularity has been done for joints, especially under 2D deformation assumptions owing to the simplicity of mathematics [1]-[12]. Stress singularities at bi-material corners makes macro-scale interfacial strength measurement as a big challenge [13]-[15], the theoretical stress will be infinite at the corners of free edges. 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 material joints subjected to fatigue and dynamic loading, since failure often occurs from the bi-material free edge due to stress singularities. [16]

In this investigation it is proposed a novel specimen design (a convex plane-joint) to remove the stress singularity, and therefore to provide reasonable interfacial strength measurements and suppress edge debonding of dissimilar material joints. Polycarbonate-Aluminum joints will be selected for demonstration of the proposed new design through finite element analysis by ABAQUS and Photoelasticity experiments. Finite-element analysis will be conducted to verify and compare stress changes in the convex plane-joints to experimental findings.

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II. THEORETICAL BACKGROUND

The asymptotic stress field of a bi-material corner can be expressed by;

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

Where $f_{ijk}(\theta)$ is an angular function and K_k is also known as the "stress intensity factor". The stress singularity order k may be real or complex. As seen from "1", the theoretical stress values will become infinite as r approaches zero, if λ has a positive real part. This leads to a problem referred to as the ''stress singularity problem''. Existence of this stress singularity leads to erroneous results in current interfacial strength measurements and debonding in dissimilar material joints. However, if λ has a negative real part, then the stress concentration disappears. So the main effort is focused on producing a negative real part for λ [17].
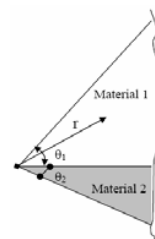

Fig. 1 Angular definitions at corners or bi-material edges

Bogy [18] in 1971 found that the stress concentration was determined by the material property mismatch and two joint angles of the bi-material corner θ1, θ2 (defined in Fig. 1).

Generally, the material property mismatch can be expressed in terms of the Dundurs parameters α and β [19], which are two non-dimensional parameters computed from the elastic constants of two bonded materials:

$$\alpha = \frac{\mu_1 m_2 - \mu_2 m_1}{\mu_1 m_2 + \mu_2 m_1} \quad , \quad \beta = \frac{\mu_1(m_2 - 2) - \mu_2(m_1 - 2)}{\mu_1 m_2 + \mu_2 m_1} \qquad (2)$$

Here, μ_1 is the shear modulus of material 1, μ_2 is the shear modulus of material 2, υ is the Poisson ratio, m = 4(1 - υ) for plane strain and m = 4/(1 + υ) for plane stress. The stress singularity order depends on material and geometric parameters, and it is determined by a characteristic equation of coefficients *A* through *F* that each of them are functions of θ1, θ2, and λ.

$$f(\theta_1, \theta_2, \alpha, \beta, p) = A\beta^2 + 2B\alpha\beta + C\alpha^2 + 2D\beta + 2E\alpha + F = 0 \qquad (3)$$

Where p=1 − λ. Therefore, our basic idea is to vary these four independent parameters (θ1, θ2, α, β) in order to obtain a negative real value of the stress singularity order λ, then the stress singularity will be removed and the stress distribution close to the free edge will become smooth.

As recently noticed by Mohammed and Liechti [20], an appropriate joining angle design at the bi-material edge is a possible approach to reduce the stress singularity. Since we can choose appropriate angular combinations according to different material combinations, it is possible to obtain a negative or zero Re[λ] and this means that the degree of singularity can be reduced or removed. If material 1 is a typical soft material and material 2 is a hard material as shown in Fig. 1, a convex interfacial design with two joint angles θ1= 45˚ and θ2 = 65˚ can remove free-edge stress singularities for a wide range of current engineering materials. This result is illustrated in Fig. 2 showing the entire possible range of two Dundurs parameters [21]. By choosing polycarbonate and aluminum as a different material combination and considering a generalized plane stress case, the Dundrus parameters are obtained as α=-0.935, β=-0.308 [17], so there will be no stress concentration for this specific joint as it is shown in figure 2.
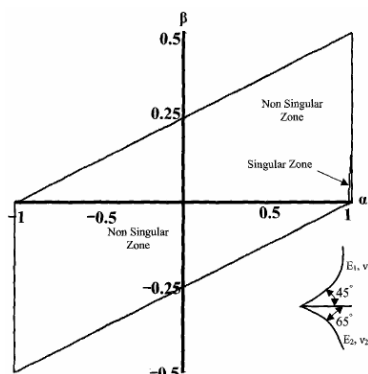

Fig. 2 Stress singularity order k as a function of two Dundurs parameters for a proposed pair of joint angles

III. NUMERICAL AND EXPERIMENTAL INVESTIGATION

A. Finite-element modeling

A baqus 6.7 software was used In order to elastic finite element analysis of the baseline and the proposed convex Aluminum-Polycarbonate joint specimen. The dimensions of the straight-edge specimen were: length L= 220 mm, width W= 30 mm, convex extension distances d= 0, 0.5, 1, 2, 3 mm, thickness T= 4 mm for thin specimens and 9 mm for thick specimens. The stiffness properties of first material was chosen as E= 2.4 Gpa, υ = 0.34, and for second material, E= 2.4, 10, 71, 200 Gpa, and υ = 0.33. In this investigation, four different joint types, with the same bi-material combination and equal bonding area, were subjected to the same in-plane tension load as shown in Fig. 3.
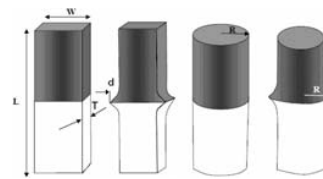

Fig. 3 Schematic diagrams of aluminum polycarbonate joint specimens

B. Specimen design and preparation

Photoelasticity experiment was performed to investigate stress distribution close to the interface. The transition from the straight edge to the curved edge at the interface corner was achieved by means of a circular arc of radius R = {d/[1 - sin(θ)] }, where θ is the joining angle and d is the convex extension distance, as illustrated in Fig. 4. Milling machine was used to produce convex aluminum and polycarbonate specimens.
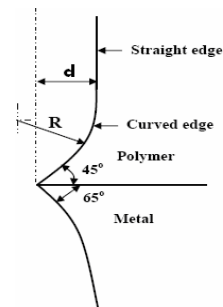

Fig. 4 Illustration of a proposed convex joint of metal and polymer interface

A commercial epoxy (Weld-on 10, Meyer Plastics Inc., Santa Ana, CA) was used as the bonding agent. The reason to choose this particular adhesive is that its properties are very close to those of polycarbonate. Hence, the possible involvement of a third material in a typical bi-material problem was removed. The adhesive had two components, A and B. They were mixed with each other 6:1 before bonding. After 24 or 48 hours, it reached the design strength. Before the adhesive bonding, bonding areas were cleaned using acetone.

IV. RESULTS AND DISCUSSION

A. The effects of angle Junction on interface stress

Four cases have been examined for AL90˚-PC90˚, AL65˚-PC45˚, AL65˚-PC65˚, AL45˚-PC65˚ and the results have been illustrated in Fig. 5.
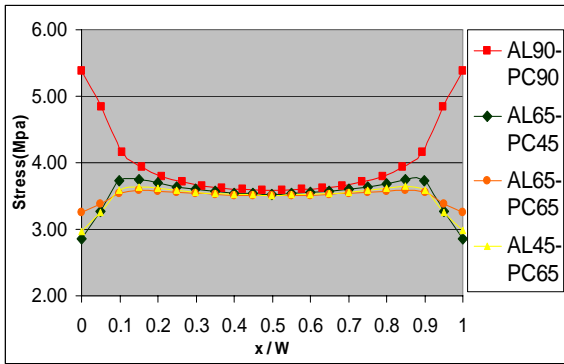
Fig. 5 Variation of interfacial normal stress with different joint angles

As it is shown in fig. 5, the interfacial normal stress value at the corners for the AL65˚-PC45˚ angle combination is the minimum. However, the AL65˚-PC65˚ angle combination results in the most uniformity.

B. The effect of extension distance on interface stress

Five cases have been examined for d= 0, 0.5, 1.0, 2 and 3.0 mm with a thickness T= 4 mm. For zero extension distance (straight-edge specimens), a prominent stress is seen at the interface corners. However, by increasing extension distances, the interfacial normal stress value decrease at the corners as it is shown in fig. 6.
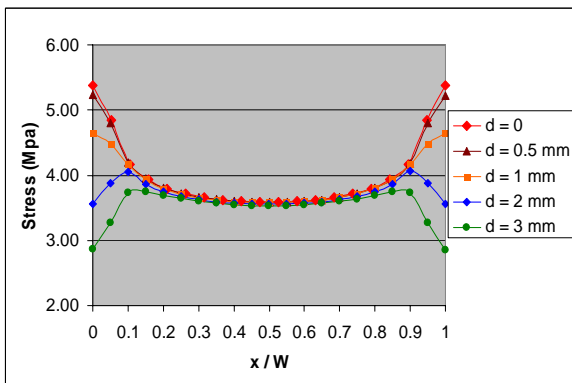

Fig. 6 Variations of interfacial normal stress with different extension distances

From this analysis, we find that the free-edge stress singularity is successfully removed and the convex extension distance d mainly affects local stress distributions close to free-edges. Since stress singularity directly contributes to free-edge debonding, so convex joint and increasing the extension distance plays important role in bond strength.

C. The effect of convex joint in axisymmetric specimens

Fig. 7 compares the interfacial stress states in an axisymmetric cylindrical specimen with convex interfacial joints (d= 3mm) to that in an axisymmetric cylinder with straight edges (d= 0).
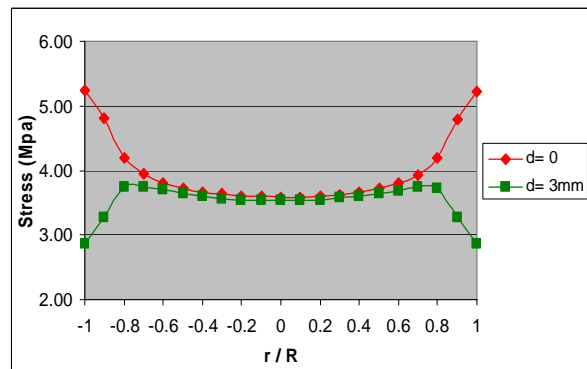

Fig. 7 Variation of interfacial normal stress in an axisymmetric specimen

As it is shown in fig. 7 Singular stresses are normally expected close to the free-edge in specimen with straight edges; on the other hand, it clearly shows that stress singularities are eliminated if the specimen with convex interfacial joints is used. So final tensile strength increase was predicted for the convex axisymmetric specimen over the straight cylindrical joint.

D. Comparison of Experimental Results with finite element analysis

Photoelasticity experiment with test machine model 061 was employed to make a direct comparison with the finite element simulation. Fig. 9 and Fig. 10 bear the most conclusive testimony to the reduction of the interfacial normal stress value at the interface corners in convex joint. The photoelastic fringe patterns are contours of the maximum in-plane shear stress according to the classical photoelasticity equation:

$$\sigma_1 - \sigma_2 = \frac{N f_\sigma}{t} \tag{4}$$

Where $\sigma 1$ and $\sigma 2$ are in-plane principal stresses, N is the fringe order, t is the specimen thickness and $f\sigma$ is the stress fringe constant calculated from "5". (7.2 kN/m for polycarbonate)

$$f_\sigma = \frac{p}{N w} \tag{5}$$

Which P is the given force and w is width of the samples. The photoelastic color sequence (showing increasing stress) is shown in fig. 8.

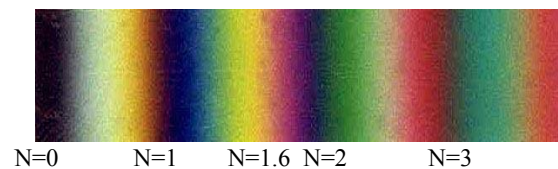N=0   N=1   N=1.6 N=2   N=3

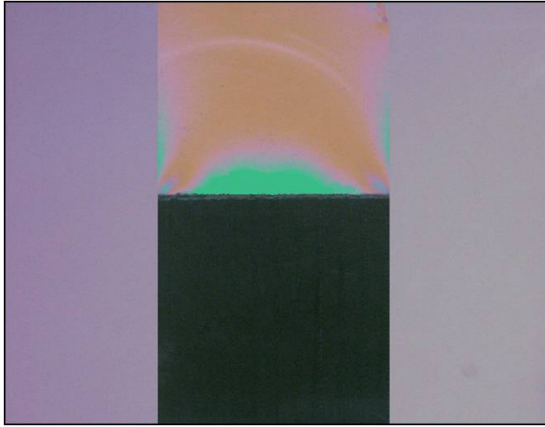Fig. 8 The photoelastic color sequence

Fig. 9 Experimental photoelasticity pattern for PC/AI joint with straight edges
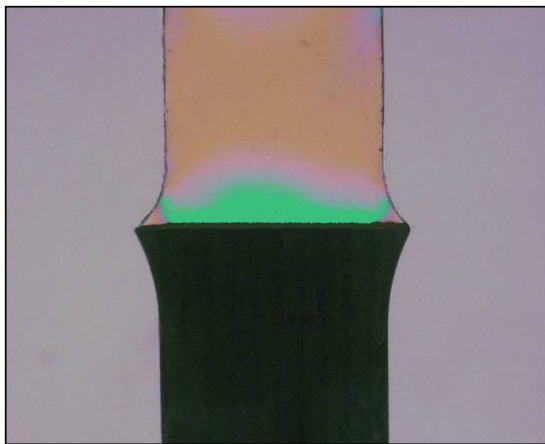

Fig. 10 Experimental photoelasticity pattern for PC/AI joint with 65-45 angle edges

Fig. 9 shows that a green fringe of order $N = 2$ is at the center of interface in the straight edges joint, and by moving to the corners, the green fringe changes to blue-green fringe of order $N = 3$. Then, by using "4", the values of normal stress at the center of interface calculated 3.6 Mpa and for corners 5.4 MPa. On the other hand, fig. 10 shows that a green fringe of order $N = 2$ is at the center of interface in the convex edges joint, and by moving to the corners, the green fringe changes to pink-yellow fringe of order $N = 1.6$. So the values of normal stress at the center of interface calculated 3.6 Mpa and for corners 2.9 MPa. Therefore, experimental results confirm finite element analysis as it was shown in fig. 5.

V. CONCLUSIONS

Stress distribution and its concentration depend on geometry of the junction. Convex interfacial joints prove to be quite effective in stress relaxation at interface of dissimilar materials, and increasing extension distances makes the interfacial normal stress value decrease at the corners. An axisymmetric design was shown to eliminate non-uniformity

stress distribution along the periphery of the interface and this should lead to increased load transfer capability of the dissimilar material joints.

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