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Publisher's version / Version de l'éditeur:

31st Annual Meeting of the Adhesion Society [Proceedings], 2008-02

Numerical evaluation of strain energy release rate in adhesive joints

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A generalized engineering approach to fracture load predictions for adhesive joints has been already presented in Refs. [1] and [2]. The approach is based on the premise that the strength of any adhesive system can be characterized by an experimentally measured fracture envelope, which is the variation of critical strain energy release rate, G_c, as a function of loading mode (mode ratio). The results of quasi-static fracture tests on double-cantilever-beam (DCB), cracked-lap-shear (CLS) and single-lap-shear (SLS) joints made of aluminum and steel confirmed the applicability of the model for engineering design of adhesive joints. In the present work, a series of finite element models (ANSYS / LS-Dyna) were used to calculate the strain energy release, G, as a function of loading mode for a variety of adhesive joints. The adhesive was modeled as a rate-independent plastic-elastic material, while elastic behavior was assumed for the adherends. The critical energy release rate in adhesive joints was evaluated on the basis of adhesive bulk material properties. The effects of geometry and substrate material were also studied by comparing the G_c values, the stress fields and the strain rates in the adhesive layers of aluminum and steel DCB, CLS and SLS joints. Comparisons are made between analytical and numerical predictions of G_c.

References:

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Papini	Marcello			Ryerson Univ.			
Spelt	Jan K.			UofT			

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○ **Sommaire (abstract)** Écrit final à suivre : ○ Oui ◉ Non Si oui, date :

○ **Rapport** ○ Technique ○ Industriel de service

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◉ **Document soumis pour publication**

Si un sommaire (abstract) a été soumis précédemment, veuillez indiquer les numéros :

IMI 116966 CNRC CNRC

À présenter dans le cadre de : 31st Annual Meeting of the Adhesion Society

Date de la conférence : Lieu : Austin, Texas

À paraître dans : Procès-verbaux de conférence Date :

Statut de publication

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☐ Autre

Date de publication: 2008-02-17 Année cal. publication: 2008

Paru dans (vol. pp) :

Autres informations

Partenaires : General Motors

Déclaration d'invention : Non Date :

Demande de brevet déposée : Non Pays :

Si non, explications : Non-patentable research test results

Approbations

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Numéro IMI 2008 - 116966 - G CNRC 48401

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M. Eskandarian, G. D'Amours, M. Papini and J.K. Spelt

2008 Annual Meeting of The Adhesion Society, Austin, TX
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Abstract

A generalized engineering approach to fracture load predictions for adhesive joints has been already presented in Refs. [1] and [2]. The approach is based on the premise that the strength of any adhesive system can be characterized by an experimentally measured fracture envelope, which is the variation of the critical strain energy release rate, G_c, as a function of loading mode (mode ratio). The results of quasi-static fracture tests on double-cantilever-beam (DCB), cracked-lap-shear (CLS) and single-lap-shear (SLS) joints made of aluminum and steel confirmed the applicability of the model for engineering design of adhesive joints.

In the present work, a series of finite element models (ANSYS / LS-Dyna) were used to calculate the strain energy release, G, as a function of loading mode for a variety of adhesive joints. The adhesive was modeled as a rate-independent plastic-elastic material, while elastic behavior was assumed for the adherends. The critical energy release rate in adhesive joints was evaluated on the basis of adhesive bulk material properties. The effects of geometry and substrate material were also studied by comparing the G_c values, the stress fields and the strain rates in the adhesive layers of aluminum and steel DCB, CLS and SLS joints. Comparisons are made between analytical and numerical predictions of G_c.

Introduction

Recent results of quasi-static fracture tests on DCB specimens made of aluminum and steel revealed that Gc appeared to depend on the substrate material but not on adherends thickness. The average value of the measured energy release rate for steel DCB was almost 8% lower than for aluminum DCB as shown in Fig. 1a. The mismatch of the R-curves of the adhesive systems were initially supposed to be subsequent of the differences in operator readings, the strain rates in adhesive layers, the degrees of interfacial debonding, the stress field around crack tip and perhaps the size of damage zone ahead of crack. The failure of aluminum adhesive joints was totally cohesive while some signs of local interfacial debonding was observed for steel DCBs, Fig. 1b. In order to minimize the operator interference, the testing machine was programmed to automatically detect the crack propagation in adhesive joint from the variation of joint compliance. The main objective of current research was to conduct a series of finite element simulations for evaluating the effects of other potential influencing parameters such as strain rate in adhesive layer, stress field ahead of crack and the degree of triaxiality in stress field providing higher constraint in the adhesive layer of steel joints. The concept of change in strain energy was also implemented to compare the Gc values of both adhesive systems.

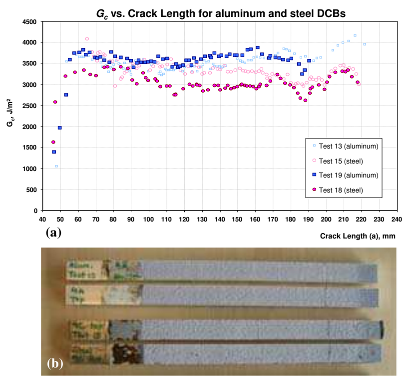

Fig. 1: Comparison of the R-curves obtained for steel (semi-cohesive failure) and aluminum DCB specimens (bars thickness 12.7 mm, width 18 mm, bondline 0.4 mm).

Results and discussions

a) Strain rate in adhesive layer – 2D FE models

The adhesive joints made of aluminum bars bonded by a heat-cured toughened epoxy adhesive were modeled through a series of 2-dimensional finite elements simulations by using ANSYS software. The adhesive was a toughened heat-cured epoxy used in automotive industry with apparent rate-dependent behavior. It was however modeled as a rate-independent plastic-elastic material for simplicity. The first series of FE analyses have been conducted in order to validate this assumption and also to compare the adhesive strain rates for the aluminum and steel DCBs. The results revealed that the strain rate in the bondline of steel DCBs close to crack tip were almost two times higher than the similar value for aluminum DCBs. The variations of adhesive strain rate with crack length for the simulations done at mode-I & -II, and the mode ratio of 51 deg. are shown in Fig. 2.

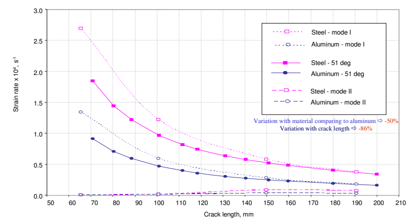

Fig. 2: Comparison of the strain rates in the bondline of aluminum and steel DCBs under two loading conditions (mode-I & -II and the mode ratio of 51°), Pin-displacement-rate 1.5 mm/min, Total time = 300 s, Δt = 15 s.

As it is shown in Fig. 2, there is also another significant variation of strain rate with crack length for each material, which did not affect the plateau region of R-curves. It means that different strain rates could not be considered as the main reason for having the substrate material dependency in adhesive joints. In order to eliminate the potential influence of strain rate on the experimental measurements, the DCB tests were performed at constant load rate of 10 N/s rather than conventional test under constant crosshead speed. For the CLS and SLS tests, on the other side, the crosshead speeds were calculated to give similar strain rates in the bondline of DCB and CLS or SLS specimens tested at similar mode ratios.

b) Stress field ahead of crack tip – 2D models

In the next series of 2D FE simulations, the stress field in the bondline of aluminum and steel DCBs were compared. The specimen pins were loaded through a constant-displacement-rate simulation up to the time when the opening stress in the adhesive elements, close to crack tip, has been reached to the ultimate strength of adhesive (45 MPa) measured by the bulk adhesive tests. In order to validate this procedure, the pin openings at such positions were compared with the experimental values measured in the quasi-static tests on DCB samples. Good agreements were found between the simulation and the experimental values. The adhesive opening stress and its variation with x-coordinate (along the bars) are compared in Fig. 3 for the steel and aluminum DCB samples having similar geometries. The opening and von-Mises stresses in the bondline of steel DCB are more elevated (Max. 20%) comparing to aluminum DCB in a shorter value of time-to-fracture (90 rather than 200 sec., respectively). This difference however cannot be considered as the main reason of having lower value of G_c for steel as it has an inverse effect on G_c, i.e. the energy release rate increases when the value of bondline stresses are higher.

Similar simulations have been carried out on thicker aluminum DCB to evaluate the stiffness effects on Gc, where no significant differences were observed in the value of energy release rates measured from simulation or from quasi-static tests on DCBs made of both materials, Fig. 4. This means that the stiffness of adhesive joins has no significant effect on adhesive bondline stresses.

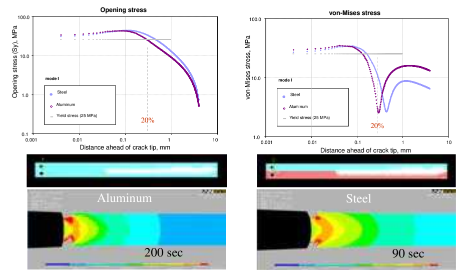

Fig. 3: Comparison of the stress fields ahead of crack tip in the bondline of aluminum and steel DCBs having similar geometries

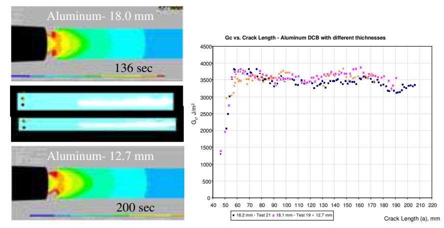

Fig. 4: Comparison of the adhesive stress fields and the experimental measurements of G_c for aluminum DCBs having different thicknesses.

c) Constraint in adhesive layer – 3D models

The degree of triaxiality in adhesive layers of aluminum and steel DCBs was investigated by conducting a series of 3D FE simulations on half on DCB samples by using LS-Dyna software. The half specimen geometry, the singular elements used to represent the crack tip, and the von-Mises stress field in adhesive layer are typically demonstrated in Fig. 5.

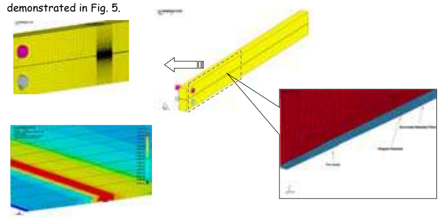

Fig. 5: Geometry, mesh, singular elements and the contours of von-Mises stress in the bondline.

The hydrostatic pressure across the bondline was determined from result files, which shows a minor difference of 2% for the average bondline pressure. Higher absolute value and then higher degree of triaxiality was corresponded to steel DCB as shown in Fig. 6.

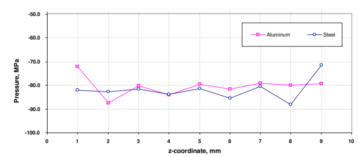

Fig. 6: Hydrostatic pressure in the bondline of aluminum and steel DCBs

d) Energy release calculations – 3D models

In the next series of 3D FE simulations, the critical energy release rate G_c was calculated from the total strain energy of parts during a finite crack propagation by using the following formula.

$$G_c = \frac{U_{a+\Delta a} - U_a}{b\Delta a}$$

Where a denotes crack length, Δa the finite crack propagation, U_a the strain energy when the crack length of a, $U_{a+\Delta a}$ similar term at crack length of a+Δa, and b is the with of DCB joint. For G_c calculations, the model was firstly run at crack length of a to the time when the adhesive von-Mises stress meets its ultimate value (45 MPa). The total strain energy of all parts was then calculated. In the second run, the gradual displacements were applied to pins up to the time when the pin opening was the same as in the previous run. The second value of strain energy was then calculated and the difference represents the critical strain energy of each adhesive system. The results overestimated the experimental values but represents not a significant difference in the measured values of G_c for aluminum and steel DCBs as shown in Fig. 7.

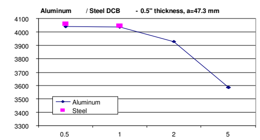

Fig. 8: Energy release rate in aluminum and steel DCBs at various crack advancements

Conclusions

The FE simulations on various adhesive joints have been developed in order to investigate the effects of substrate material on the fracture behavior of adhesive joints. The energy calculations on the basis of the change in strain energy of parts were very sensitive to parts movement but represents a non-significant difference in G_c values calculated for aluminum and steel DCBs. The experimental difference in R-curves of those adhesive systems could be corresponded to different surface preparation procedures and the quality of debonded surfaces.

Acknowledgments

The authors wish to acknowledge General Motors of Canada, the Natural Sciences and Engineering Research Council of Canada, Ontario Centers of Excellence, and the Aluminum Technology Centre of the National Research Council Canada for their financial and technical supports.

References

[1] G. Fernlund, M. Papini, D. McCammond and J.K. Spelt, Fracture load predictions for adhesive joints, Compos. Sci. Technol., vol. 51, 587 (1994).

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