Fracture load predictions for adhesive joints subject to quasi-static loads

Eskandarian, M.; Azari, S.; Papini, M.; Spelt, J. K.

Publisher's version / Version de l'éditeur:

Proceedings of the Light Metals Technology Conference 2007, 2007-09-24

Fracture load predictions for adhesive joints subject to quasi-static loads

M. Eskandarian[1)], M. Papini[2)] and J.K. Spelt[3)*]

[1)] Aluminium Technology Centre, Industrial Materials Institute, National Research Council Canada (ATC/IMI/NRC), 501 boul. de l'Université, Chicoutimi (Québec), Canada G7H 8C3

[2)] Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario, Canada M5B 2K3

[3)] Department of Mechanical and Industrial Engineering, University of Toronto, 5 King's College Road, Toronto, Ontario, Canada M5S 3G8

* Corresponding Author

An engineering approach to fracture load predictions for adhesive joints was presented in Refs. [1] and [2]. A series of quasi-static fracture tests on double-cantilever-beam (DCB), single-lap-shear (SLS) and cracked-lap-shear (CLS) joints were conducted in order to investigate the applicability of this approach to a variety of joints bonded by a toughened epoxy adhesive. First, the dependence of the critical energy release rate (G_c) on the mode ratio was determined experimentally for DCB specimens. This approach was then used to predict the ultimate strength of SLS and CLS joints.

The effects of adhesive strain rate, adherend geometry and substrate material on G_c were investigated. This revealed that the adherend flexural rigidity had the most significant influence on G_c and the shape of the R-curve. These joints, having different materials and geometries, were also modeled in a series of finite element analyses to gain a better understanding of the loading and fracture phenomena.

References

1. G. Fernlund, M. Papini, D. McCammond and J.K. Spelt, Fracture load predictions for adhesive joints, *Compos. Sci. Technol.*, 1994, 51, pp. 587-600.
2. M. Papini, G. Fernlund and J.K. Spelt, Effect of crack-growth mechanism on the prediction of fracture load of adhesive joints, *Compos. Sci. Technol.*, 1994, 52, pp. 561-570.

Conseil national de recherches Canada — National Research Council Canada

Institut des matériaux industriels — Industrial Materials Institute

Fiche d'information et d'autorisation pour documents internes, externes et conférences

CTA

Auteurs

Auteur principal pour l'IMI

Nom	Prénom	Centre financ.	Centre de coût	Commande interne	Signature	Date sign.	Premier auteur publication
Eskandarian	M.	502300	502305	859	M. Eskandarian	08/14/2007	*

Autres auteurs

				Externe			
Papini	Marcello			Ryerson Univ.			
Spelt	Jan K.			U. of Toronto			
Azari	Shahrokh			U. of Toronto			

* Je certifie, en tant que premier auteur, que j'ai vérifié avec le(s) partenaire(s) qu'il(s) n'a (n'ont) pas d'objection à ce document.

Document

Titre

Fracture load predictions for adhesive joints subject to quasi-static loads

Statut de distribution Général

Type

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

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

○ **Autre**

◉ **Document soumis pour publication**

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

IMI 2007-115411-G CNRC CNRC

À présenter dans le cadre de : Light Metal Technology Conference 2007

Date de la conférence : 2007-09-24 Lieu : St. Sauveur, QC

À paraître dans : Conference Proceedings Date : 2007-09-24

Statut de publication

À être complété par votre adjointe. Veuillez l'aviser lorsque l'information sera disponible. ☒

☐ Revue ou livre avec comité de lecture

☒ Procès-verbal de conférence avec comité de lecture

☐ Procès-verbal de conférence sans comité de lecture

☐ Autre

Paru dans (vol. pp) :

Date de publication 2007-09-24 **Année cal. publication** 2007

Autres informations

Partenaires : GM / UofT

Déclaration d'invention : Non Date :

Demande de brevet déposée : Non Pays :

Si non, explications : Non-patentable research results

Approbations

[signature]	31/08/2007	[signature]	[illegible]	B. Champagne	
Signature Chef de groupe	Date	Signature Directeur de section	Date	Signature Directeur général	Date

Numéro IMI 2007 - 115411 - G CNRC 48397

Canada | Canada

Institut des matériaux industriels | Industrial Materials Institute

Fiche d'information et d'autorisation pour documents internes, externes et conférences

Année calendrier 2007

No de projet 50-859-01

Titre du document Fracture load predictions for adhesive joints subject to quasi-static loads

Statut du document Général

Types de document

☐ **Sommaire (Abstract)** Écrit final suivra ? ☐ Non ☐ Si Oui Date

☑ **Document soumis pour publication**

Si un sommaire (abstract) a été soumis précédemment, veuillez indiquer les numéros IMI ______ CNRC ______

À présenter dans le cadre de Light Metals Technology Conference

Date de la conférence 24-26 Sep. 2007 Lieu St Sauveur, QC

À paraître dans Conference proceeding Date Sep. 2007

☐ **Rapport**

☐ Technique ☐ Industriel de service

☐ **Autre (spécifiez)** ______

À être complétée par votre adjointe. Veuillez l'aviser lorsque l'information sera disponible.

Année calendrier (janvier à décembre) 2007

☐ **Publication**

☐ Revues et livres avec comité de lecture

☐ Procès-verbaux de conférence avec comité de lecture

☐ Procès-verbaux de conférence sans comité de lecture

Si un sommaire (abstract) a été soumis précédemment, veuillez indiquer les numéros IMI 2007-115411-G CNRC CNRC

Paru dans (vol. pp)

Partenaires GM

Déclaration d'invention ______ Date ______

Demande de brevet déposée ______ Pays ______

Si non, explications: Non-patentable research results

Auteur (nom prénom)	Affiliation: Section	Affiliation: Groupe	Affiliation: Externe	Signature	Date
* Eskandarian Mojtaba				M. Eskandarian	12/12/06
Papini Marcello					
Spelt Jan K.				[signature]	30/11/06
Azari Shahrokh					

* Je certifie, en tant que premier auteur, que j'ai vérifié avec le(s) partenaire(s) qu'il(s) n'a (n'ont) pas d'objection à ce document.

Approbations:

Signature Chef de groupe	Date	Signature Directeur de section	Date	Signature Directeur général	Date

Numéro IMI 2007 - 115411 - G CNRC 48397

Conseil national de recherches Canada | National Research Council Canada

Institut des matériaux industriels | Industrial Materials Institute

Fiche d'information et d'autorisation pour documents internes, externes et conférences

CTA

Auteurs

Auteur principal pour l'IMI

Nom	Prénom	Centre financ.	Centre de coût	Commande interne	Signature	Date sign.	Premier auteur publication
Eskandarian	M.	502300	502305	859		08/14/2007	*

Autres auteurs

Nom	Prénom	Centre financ.	Centre de coût	Externe	Signature	Date sign.	
Papini	Marcello			Ryerson Univ.	[signature]	08/16/07	
Spelt	Jan K.			U. of Toronto			
Azari	Shahrokh			U. of Toronto			

* Je certifie, en tant que premier auteur, que j'ai vérifié avec le(s) partenaire(s) qu'il(s) n'a (n'ont) pas d'objection à ce document.

Document

Titre

Fracture load predictions for adhesive joints subject to quasi-static loads

Statut de distribution Général

Type

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

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

○ **Autre**

◉ **Document soumis pour publication**

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

IMI 2007-115411-G CNRC CNRC

À présenter dans le cadre de : Light Metal Technology Conference 2007

Date de la conférence : 2007-09-24 Lieu : St. Sauveur, QC

À paraître dans : Conference Proceedings Date : 2007-09-24

Statut de publication

À être complété par votre adjointe. Veuillez l'aviser lorsque l'information sera disponible. ☒

☐ Revue ou livre avec comité de lecture

☒ Procès-verbal de conférence avec comité de lecture

☐ Procès-verbal de conférence sans comité de lecture

☐ Autre

Paru dans (vol. pp) :

Date de publication 2007-09-24

Année cal. publication 2007

Autres informations

Partenaires : GM / UofT

Déclaration d'invention : Non Date :

Demande de brevet déposée : Non Pays :

Si non, explications : Non-patentable research results

Approbations

Signature Chef de groupe	Date	Signature Directeur de section	Date	Signature Directeur général	Date

Numéro IMI 2007 - 115411 - G CNRC 48397

Conseil national de recherches Canada — National Research Council Canada
Institut des matériaux industriels — Industrial Materials Institute

Fiche d'information et d'autorisation pour documents internes, externes et conférences

CTA

Auteurs

Auteur principal pour l'IMI

Nom	Prénom	Centre financ.	Centre de coût	Commande interne	Signature	Date sign.	Premier auteur publication
Eskandarian	M.	502300	502305	859		08/14/2007	*

Autres auteurs

Nom	Prénom	Centre financ.	Centre de coût	Externe	Signature	Date sign.	
Papini	Marcello			Ryerson Univ.			
Spelt	Jan K.			U. of Toronto			
Azari	Shahrokh			U. of Toronto	Sh. Azari	08/16/07	

* Je certifie, en tant que premier auteur, que j'ai vérifié avec le(s) partenaire(s) qu'il(s) n'a (n'ont) pas d'objection à ce document.

Document

Titre

Fracture load predictions for adhesive joints subject to quasi-static loads

Statut de distribution Général

Type

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

○ Rapport — ○ Technique ○ Industriel de service

○ Autre

● Document soumis pour publication

Si un sommaire (abstract) a été soumis précédemment, veuillez indiquer les numéros :
IMI 2007-115411-G CNRC CNRC

À présenter dans le cadre de : Light Metal Technology Conference 2007

Date de la conférence : 2007-09-24 Lieu : St. Sauveur, QC

À paraître dans : Conference Proceedings Date : 2007-09-24

Statut de publication

À être complété par votre adjointe. Veuillez l'aviser lorsque l'information sera disponible. ☒

☐ Revue ou livre avec comité de lecture
☒ Procès-verbal de conférence avec comité de lecture
☐ Procès-verbal de conférence sans comité de lecture
☐ Autre

Date de publication: 2007-09-24
Année cal. publication: 2007

Paru dans (vol. pp) :

Autres informations

Partenaires : GM / UofT

Déclaration d'invention : Non Date :

Demande de brevet déposée : Non Pays :

Si non, explications : Non-patentable research results

Approbations

Signature Chef de groupe	Date	Signature Directeur de section	Date	Signature Directeur général	Date

Numéro IMI 2007 - 115411 - G CNRC 48397

Proceedings of the Light Metals Technology Conference 2007

FRACTURE LOAD PREDICTIONS FOR ADHESIVE JOINTS SUBJECT TO QUASI-STATIC LOADS

M. Eskandarian[1], S. Azari[2], M. Papini[3], and J.K. Spelt[2*]

1) Aluminium Technology Centre, Industrial Materials Institute, National Research Council Canada, 501 boul. de l'Univ., Chicoutimi, Québec, Canada G7H 8C3

2) Department of Mechanical and Industrial Engineering, University of Toronto, 5 King's College Road, Toronto, Ontario, Canada M5S 3G8, spelt@mie.utoronto.ca

3) Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario, Canada M5B 2K3

* Corresponding author

Abstract

The applicability of the fracture envelope approach for fracture load predictions of adhesive joints was investigated by carrying out a series of quasi-static fracture tests on various adhesive specimens. The fracture envelopes of aluminum and steel adhesive systems were determined from the mixed-mode tests on double cantilever beam specimens (DCB). The results were then used to predict the ultimate strength of more practical adhesive joints such as cracked lap shear (CLS) and single lap shear (SLS) joints. Good agreement was observed between the predicted and experimental fracture loads of tested adhesive joints.

Introduction

For many years, lightweight materials for structural and functional applications have been of interest in various industries. Recent production of composite materials together with the advancement of light metal engineering motivated the development of new features for joining dissimilar materials. In such a situation, the traditional joining technologies such as welding, soldering, and mechanical fastening are either not applicable or increase the weight of the assemblies. The appropriate combination of the usage of lightweight materials such as aluminum or magnesium and light joining techniques such as adhesive bonding can optimize production cost, performance and energy consumption if the strength, durability and corrosion considerations are taken into account. In the transportation industries, aluminum has been widely used in non-structural assemblies. In recent years, the usage of high-strength aluminum alloys was extended to some structural parts, which causes 40% to 60% automobile mass reduction when replacing steel or cast iron components [1]. The joining of aluminum parts was a challenging subject for many years. The use of adhesive joints for structural design has been considered as an alternative to traditional joints in aerospace and construction industries since the 1940s [2]. Adhesive jointing improves the fatigue performance and vibration damping in components; diminishes corrosion problems for dissimilar materials regardless of size and shape; reduces the stress concentrations in complex geometries while providing structural integrity. Adhesive bonds give a smoother appearance to designs and enable a reduction in material thicknesses in lighter materials when required. However, care must be taken for the design of adhesive joints especially in the presence of environmental degradation.

Analysis and formulation

A generalized engineering approach to fracture load predictions for adhesive joints was presented in Refs. [3], [4] and [5]. The approach is based on the premise that the strength of any adhesive system can be characterized by an experimentally measured fracture envelope. The term refers to the variation of critical energy release rate, G_c, as a function of the loading mode (mode ratio or phase angle ψ). The concept of a cracked adhesive sandwich is used in the calculation of strain energy release rate G for the adhesive joint. The bonded overlap is isolated from the surrounding structure as a free-body as shown in Figure 1. The von-Karman beam theory of large deformation was applied to determine the response of the joint as the reacting forces and moments on the boundary of the free body. The energy release rate, G, for the cracked adhesive sandwich was then calculated using a closed-form expression of *J*-integral assuming the materials undergoes the finite elastic deformations under the loading configuration. For planar adhesive joints, the mode ratio or phase angle ψ is analytically calculated from the ratio of the mode components G_{II} and G_I, which is related to joint geometry for any particular loading configuration.

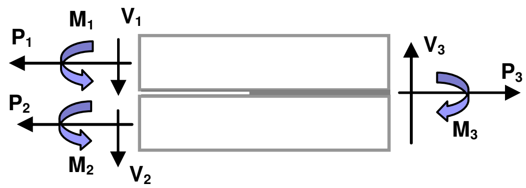


Figure 1: The reacting forces and moments on the cracked adhesive sandwich element.

The calculated energy release rate and the phase angle for any adhesive joint system then represent an energy point on the plane of a fracture envelope. In a typical quasi-static loading condition, a joint can be considered safe, transient or unsafe if the corresponding energy point lies within, coincides or is above the fracture envelope of the adhesive system, respectively. The concept of a cracked adhesive sandwich element makes the approach applicable to a variety of adhesive joints including the standard double-cantilever-beam (DCB) joints or the more practical ones such as the single-lap-shear (SLS) and cracked-lap-shear (CLS) joints. The detailed energy release rate formulations for DCB, CLS, and SLS joints can be found in Refs [3] to [5].

Experiments and results

In this work, the fracture envelopes of a heat-cured toughened epoxy adhesive system were measured by conducting a series of quasi-static fracture tests on aluminum and steel double cantilever beam (DCB) specimens. The results were then used to predict the quasi-static critical loads of CLS and SLS adhesive joints made of aluminum adherends. The sample sizes and materials were chosen carefully to ensure the adherends underwent only elastic deformation during the quasi-static tests. The DCB specimens used for the tests at lower mode ratios were fabricated from aluminum 6061-T651 and steel AISI 1018. Due to the elevated load levels at higher mode ratios, the CLS, SLS and some of the DCB specimens were made of the aluminum 7075-T651 and the steel AISI 4140 flat bars. The aluminum parts were abraded, degreased and then surface pretreated by following the P2-etch surface preparation technique, ASTM D2651-01. The steel parts, however, were only abraded and degreased prior to bonding. The aluminum or steel flat bars were then bonded using a toughened epoxy adhesive and cured in the oven at 180°C. The bondline thickness of 0.4 mm was selected and controlled by placing two steel wires, one prior to precrack and another one close to the end of specimens. The bonded specimens were kept in the oven over night to be gradually cooled down to room temperature. The both sides of specimens were then milled using a four-blade carbide cutter to remove both the excess adhesive and the round edges of the flat bars. The typical final finished DCB and CLS specimens are shown in Figure 2. The schematic representations of different adhesive joints and the geometry of the tested DCB, CLS and SLS specimens can be found in Appendix A.

Figure 2: The finished aluminum and steel DCB (left) and aluminum CLS specimens (right) tested.

The DCB specimens were first tested using the load jig of Ref. [3] at different mode ratios to determine the fracture envelope of the adhesive systems. The cohesive fracture through the adhesive layer was observed for aluminum DCBs while some local interfacial failures occurred for steel specimens. During the test, the specimens were loaded with a constant crosshead speed of 1.5 mm/min up to the point of crack propagation and were then unloaded. The critical energy release rate G_c corresponding to this point was calculated from the crack length, fracture load, specimen geometry, and the mechanical properties of the adhesive and adherends. The analytical method based on large deformation beam theory was used for the energy calculations. The procedure was then repeated for different crack lengths up to the end of the DCB specimen. The typical R-curves resulting from the quasi-static fracture tests on aluminum and steel DCBs under mode-I loading are compared in Figure 3. The average value of G_c in the plateau region of each curve represents an energy point on the plane of the fracture envelope of the adhesive system for the corresponding mode ratio. The fracture envelope of adhesive system is then obtained by repeating the fracture tests at different mode ratios.

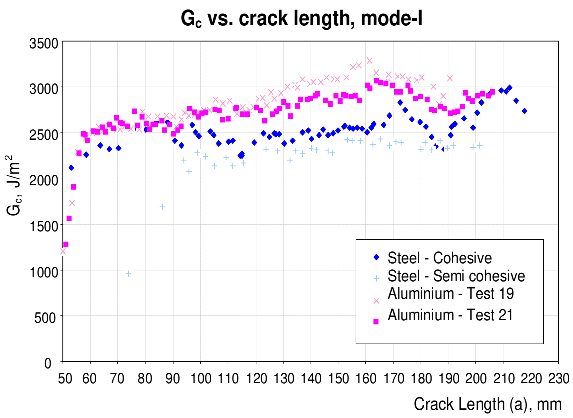


Figure 3: R-curves for aluminum and steel DCBs.

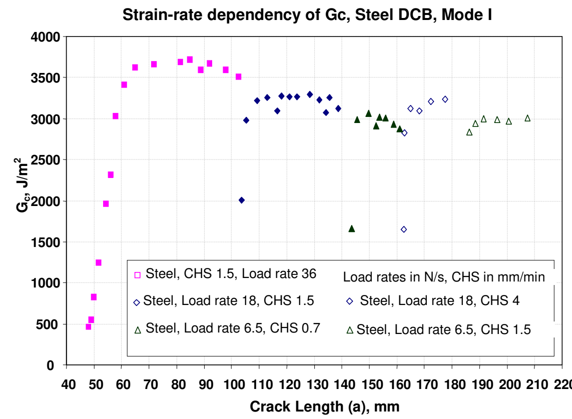
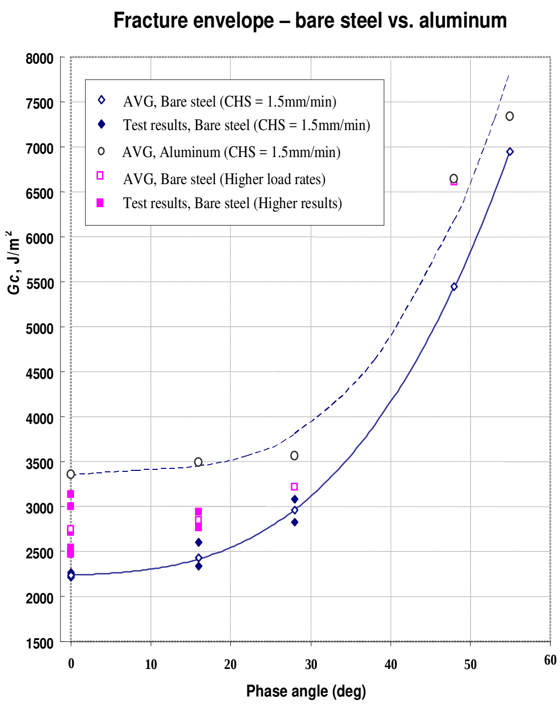


Figure 5: Strain-rate dependency of G_c measured with steel DCBs.

In Figure 4, the fracture envelopes of steel and aluminum adhesive systems are compared. The differences in G_c of aluminum and steel systems decreased at higher phase angles. The testing parameters such as the loading rate also contribute to this difference, especially when more viscoelastic adhesives are used. Higher values of G_c were measured for the tests at higher loading rates. The typical results are shown in Figure 5 for the steel adhesive system.

A third-order polynomial curve was fitted on the data, giving G_c as a function of ψ (fracture envelope) as shown at the bottom of Figure 4. To verify the accuracy of the model for fracture load predictions, six CLS and eight SLS joints of different geometries were made from 1”×3/4” aluminum 7075-T651 flat bars. The specimens were then loaded to ultimate fracture on a servo-hydraulic load frame under constant crosshead speed (CHS). A series of ANSYS™ finite elements analyses have been conducted in order to find the appropriate CHS for CLS and SLS tests to provide similar strain rates in the adhesive layers of CLS, SLS and DCB specimens at the same mode ratio. The CHS of 0.25 mm/min was typically selected for the CLS tests based on the results of FE models to give strain rates equal to those in the DCB specimens tested at 1.5 mm/min, as typically shown in Figure 6.



$$G_{c,AL} = 3237.9 + 13.3420\,\psi - 0.6832\,\psi^2 + 0.0345\,\psi^3$$

$$G_{c,ST} = 2357.5 + 0.3847\,\psi + 0.1509\,\psi^2 + 0.0209\,\psi^3$$

Figure 4: Fracture envelopes of aluminum and steel adhesive systems.

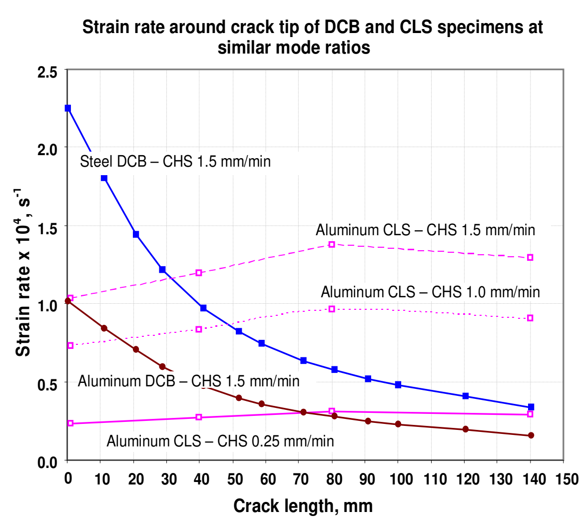


Figure 6: Strain-rate variation in adhesive layer of DCB and CLS specimens versus crack length.

The crack initiation and crack growth on both sides of the joint overlap were examined by using two CCD cameras. It was observed that the crack initiated at lower load levels, but the final catastrophic failure occurred after a subcritical crack of about 50 mm, which was almost equal to the length of the rising part of the DCB R-curve at a similar mode ratio as measured using the fracture envelope load jig. The CLS and SLS joint geometries were then modified by the length of the subcritical crack, which is 50 mm from the point of crack initiation. The initial and the ultimate fracture loads for the six CLS and eight SLS experiments are given in Table 1 and 2. Good agreement was observed between the predicted and experimental fracture loads.

Table 1: Predicted and experimental measurement of fracture loads for aluminum CLS specimens.

Specimen	$P_{Initial}$ (kN)	P_{Exp} (kN)	P_{Pred} (kN)	Error % $(P_{Exp} - P_{Pred}) / P_{Exp}$
CLS 12A	46.5	66.0	61.3	-7
CLS 12B	41.0	65.0	61.1	-6
CLS 12 C	47.8	65.9	74.5	13
CLS 13A	42.0	64.2	63.8	-1
CLS 13B	53.4	65.2	56.6	-13
CLS 13C	40.7	71.3	68.9	-3

Table 2: Predicted and experimental measurement of fracture loads for aluminum SLS specimens.

Specimen	$P_{Initial}$ (kN)	P_{Exp} (kN)	P_{Pred} (kN)	Error % $(P_{Exp} - P_{Pred}) / P_{Exp}$
SLS 1A	34.0	38.4	41.0	-6.6
SLS 1B	---	39.7	39.6	0.2
SLS 2A	28.0	45.3	47.6	-5.8
SLS 2B	---	43.8	44.6	-1.9
SLS 3A	---	45.7	44.6	2.4
SLS 3B	---	50.6	49.8	1.6
SLS 4A	16.5	35.6	34.4	3.4
SLS 4B	30.2	38.5	38.2	0.8

Conclusions

The accuracy of the fracture envelope approach for fracture load predictions of adhesive joints was evaluated for a heat-cured toughened adhesive system by performing a series of quasi-static fracture tests on DCB and CLS specimens made of aluminum and steel. The loading rate was found to be an important parameter in joint behavior when a tough and viscoelastic adhesive is used. Good agreement was observed between the predicted and experimental fracture loads of CLS joints made of aluminum when tested at similar loading rate conditions.

Acknowledgements

The authors wish to acknowledge General Motors of Canada and the Aluminium Technology Centre of the National Research Council of Canada for their financial support.

References

[1] William F. Powers, Advanced Materials and Processes, May 2000, pp. 38 – 41

[2] K.L. Mittal, Adhesive joints: Formation, Characteristics and testing, 2, pp 159 – 199

[3] G. Fernlund and J.K. Spelt, Failure load prediction of structural adhesive joints, Int. J. Adhes. Adhes., 1991, 11, pp. 213 – 220

[4] G. Fernlund and. J.K. Spelt, Mixed-mode fracture characterization of adhesive joints, Comp. Sci. Technol., 1994, 50, pp. 441– 449

[5] G. Fernlund, M. Papini, D. McCammond and J.K. Spelt, Fracture load predictions for adhesive joints, Compos. Sci. Technol., 1994, 51, pp. 587 – 600

Appendix A

The DCB specimens were made of aluminum and steel ½” × ¾” flat bars, while the 1” × ¾” flat bars were used for the fabrication of CLS specimens due to higher load levels. The final finished geometry of tested DCB and CLS joints are given in Table A1 and A2. The schematic representations of the specimens are also shown in Figure A1 to A3.

Table A1: Geometry and initial condition of CLS specimens

Specimen	Initial Condition	Material	Width (mm)	L_1 (mm)	L_2 (mm)	L_3 (mm)
CLS 12A	Lump, pre	Alum.	17.9	125	101	-
CLS 12B	Lump	"	17.2	296	122	-
CLS 12 C	Fillet	"	17.4	288	160	-
CLS 13A	Fillet	"	17.5	180	120	-
CLS 13B	Fillet, pre	"	17.9	310	140	-
CLS 13C	Lump	"	17.6	300	100	-

Table A2: Geometry and initial condition of SLS specimens

Specimen	Initial Condition	Material	Width (mm)	L_1 (mm)	L_2 (mm)	L_3 (mm)
SLS 1A	Fillet	"	16.8	197	99	120
SLS 1B	Fillet	"	16.7	159	108	82
SLS 2A	Precracked	"	17.4	172	121	143
SLS 2B	Lump	"	16.7	207	123	148
SLS 3A	Fillet	"	17.3	192	125	145
SLS 3B	Lump	"	17.5	158	153	122
SLS 4A	Fillet	"	17.7	217	87	93
SLS 4B	Lump	"	17.7	174	97	102

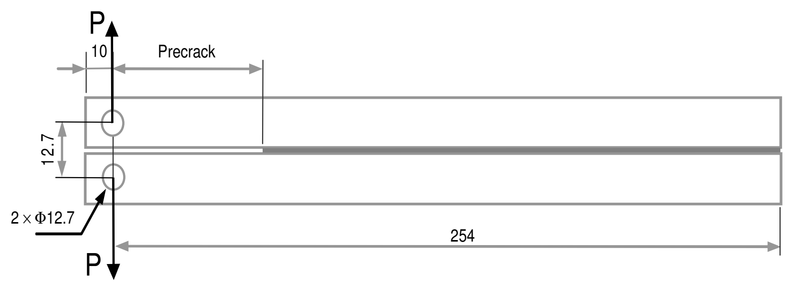


Figure A1: The schematic representations of DCB adhesive specimen

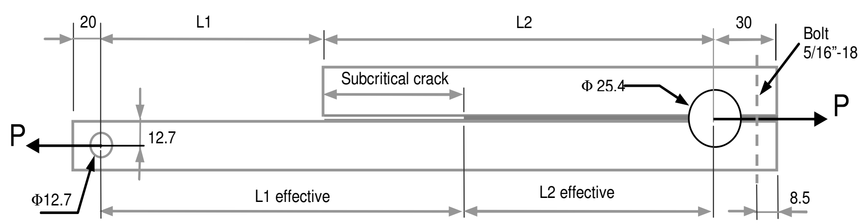


Figure A2: The schematic representations of CLS adhesive specimen

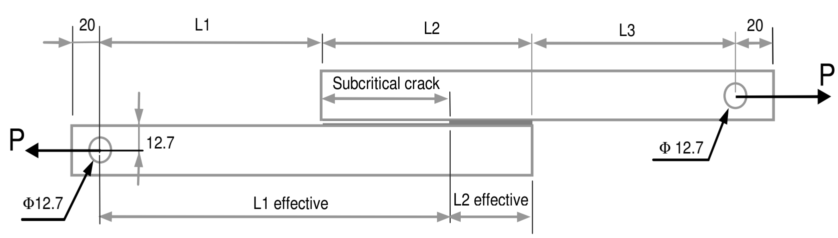


Figure A3: The schematic representations of SLS adhesive specimen