THE DETERMINATION OF DELAMINATION STRAIN ENERGY RELEASE RATE OF COMPOSITE BI-MATERIAL INTERFACE

Jaroslav Juracka*, Vladimir Matejak*
***Brno University of Technology, Institute of Aerospace Engineering**
juracka@fme.vutbr.cz; matejak@fme.vutbr.cz

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Abstract

Increasing use of composite materials in aircraft structures requires a development of new analysis methods. These methods should account for possible influences of structural damage and imperfections typically occurring in these materials. Delaminations are the main interest here.

Fracture mechanics and strain energy release rate approach have been widely used for characterizing delamination in composite materials. This paper focuses on extending this approach to delaminations at bi-material interface of GRFP and CRFP. Combination of these materials is a common design practice in small aircrafts and enables the utilization of carbon composite materials superior mechanical properties and glass composite lower cost.

Modification of FRMM (Fixed Ratio Mixed Mode) testing method was used in order to get critical strain energy release rate in various levels of mixed mode (mode I / mode II). Beam theory analysis with conjunction of VCCT (Virtual Crack Closure Technique) was utilized for establishing equations for previously mentioned test method. Another modification of common testing procedure was application of Aramis photogrammetry system during the measurement of crack tip propagation in a specimen and following image post-processing by Python programming language.

Only a narrow interval of mode mixity was achieved by FRMM specimen configuration. More testing needs to be done in pure mode I and Mode II condition in order to get a complete characterization of delamination behavior.

1 Introduction

Delamination is one of the most commonly observed failure modes in composite materials. The most common sources of delamination are the material and structural discontinuities that give rise to interlaminar stresses. Delaminations usually occur at stress-free edges, ply drops or regions subjected to out-of-plane loading, such as bending of curved beams. Delaminations may be formed during manufacture under residual stresses or as a result of the lay-up process or in-service.

Fracture mechanics are commonly applied for analyzing delaminations, due to the crack-like type of discontinuity accompanying these defects. The strain energy release rate approach has been used in most studies of composite delaminations (both experimental and computational) instead of stress intensity approach which is typically used for isotropic materials fracture mechanics. The critical strain energy release rate, G_c, is a measure of fracture toughness and may be different for three different types of loading (mode I - opening, mode II - in-plane shear, mode III - out-of-plane shear). Usually delaminations occur in certain combination of this three modes.

Bi-material interface in composite laminates may be another source of delamination initiation, because the material and stress discontinuity at this interface. Very few studies were done so far, which includes the effect of delamination between two dissimilar materials. In real life constructions made of composite materials, for example small aircrafts, the combination of glass and carbon reinforced plastics is a common design practice. This enables the utilization of carbon composite materials superior mechanical properties and glass composites lower cost.

Several methods have been developed for testing of composites fracture toughness of a single material. A good overview of these methods give for example Ref. [2]. Fixed ratio mixed mode (FRMM) will be further analyzed in more detail, accounting for the effect of bi-material interface. This test is simple to perform and various ratios between Mode I and Mode II can be achieved by modifying the geometry of specimen.

2 Mixed mode delamination analysis

2.1 Beam theory

After the deduction of Williams [1], it is possible to determine the energy release rate, G, of a delamination specimen based on the applied moments and forces at the end of crack. Figure 1 shows a composite laminate of thickness $2h$ and width b containing a delamination at an interface of the two components at a distance h_1 from the top surface.

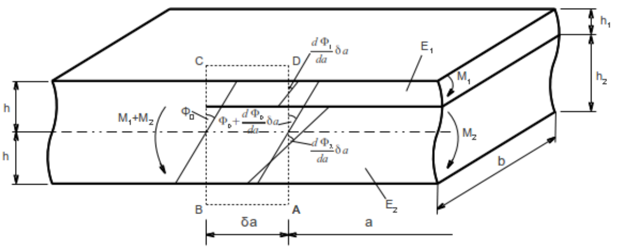


Fig. 1 Interface crack

Let us first consider the end of a delamination as shown in Figure 1 in which bending moments M_1 and M_2 are applied to the upper and lower sections respectively. We may use the usual method of finding G and consider that crack growths from section AB to CD by δa. G may be defined as

$$G = \frac{1}{b}\left(\frac{dU_e}{da} - \frac{dU_s}{da}\right) \tag{1}$$

for the contour where U_e is the external work performed and U_s is the strain energy. This may be rewritten as

$$G = \frac{1}{b}\frac{dU_c}{da} = \frac{1}{b}\frac{dU_s}{da} \tag{2}$$

where U_c is the complementary energy which is equal to U_s for the linear case. The strain energy in a beam is given by

$$\frac{dU_s}{da} = \frac{1}{2}\frac{M^2}{EI} \tag{3}$$

so the change within the contour is

$$\begin{aligned} \Delta U_s &= \frac{M_1^2}{2E_1I_1}\Delta a + \frac{M_2^2}{2E_2I_2}\Delta a - \\ &- \frac{(M_1+M_2)^2}{2EI}\Delta a \end{aligned} \tag{4}$$

where

$$I_0 = \frac{2bh^3}{3} \tag{5}$$

$$I_1 = \frac{2bh_1^3}{12} = \xi^3 I_0 \tag{6}$$

$$I_2 = \frac{2bh_2^3}{12} = (1-\xi)^3 I_0 \tag{7}$$

$$\xi = \frac{h_1}{2h} \tag{8}$$

$$(1-\xi) = \frac{h_2}{2h} \tag{9}$$

$$\begin{aligned} EI &= \frac{bh_2^3h_1E_2E_1}{12(h_1E_1+h_2E_2)}\left[4+6\frac{h_1}{h_2}+\right. \\ &\left.+4\left(\frac{h_1}{h_2}\right)^2+\frac{E_1}{E_2}\left(\frac{h_1}{h_2}\right)^3+\frac{E_2}{E_1}\frac{h_2}{h_1}\right] \\ &= \frac{2I_0(1-\xi)^3\xi E_2E_1h}{(h_1E_1+h_2E_2)}\star \end{aligned} \tag{10}$$

$$\star = \left[4 + 6\frac{\xi}{1-\xi} + 4\left(\frac{\xi}{1-\xi}\right)^2 + \right.$$
$$\left. + \frac{E_1}{E_2}\left(\frac{\xi}{1-\xi}\right)^3 + \frac{E_2}{E_1}\frac{1-\xi}{\xi}\right] \qquad (11)$$

After substitution we may rewrite the strain energy release rate from Eq.(11) as

$$G = \frac{3}{4b^2h^3}\left(\frac{M_1^2}{E_1\xi^3} + \frac{M_2^2}{E_2(1-\xi)^3} - \right.$$
$$\left. - \frac{(M_1+M_2)^2(h_1E_1+h_2E_2)}{2E_2E_1h(1-\xi)^3\xi[\star]}\right) \qquad (12)$$

2.1.1 Strain energy release rate for FRMM test specimen

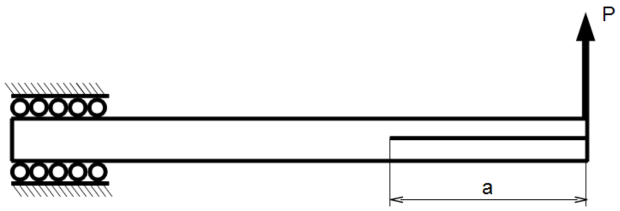


Fig. 2 Fixed ratio mixed mode test

Only one beam of the specimen is loaded by a load P in the FRMM test (Figure 2). If only bending moments are taken into account and the load is applied to the upper beam, which thickness is h_1, the resulting moments are $M_1 = -Pa$ and $M_2 = 0$. After simplification, the total strain energy release rate is

$$G = \frac{3P^2a^2}{4b^2h^3}\left(\frac{1}{E_1\xi^3} - \right.$$
$$\left. - \frac{h_1E_1+h_2E_2}{2E_2E_1h(1-\xi)^3\xi[\star]}\right) \qquad (13)$$

2.1.2 Mode partitioning

As the contribution of mode III is not considered, the total energy release rate in equation (12) is the sum of mode I and mode II. To obtain the contribution of each individual mode, equation (12) must be partitioned. This cannot be done by simple analytical deduction, as will be showed later in this chapter.

Pure mode II propagation occurs when the curvature of both arms is the same and therefore

$$\frac{d\theta_1}{da} = \frac{d\theta_2}{da} \qquad (14)$$

and if we have M_{II} on the upper arm and ψM_{II} on the lower then

$$\frac{M_{II}}{E_1I_1} = \frac{\psi M_{II}}{E_2I_2}, \quad i.e. \quad \psi = \frac{E_2(1-\xi)^3}{E_1\xi^3} \qquad (15)$$

The opening mode only requires moments in opposite senses so we have M_1 on the upper arm and M_1 on the lower arm so that the applied moments may be resolved as

$$\begin{aligned} M_1 &= M_{II} - M_I \\ M_2 &= \psi M_{II} + M_I \end{aligned} \qquad (16)$$

i.e.

$$\begin{aligned} M_I &= \frac{M_2 - \psi M_1}{1+\psi} \\ M_{II} &= \frac{M_2 + M_1}{1+\psi} \end{aligned} \qquad (17)$$

Substituting these expressions in Eq.(12), we have

$$G = \frac{3}{4b^2h^2}\left[\frac{M_I^2}{E_1\xi^3} + \frac{M_I^2}{E_2(1-\xi)^3)} + \right. \qquad (18a)$$
$$+ \frac{M_{II}^2}{E_1\xi^3} + \frac{M_{II}^2}{E_2(1-\xi)^3)} - \qquad (18b)$$
$$- \frac{M_{II}^2(1+\psi)^2(h_1E_1+h_2E_2)}{2E_1E_2h\xi(1-\xi)^3[\star]} + \qquad (18c)$$
$$\left. + \frac{2\psi M_IM_{II}}{E_2(1-\xi)^3} - \frac{2M_IM_{II}}{E_1\xi^3}\right] \qquad (18d)$$

where on the line (18a) are pure mode I terms, on the lines (18b) and (18c) pure mode II terms and on the line(18d) are cross-terms of both modes, which cannot be partitioned, unless $E_1 = E_2$ and the contribution of the (18d) is 0.

FE methods offer other possibility of investigating mode mixity ratio. This will described in the next section.

2.2 VCCT

The goal of the FE analysis was to determine a mode mixity ratios of the bimaterial interface in FRMM configuration. This ratio is a function of two parameters: E_1/E_2 and thickness ratio ξ. Twelve models were created using MSC.Marc software, with different combinations of mentioned parameters. Mode mixity function is then obtained by surface interpolation of these points.

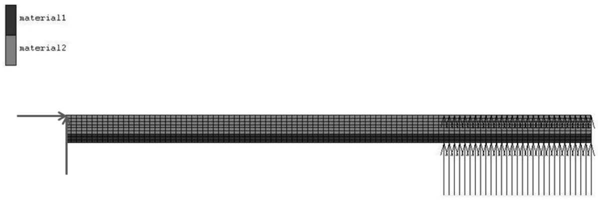


Fig. 3 FE model

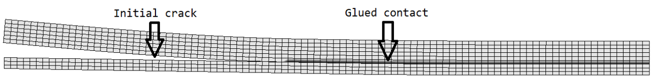


Fig. 4 Initial crack definition

Figure 3 shows geometry and boundary conditions for one of the models. Three ratios of E_1/E_2 were modelled: 0.1, 1 and 2. Glued contact was prescribed between lower and upper arm of the specimen, where the initial crack was modelled as a glue deactivation region (Figure 4). Thickness ratio $\xi = \frac{h_1}{h_1+h_2}$ was set to 0.21, 0.515, 0.68 and 0.81 for different models. Resulting mode mix ratios G_{II}/G_{total} for all models are given in Table 1.

Several 3D surface models were fitted to these results, three of them are shown at the Fig. 5. Fitted models are noted as: Rational (Eq.19a), Simplified Quadratic (Eq.19b) and Cosh-Transformed (Eq.19c).

E_1/E_2	ξ	G_{II}/G_{total}
0.1	0.21	0.47
0.1	0.515	0.57
0.1	0.68	0.67
0.1	0.81	0.76
1	0.21	0.35
1	0.515	0.39
1	0.68	0.43
1	0.81	0.47
2	0.21	0.27
2	0.515	0.3
2	0.68	0.34
2	0.81	0.38

Table 1 Mode mixity results from VCCT

$$\frac{G_{II}}{G_{total}} = \frac{A + Be^{\frac{E_1}{E_2}} + Ce^{\xi}}{1 + D\frac{E_1}{E_2} + F\xi} \tag{19a}$$

$$\frac{G_{II}}{G_{total}} = A + B\frac{E_1}{E_2} + C\xi + D\left(\frac{E_1}{E_2}\right)^2 + F\xi^2 \tag{19b}$$

$$\frac{G_{II}}{G_{total}} = Acosh\left(B\frac{E_1}{E_2} + C\right)cosh(D\xi + F) \tag{19c}$$

coef.	Rational	Simpl. Quadratic	Cosh-Trans.
A	3.6188E-01	5.5847E-01	2.4653E-01
B	1.0664E-02	-3.1337E-01	6.1721E-01
C	5.2493E-02	-5.8497E-02	-1.3430E+00
D	4.6812E-01	7.52923E-02	-1.2680E+00
F	-4.8953E-01	3.41795E-01	1.3821E-02

Table 2 Fitted models coefficients

From the results we can deduce that mode II contribution to the total strain energy release rate is increasing with increasing elastic modulus ratio and thickness ratio. Whereas contribution of mode I is increasing with higher compliance of the upper arm.

3 Delaminatin resistance testing

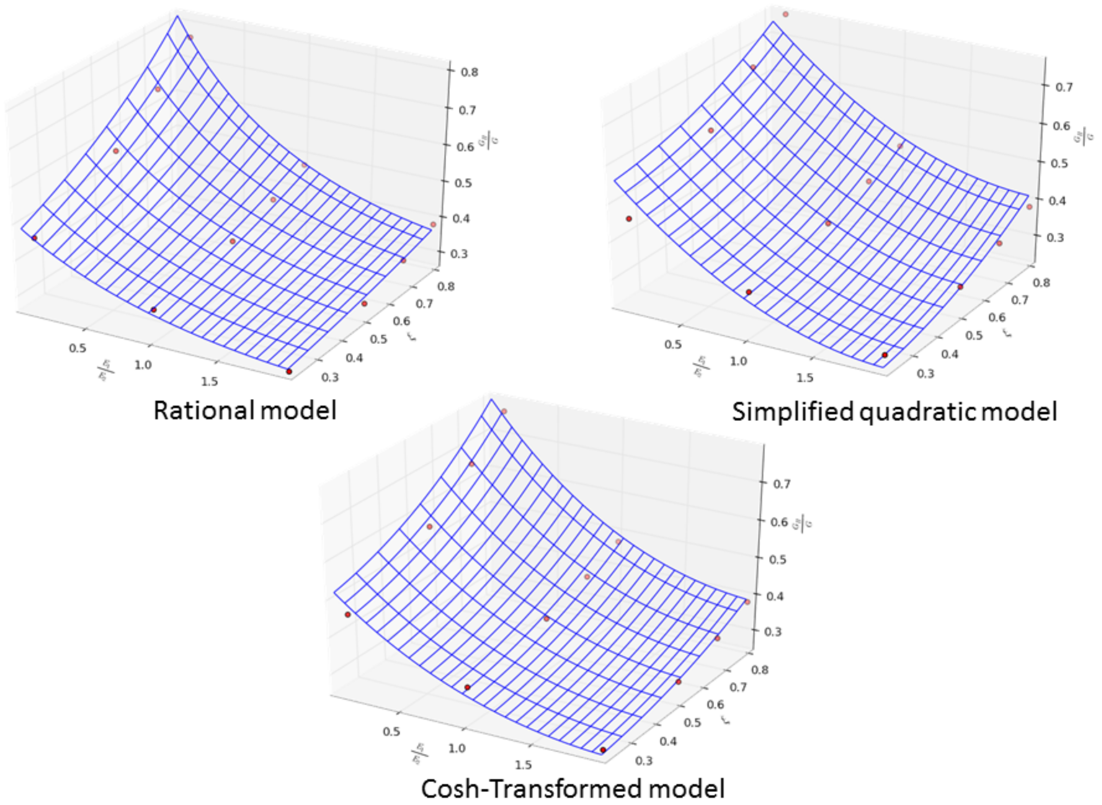


Fig. 5 Surface interpolation of VCCT results

3.1 Specimen description

A set of 15 specimens from combination of CRFP and GRFP was made. Initial delamination was substituted by a thin foil inserted at the material interface. Specimens were made in three different ratios of component thickness. Geometry and material composition is described in Fig. 7.

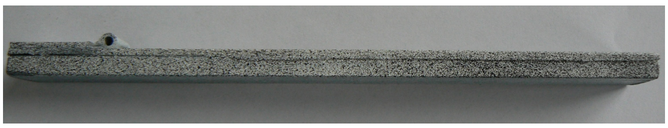
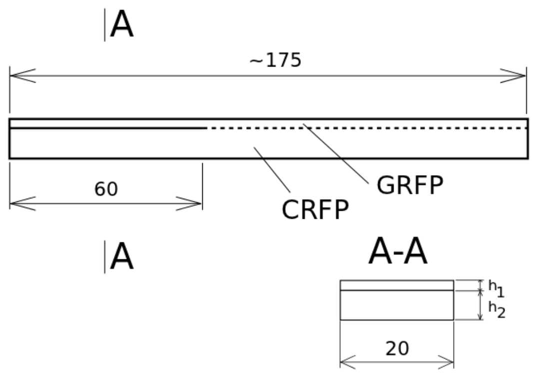


Fig. 6 Contrast paint



Spec. No.	Thickness [mm]		Material	
	h_1	h_2	GRFP	CRFP
1 – 5	4.3	2.35	$[0]_{12}$	Unidirectional roving, fibers TENAX HTA 5131
6 – 10	1.7	5.3	$[0]_4$	
11 – 15	2.2	2.35	$[0]_6$	

Fig. 7 Specimen geometry and material

Specimens were also painted by white undercoat with fine black spray pattern to enable a photogrammetry measurement and ease subsequent image processing. This paint is apparent from Fig. 6

3.2 Testing procedure

Fixed ratio mixed mode specimen requires a loading fixture, which enables a free movement of the clamped end in the horizontal direction, in order to minimize axial forces in the specimen and to introduce correct delamination mode. This loading fixture also makes easier to set-up the specimen of different lengths into the testing machine. The designed loading fixture is depicted in Fig. 8.

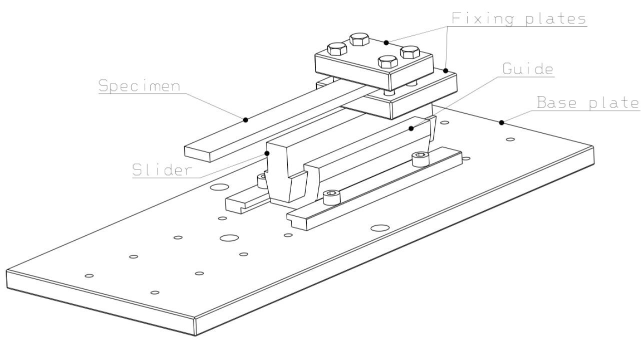


Fig. 8 FRMM loading fixture

Specimens were fixed in the loading fixture and loaded by piano hinges bonded to the upper arm as can be seen in Fig. 9. The procedure was monitored and recorded by a photogrammetry system Aramis with 1Hz frequency. Load cell record was synchronised with the cameras record.

4 Evaluation and results

Total force and loading point displacement were obtained from photogrammetry measurement as a time dependent quantities. An image processing script was written in Python programming language and used for the detection of delamiantion front from every stage recorded by the camera.

The image processing consisted of loading and filtering the image as a matrix of binary values, where ”0” means black pixel a ”1” means white pixel. Then the starting position was set

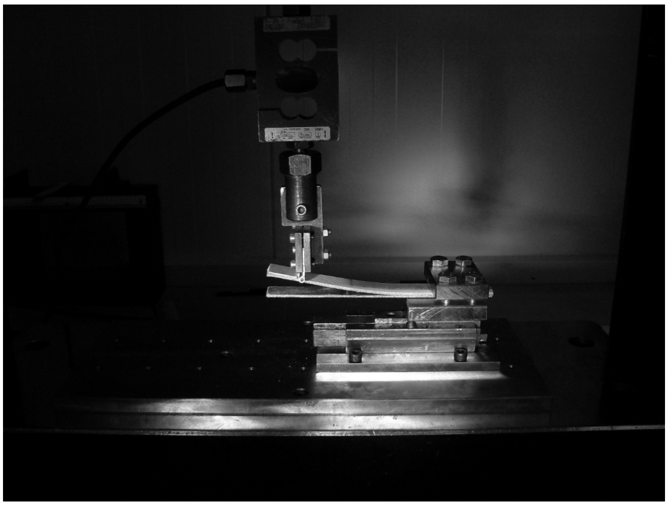


Fig. 9 Test procedure

and delamination front found by stepping procedure as can be seen on Fig. 10. For early stages of loading the script gives an error because no crack is usualy found. However, for the main part of the loading record after the delamination begins to grow from the starting position a_0, the script gives a reasonable results. Pixel coordinates are then used to calculate a delamiantion length a by applying a scale.

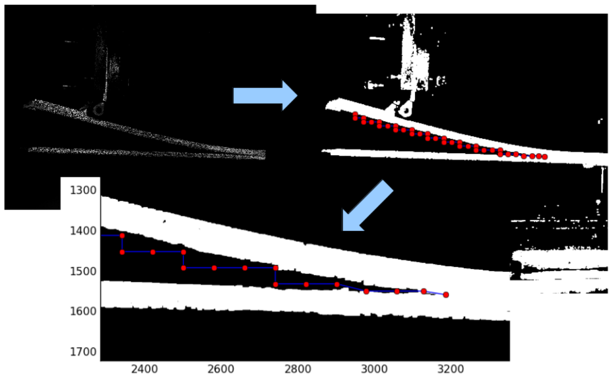


Fig. 10 Image processing to find the delamiantion front

Eq. (12) was used to calculate critical energy release rate and Eq. (19c) - Cosh-Transformed model was used to estimate mode mixity ratio.

Resulting values of critical energy release rate in varius configuration of tested mixed mode delamination at bimaterial interface are plotted in the graph (Fig. 11) as a function of mode mixity ratio. This ratio, representing the contribution of mode II to the total energy release rate (G_{II}/G_{total})varies between 0.5 and 0.64. Scatter of the G_c values is simmilar for all tested configurations.

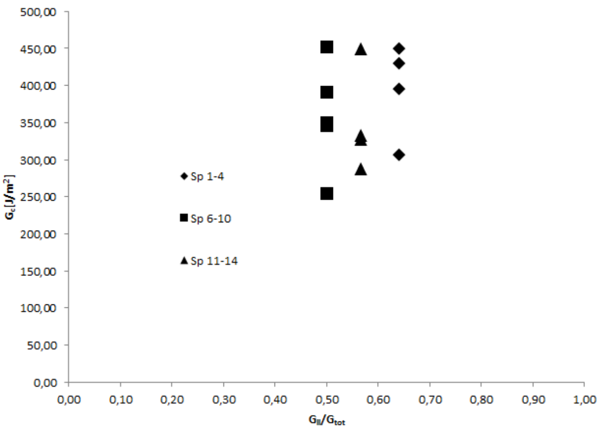


Fig. 11 Critical energy release rate results

5 Conclusions

Mixed mode delamination testing was done so far. This required modification of previously applied test methods to incorporate the influence of bimaterial interface. FE modeling and VCCT method were used to help developping an analytical prediction of mode mixity. FRMM tests ability to test different mixed mode ratios by changing thikness ratio of the specimens arms was confirmed. Although for the three tested configuration the mode mixity (G_{II}/G_{total}) was only between 0.5 a 0.64.

Different testing procedure needs to be analyzed and conducted in the further study in order to get values of fracture toughnes in pure mode I and mode II. This will enable construction of power law function, characterizing whole span of possible mixed modes in real structure.

Following steps will concentrate on application of developed methods on more complex structures, such as small aircraft wing root section.

References

[1] Williams, J.G., *On calculation of energy release rates for cracked laminates*. International Journal of Fracture, 36:101-119, 1987.

[2] Davies, P., *Review of standard procedures for delamination resistance testing*. Delamination behaviour of composites, Woodhead Publishing Limited, 2008.

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