ON MODE I AND MODE II BRIDGING LAWS AND BRIDGING MECHANISMS IN Z-PINNED COMPOSITE LAMINATES

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ABSTRACT

This paper reviews our recent progresses in the research on z-pinning reinforcement. The contents will include theoretical, numerical and experimental studies on mode I and mode II z-pinned delamination fracture and corresponding bridging laws. Experimental method of bridging law evaluation will be introduced. Comparison of experimental results and theoretical prediction on a z-pinned double-cantilever beam (DCB) mode I delamination with the evaluated bridging law will be provided to confirm the reliability of the methods. A parametric study by the finite element method (FEM) will be presented to both Mode I and Mode II z-pinned delaminations. A latest result of the effect of loading rate on Mode I delamination growth will also be introduced.

1 INTRODUCTION

Through-thickness-reinforcement technology such as z-pinning and stitching has attracted many attentions owing to its contribution to the fracture toughness of laminated composites against delamination. In the last decade, many papers were published to study the effects of through-thickness reinforcement on mode I, Mode II and mixed mode delamination and the corresponding bridging mechanisms (Jain and Mai, [1], [2], Cox [3], Cartie [4]). Following our earlier study on through-thickness stitching (Jain and Mai, [1], [2]), in recent years, some new investigations were carried out on z-pinning reinforcement in the Centre for Advanced Material Technology (CAMT), which focused on modeling z-pinned Double-Cantilever-Beam (DCB) mode I delamination (Liu et al, [5]), parametric studies on z-pinned mode I and mode II delamination (Yan et al [6], [7]), bridging law evaluation (Dai et al, [8], Liu et al, [9]) and effect of loading rate on z-pinned mode I delamination (Liu et al, [10]). In this paper, these latest studies will be briefly reviewed.

2 Z-PINNED DCB MODE I DELAMINATION

2.1 Z-pinned DCB mode I delamination and Z-pin bridging law

A theoretical model on z-pinned DCB mode I delamination was developed by Liu et al [5] to study the effect of z-pin bridging on delamination growth. In this study, the z-pins were treated as additional bridging forces which were applied to the bent DCB. In the modeling, the relationship between z-pin bridging force and its displacement was given by an assumed z-pin bridging law. Based on a general beam theory, the fracture behaviour of DCB affected by z-pinning was examined in detail. It was also concluded by above work that the delamination behaviour of DCB was greatly dependent on the value of z-pin bridging force but not sensitive to the shape of z-pin bridging law curve. Therefore, a simple form of bridging law which was described by two (bi-linear) or three (tri-linear) linear functions was suggested as shown in Figure 1. The functional relationship is given as

$$P = \begin{cases} \dfrac{\delta}{\delta_1} P_d & (0 \le \delta \le \delta_1) \\ \dfrac{\delta_2 - \delta}{\delta_2 - \delta_1} P_d + \dfrac{\delta - \delta_1}{\delta_2 - \delta_1} P_f & (\delta_1 \le \delta \le \delta_2) \\ P_f + \dfrac{\delta_2 - \delta}{h - \delta_2} P_f & (\delta_2 < \delta \le h) \end{cases} \tag{1}$$

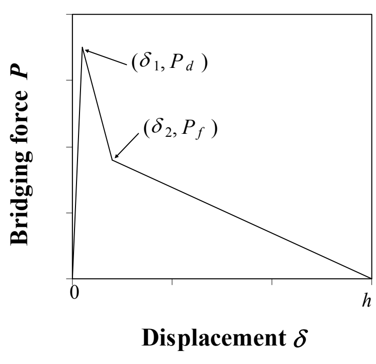

Figure 1 A simplified Z-pin bridging law suggested by Liu et al [5].

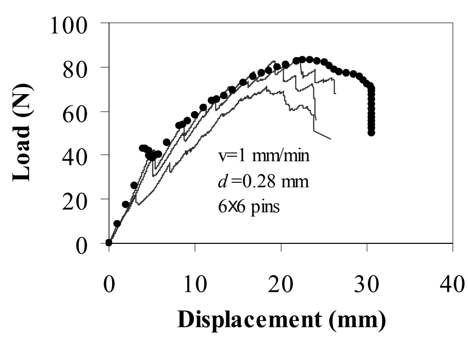

Figure 2 Load-displacement curve of DCB mode I delamination, in which dotted line shows simulated results and solid lines show experimental results from three tests.

in which P_d; and P_f are debonding force and maximum frictional force, δ_1 ,δ_2; are the corresponding displacement and h is the half length of z-pin. To determine those parameters, a series of z-pin pullout tests were performed in CAMT, see Dai et al [8]. The experimental results have confirmed our previous assumption on bridging law as given by Eqn.(1). Also, from the tests, the parameters in the bridging law Figure 1: P_d, P_f , δ_1 and δ_2 were evaluated. Using these data in the computer simulation, see Liu et al [9], the load-displacement curve of z-pinned DCB delamination was obtained. The comparison between the experimental results and simulated results shows good agreement (Figure 2).

2.2 Parametric study by FEM

A parametrical study on z-pinned DCB delamination has been carried out by using FEM, see Yan et al [6]. Fig. 3 shows the influence of the normalized pullout model parameter, δ_a/h, on the normalized energy release rate, G_R/G_{IC}, during crack growth. Here, a bi-linear z-pin bridging law is considered and δ_a is the pullout displacement corresponding to the peak pullout force P_a. Fig. 3 indicates the effect of the pullout parameter δ_a on toughness enhancement is not significant. The effect of the normalized pullout peak force, $P_a/G_{IC}h$, is shown in Fig. 4. It can be seen that the total energy release rate or crack-resistance increases significantly as the peak pullout force, P_a, increases.

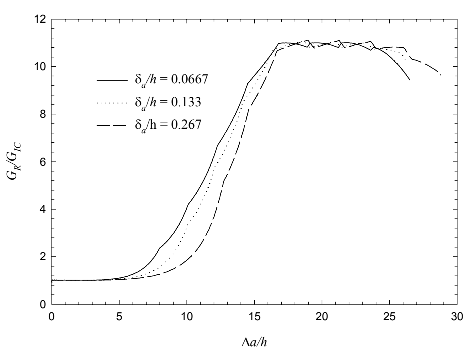

Figure 3: Influence of pullout model parameter, δ_a/h, on delamination toughness, G_R/G_{IC}, with n_c = 8, $P_a/G_{IC}h$ = 61.9 and d_c/h = 2.33.

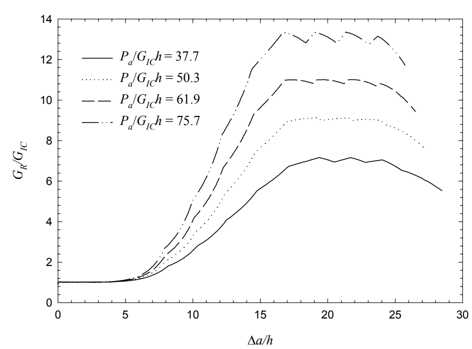

Figure 4: Influence of pullout model parameter, $P_a/G_{IC}h$, on delamination toughness, G_R/G_{IC}, with n_c = 8, δ_a/h = 0.0667 and d_c/h = 2.33.

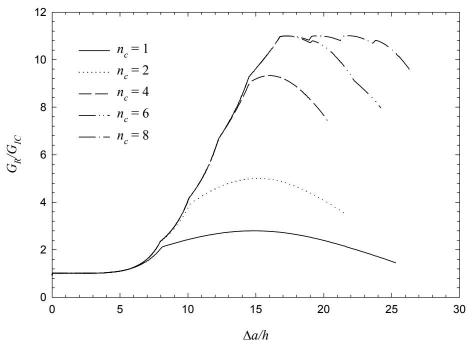

Figure 5: Influence of z-pin column number, n_c, on delamination toughness, G_R/G_{IC}, with $P_a/G_{IC}h$ = 61.9, δ_a/h = 0.0667 and d_c/h = 2.33.

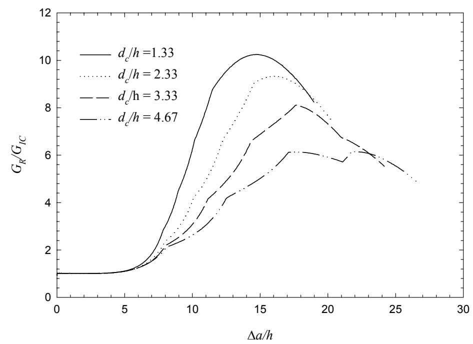

Figure 6: Influence of column spacing, d_c/h, on delamination toughness, G_R/G_{IC}, with $P_a/G_{IC}h$ = 61.9, δ_a/h = 0.0667 and n_c= 4.

Figure 5 shows the influence of the number of z-pin columns, n_c, arranged in beam axis direction on the energy release rate of z-pinned laminates. The number of z-pin columns represents the size of the z-pinned zone in the crack growth direction for a given column spacing, d_c. Therefore, it is not surprised to see that the enhanced toughness G_R/G_{IC} covers a longer delaminated distance for higher number of z-pin columns. Fig. 5 also shows that the maximum crack-resistance G_R increases rapidly from n_c = 1 to 4. This observation indicates that interaction between pin columns can also enhance the delamination toughness of the composite laminate. With n_c increasing continuously from 4 to 8, this effect becomes less efficient. The influence of the normalized column spacing, d_c/h, on the normalized energy release rate, G_R/G_{IC}, is shown in Fig. 6. By keeping the same number of z-pin columns, the delamination toughness is shown to increase with decreasing column spacing. This prediction is consistent with experimental results.

3 Z-PINNED ENF MODE II DELAMINATION

The finite element method has also been applied to study mode II delamination in z-pinned end-notched-flexure (ENF) beam. A bi-linear z-pin bridging law with peak shear force, T_a, is utilized in the numerical investigation. Detailed discussion about the simulation can be found in Yan et al [7]. Some of the numerical results are reported in this section.

Figure 7 shows the effect of the normalized pullout model parameter, δ_a/h, on the normalized energy release rate, G_R/G_{IIC}, during crack growth. It is seen that the normalized toughness G_R/G_{IIC} is higher at smaller δ_a/h, since a larger z-pin pullout force is reached sooner at a shorter normalized crack length *Δa/h.* Physically, this implies that stiffer pins should be used to obtain smaller δ_a. The effect of the dimensionless parameter, $T_a/G_{IIC}h$, is shown in Fig. 8 and is more dramatic than δ_a/h.

Figure 9 shows the influence of the number of z-pin columns n_c varying from 1 to 4 on the normalized G_R/G_{IIC} curves of z-pinned laminates. The toughening effect is felt for longer crack lengths and the maximum toughness is higher if there are more columns of z-pins. Likewise, if we keep the column of pins constant, say n_c=4 as in Fig. 10, smaller column spacing, d_c/h, gives higher normalized toughness, G_R/G_{IIC}, over a shorter bridging length, *Δa/h*. The predictions are consistent with experimental results obtained by Cartie [4], in which they increased the z-pin density (equivalent to decreasing the column spacing) and improved significantly the mode II delamination toughness of ENF specimens.

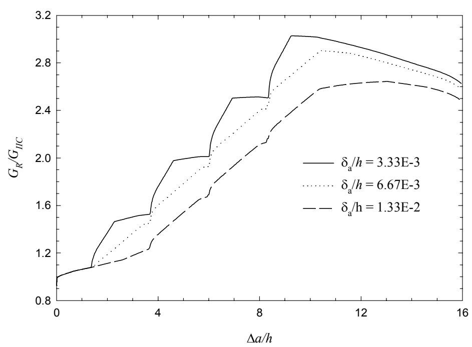

Figure 7: Influence of pullout model parameter, δ_a/h, on delamination toughness, G_R/G_{IIC}, with n_c = 4, $T_a/G_{IIC}h$ = 190.5 and d_c/h = 2.33

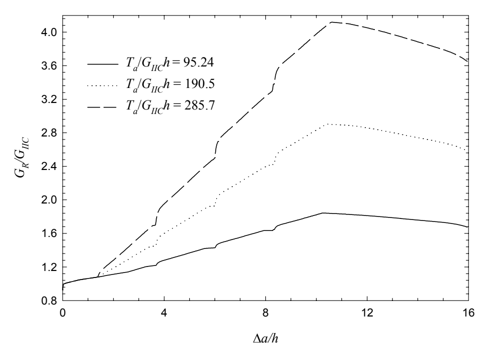

Figure 8: Influence of normalized pullout model parameter, $T_a/G_{IIC}h$, on normalized delamination toughness, G_R/G_{IIC}, during crack growth with n_c = 4, δ_a/h

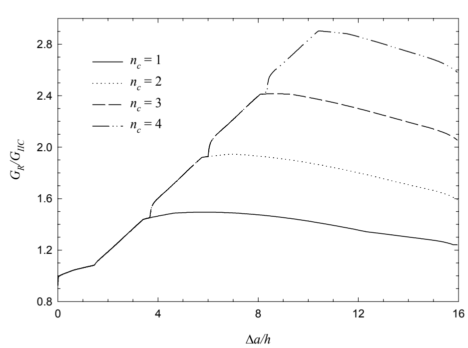

Figure 9: Influence of z-pin column number, n_c, on delamination toughness, G_R/G_{IIC}, with $T_a/G_{IIC}h$ = 190.5, δ_a/h = 0.00667 and d_c/h = 2.33.

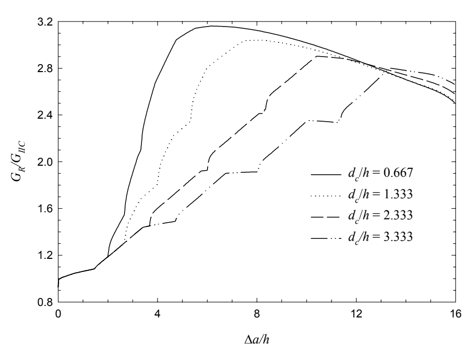

Figure 10: Influence of column spacing, d_c/h, on delamination toughness, G_R/G_{IIC}, with $T_a/G_{IIC}h$ = 190.5, δ_a/h = 0.00667 and n_c = 4.

4 EFFECT OF LOADING RATE ON DELAMINATION GROWTH

Z-pinned DCB mode I delamination tests were performed to study the effect of loading rate on z-pinning bridging mechanism, see Liu et al [10]. It is found that under different loading rates, the bridging mechanisms are different. Under a high loading rate, the pins were always pulled out accompanied by serious splitting along their lengths due to shear failure. Moreover, bending of the pins against the laminates provided an additional "snubbing" friction to deter delamination growth. Thus, the fracture load increased when the loading rate was high. Results of pullout tests showed that the adhesive strength between z-pins and laminates was degraded by loading rate. As a result, the debonding force was significantly decreased when the loading rate was increased. Due to the page limitation, the details of this study will be presented in the conference.

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